

Developing a Data-driven Design Framework for Mass Customisation of Multi-storey Residential Buildings

by Elham Yousefi

Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of Associate Professor Alireza
Ahmadian Fard Fini and Associate Professor Peter Smith

University of Technology Sydney
Faculty of Design, Architecture, and Building

August 2023

Certificate of Original Authorship

I, *Elham Yousefi*, declare that this thesis is submitted in fulfilment of the requirements for the award of *Doctorate 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.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note:
Signature removed prior
to publication.

Date: 24/08/2023

Abstract

The Australian building sector has increasingly encountered a two-sided challenge; one is to meet productivity expectations in the delivery of buildings, and another is to cope with housing variety demanded by the market. These factors have driven the need to adopt mass customisation strategies in the building construction. Mass customisation enables achieving the expected efficiency while it also satisfies demands for custom-built dwellings. Within the residential building sector, multistorey buildings present the largest segment, characterised by diverse customer demands, making them prime candidates for mass customisation. In this area, the integration of design and manufacturing is seen as a solution to the problem of achieving the balance between customisation and mass production efficiency. However, apart from some basic studies in the literature for integrating design and manufacturing, no attempt has been made to examine the potential for mass customised design of multistorey dwellings.

To fill this gap, this research intends to assess the adaptability of multistorey residential buildings to mass customisation and propose an optimisation model for mass-customisation of multi-storey building layouts. The focus was first placed on identifying similarities in architectural layouts and structural spans of different apartments to find manufacturable design patterns that are desirable for the selected developers. To this end, architectural drawings of 710 apartment units were investigated and classified into up to five similar clusters of layouts and spans. The results indicated that more than 68% of apartments have common spans that can be prefabricated offsite by Australian mass timber panel manufacturers and precast factories.

To optimise building layouts for mass customisation, the study then developed a practical framework for integrating production processes in the building design without compromising the flexibility in architecture. The framework consists of a parametric modelling approach to floor design that can adapt a fully customised architectural layout into three mass customisable scenarios. The model is most beneficial in the preliminary design stage, and it considers both manufacturer's and building developer's objectives, who are the key players in the implementation of mass customisation. The model proposes floor layouts by identifying optimal placement of load-bearing walls. The architect can examine various span dimensions to gain a preliminary cost estimation before finalising the design. The study uses Cross-Laminated Timber as a mass customisable prefabricated system increasingly gaining momentum in Australia's building sector to validate the model. The results showed that multistorey apartments can be easily adapted for mass customisation and in doing so, can result in a minimum of 10% cost saving.

*Keywords: Building Design, Mass customisation, Modularisation, Optimisation Model,
Residential Buildings*

Table of Contents

Certificate of Original Authorship	i
Abstract	ii
Table of Contents	iv
List of Figures	vii
List of Tables.....	xi
List of Abbreviations.....	xiii
List of Mathematical Notations.....	xiv
Acknowledgements	xv
Chapter 1: Introduction.....	1
1.1 Overview.....	1
1.2 What is “mass customisation” and how did it emerge and grow?	1
1.3 Mass customisation in the residential building industry	3
1.3.1 The importance of customisation in the residential building sector	3
1.3.2 . The current housing demand in Australia.....	5
1.3.3 The potential of building elements for customisation and standardisation.....	7
1.4 Role of design for MC	8
1.4.1 Importance of the early design stages in product development.....	8
1.4.2 Product family and platform design	9
1.4.3 Computer-aided design.....	10
1.5 Gap in design optimisation for mass customised prefabrication of buildings	11
1.5.1 Lack of a two-sided view towards MC:.....	11
1.5.2 Scarcity of a quantitative approach towards design and production integration:11	
1.5.3 Segregated architectural and structural design	12
1.5.4 Design parameterisation for MC prefabrication of buildings:.....	12
1.6 Research objectives.....	13
1.7 Scope of the research:	14
1.7.1 Type of prefabrication:	14
1.7.2 Taxonomy of design automation	15
1.8 Thesis structure.....	15
Chapter 2: Literature Review and Research Background.....	17
2.1 Overview.....	17
2.2 The key players in implementing MC in multi- storey residential building	19
2.3 Motivations and risks associated with the move toward MC for construction companies and mass producers.....	21
2.4 Law of variability, theory of swift even flow, and utility theory to support mass customisation	24
2.5 Implementing MC in the residential building sector.....	26
2.5.1 Three capabilities that make mass customisation work.....	26
2.5.2 Level of mass customisation in the building industry	31
2.5.3 MC enablers and their related concepts in building design	34

2.6	How to design for mass customisation in a prefabricated system?.....	46
2.6.1	Cross Laminated Timber (CLT)	47
2.6.2	Fundamentals of developing a design framework for building MC	49
2.6.3	Manufacturing processes in CLT system.....	51
2.6.4	Production process time for pressing and CNC router cutting stages	56
2.7	Literature review summary and its implications for this research	58
2.8	Research gap and innovation	58

Chapter 3: Research Design and Methodology 61

3.1	Introduction.....	61
3.2	The constructive research approach.....	62
3.3	Overview of the research process	63
3.4	Research roadmap for stage B	66
3.4.1	Data collection to find a pattern for apartments modular design.....	66
3.4.2	Statistical analysis technique to assess the data pattern and specify spatial voids dimensions.....	68
3.4.3	Clustering techniques.....	71
3.4.4	R programming.....	77
3.5	Research roadmap for stage C	77
3.5.1	Data collection to find a floor panel layout (load-bearing wall position).....	78
3.5.2	Model development	83
3.5.3	Mathematical representation of the model.....	88
3.5.4	Applying Genetic Algorithm as a solution search method of the model.....	91
3.5.5	Model validation techniques.....	93
3.6	Research design summary and its implications for this thesis.....	93

Chapter 4: Analysing and Clustering Building Layouts 95

4.1	Introduction.....	95
4.2	Applying spatial voids perspective to find a pattern for apartments' modular design. 97	
4.2.1	Apartments architectural design with a view of spatial voids	99
4.2.2	Spatial voids configuration (apartments spaces dimensions) through cluster analysis	110
4.3	Analysing manufacturability of layout designs through investigating the capability of prefabricated systems manufacturers (manufacturing perspective)	121
4.3.1	Apartments' spans analysis.....	122
4.3.2	Component manufacturing practices in Australia	125
4.3.3	Recognising modular design patterns in architectural floor plans through cluster analysis	129
4.3.4	Recognising modular design patterns considering the building vertical design (floor levels).....	137
4.4	Data analysis validation and contribution to MC in the residential building industry	140
4.5	Summary	142

Chapter 5: Analysing and Validating MC-based Modelling of Building Layout 145

5.1	Overview.....	145
5.1	Model's computational efficiency with a case study	146
5.1.1	The main characteristics considered in the proposed model	147
5.1.2	Running the model for a mass customised design scenario.....	149
5.1.3	Running the model for mass-produced and fully-customised design scenarios	159
5.2	Model validation and contribution to MC in the building industry	163

5.3	Summary.....	165
Chapter 6: Conclusions.....		166
6.1	Overview.....	166
6.2	Research objectives and key findings	166
6.2.1	Sub-objective 1: Manufacturable layout design	166
6.2.2	Sub-objective 2: Architectural-Structural Interrelationships	167
6.2.3	Sub-objective 3: Key stages in offsite prefabrication processes.....	167
6.2.4	Sub-objective 4: Optimal design for manufacture.....	168
6.3	Research contribution and potential use in the building industry	169
6.3.1	Implication for reseach	169
6.3.2	Implication for practice.....	170
6.4	Research limitation and future research direction.....	171
6.4.1	Research limitations.....	171
6.4.2	Future research	171
Bibliography.....		174
Appendices		184

List of Figures

Figure 1- The share of the residential building sector within the Australian construction industry.....	5
Figure 2- The growth of multi-storey apartments with more than 4 storey	6
Figure 3- A holistic view of a product family and platform design and development in a MC approach, adapted from.....	10
Figure 4- A schematic view of the research gap for implementing MC in the preliminary design stage	11
Figure 5- Overview of the research scope	14
Figure 6- Flow diagram of Chapter 2	18
Figure 7- Demand-side and supply-side for implementing a MC strategy adopted in the thesis.....	21
Figure 8- Leveraging customisation/ platform strategy through different decoupling points in engineering	33
Figure 9- Components and spatial perspectives hierarchical levels	38
Figure 10- Different range of modular systems in terms of component perspective,	39
Figure 11- Product family and platform within a product variant.....	40
Figure 12- Holistic view of product family and platform concept in prefabricated systems	43
Figure 13- Clustering technique to enhance repeatability in FRs and DPs.....	43
Figure 14- Two scenarios considered in this thesis for implementing MC design in a prefabricated system.....	47
Figure 15- Schematic representation of a CLT element.....	48
Figure 16- Overview of a CLT structure stages	53
Figure 17- CLT production line and manufacturing processes, adapted from.....	55
Figure 18- Calculation of CNC software estimation time (set) based on three different cutting patterns of panels from billet.....	57
Figure 19- overview of the research process	64
Figure 20- The framework of the scenario	78
Figure 21- The variables and parameters of the layout design problem in the thesis	80
Figure 22- The key parts of developing the model.....	80
Figure 23- Simply supported floor (left) compared to the continuous floor (right) ...	81
Figure 24- The stages focused in this research.....	81
Figure 25- An illustrative example of a floor design problem in 2D plan (top left) and billet cuts based on the floor panel lengths	86
Figure 26- Chromosome structure	92
Figure 27- Research roadmap for Stage B	97

Figure 28- The chapter framework to find some modular design scenarios for apartments design	98
Figure 29- Apartment unit frequencies.....	100
Figure 30- Frequency histograms of living& dining room dimensions	106
Figure 31- Frequency histograms of kitchen dimensions.....	107
Figure 32- Frequency histograms of main bedroom dimensions	107
Figure 33- Frequency histograms of additional bedroom dimensions	108
Figure 34- Frequency histograms of bathroom dimensions	108
Figure 35- Frequency histograms of balcony dimensions.....	109
Figure 36- Schematic view of minimum and maximum dimensions of spatial voids	110
Figure 37- Number of clusters for living& dining room- left to right Elbow, Silhouette, Frequency among30 indices methods	112
Figure 38- Number of clusters for kitchen- left to right Elbow, Silhouette, Frequency among30 indices methods	113
Figure 39- Number of clusters for the main bedroom- left to right Elbow, Silhouette, Frequency among30 indices methods	113
Figure 40- Number of clusters for extra bedroom- left to right Elbow, Silhouette, Frequency among30 indices methods	114
Figure 41- Number of clusters for bathroom- left to right Elbow, Silhouette, Frequency among30 indices methods	114
Figure 42- Number of clusters for laundry- left to right Elbow, Silhouette, Frequency among30 indices methods	115
Figure 43- Number of clusters for balcony- left to right Elbow, Silhouette, Frequency among30 indices methods	115
Figure 44- Clusters scatter plots, left to right, living& dining room, kitchen, main bedroom, additional bedroom, bathroom, laundry	117
Figure 45- Cluster validation with silhouette index in each spatial void. Left to right living& dining room, kitchen, main bedroom, additional bedroom, bathroom, laundry.....	118
Figure 46- A schematic view of an apartment plan and the dominant dimensions of spatial voids based on the cluster analysis results.....	120
Figure 47 -Illustration of building spans	123
Figure 48- Illustration of apartment variables and indicating how they measured ..	123
Figure 49- transverse (1) or longitudinal (2) arrangement of spans	124
Figure 50- Apartments' spans and spanning direction dimension distributions	125
Figure 51- Manufacturability of spans in different prefabricated systems.....	128
Figure 52- Cluster scatter plots regarding span and spanning direction dimensions	130
Figure 53- Schematic view of the existing arrangements of spaces in the span direction side of apartments.....	132
Figure 54- Frequency of spatial voids arrangement aligned with apartments spanning direction.....	134

Figure 55- A schematic view modular design scenario based on recognising the manufacturability of layout design and finding a pattern according to the similarities of architectural design	136
Figure 56- Span distribution in building Class1,2 and3 from left to right	138
Figure 57- Apartments spans and spanning direction dimensions scatter plots based on different building categories.....	138
Figure 58- The percentage of span direction in each group	139
Figure 59- A schematic view of modular design patterns concerning the vertical building design	140
Figure 60- Stage C research roadmap.....	146
Figure 61- A schematic view of panel length and thickness as a variable of the model	150
Figure 62- A case example	151
Figure 63- Chromosome structure	158
Figure 65- Comparing the results of three scenarios	163
Figure 66- A schematic view of comparing the results of mass customised and fully customised design scenarios.....	164
Figure 67- Frequency histograms of kitchen dimension based on kitchen type (left to right one wall kitchen and rectangular kitchen)	185
Figure 68- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data regardless of architectural design ...	186
Figure 69- Cluster validation in analysing apartments regardless of architectural design	187
Figure 70- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on apartments architectural layouts design (Living room + bedroom)	187
Figure 71- Cluster validation and scatter plots in analysing data based on apartments architectural layouts design (Living room +bedroom).....	187
Figure 72- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on apartments architectural layouts design (Living room).....	188
Figure 73- Cluster validation and scatter plots in analysing data based on apartments architectural layouts design (Living room)	188
Figure 74- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on apartments architectural layouts design (Living room and two bedrooms)	188
Figure 75- Cluster validation and scatter plots in analysing data based on apartments architectural layouts design (Living room and two bedrooms).....	189
Figure 76- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods(buildings with less than 5 storey).....	190
Figure 77- Cluster validation and scatter plots in vertical design data analysis (building Class1, i.e., buildings with less than 5 storey)	190

Figure 78- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods (buildings with between 6 to 10 storey)	190
Figure 79- Cluster validation and scatter plots in vertical design data analysis (buildings between 5 to 10 storey)	190
Figure 80- Cluster validation and scatter plots in vertical design data analysis (building buildings with more than 10 storey).....	191
Figure 81- Cluster validation and scatter plots in vertical design data analysis (building buildings with more than 10 storey).....	191
Figure 82- Problem coding in Matlab environment	193

List of Tables

Table 1- Comparing the construction company and mass producers moving toward MC	23
Table 2- Two perspectives on modularity and module classification in the building industry.....	36
Table 3- The standard CLT component thickness in CLT factory, adapted from XLAM design guide.....	50
Table 4- Pressing stage time estimated for billet 12 meters.....	56
Table 5- Buildings profile and parameters considered in the study.....	69
Table 6- Data collected from the case factory.....	82
Table 7- Preliminary structural design table.....	86
Table 8- Manufacturing time for producing billet with 3 meters width and 12 meters length and different sizes of panels which cut from billets.....	89
Table 9- Mathematical notations.....	90
Table 10- Summary of apartment design.....	101
Table 11- Average dimensions and SD sorted separately by spatial voids and apartments typ.....	103
Table 12- Average dimensions and SD sorted separately by spaces in all types of apartments.....	105
Table 13- Level of variety of spaces.....	109
Table 14- Optimum number of clusters for each space.....	112
Table 15- Cluster analysis results sorted separately by spaces.....	119
Table 16- Maximum span of panelised system regarding the maximum panel length, the common panel width, and the minimum panel thickness in meters for mid-rise residential buildings.....	126
Table 17- The details of the manufacturability of spans in different prefabricated systems.....	128
Table 17- The dominant spans and spanning direction dimensions in apartments design	131
Table 19- Spatial voids layout or arrangement aligned with spanning direction.....	132
Table 20- Optimal number of clusters in analysing data based on the apartments architectural layouts design.....	134
Table 21- The dominant spans and spanning direction dimensions patterns in apartments regarding the architectural layout.....	135
Table 22- The dominant spans and spanning direction dimensions in apartments regarding the number of floors.....	139
Table 23- Model inputs for the mass-customised design scenario.....	152
Table 24- Pressing stage time estimated for billet 3*12 meters adapted from.....	154
Table 25- Preliminary structural design table utilised as input for the model.....	155

Table 26- GA parameters in this research	158
Table 27- Model outputs for the mass-customised design scenario (optimal solution)	159
Table 28- Inputs for the mass-produced design scenario	161
Table 29- Inputs for the fully customised design scenario	161
Table 30- Results of mass-produced design scenario.....	162
Table 31- Results of fully customised design scenario	162
Table 32- Comparing the results of the mass customised and fully customised design scenarios	164
Table 33- Normality tests of all 710 apartment units dataset.....	184
Table 34- Spanning direction and average land size	185
Table 34- Comparing building frontage in each building class	186
Table 36- Number of clusters in clustering all apartments regardless of architectural design.....	186
Table 37- Optimal number of clusters in analysing data based on the apartments architectural layouts design	189
Table 38- Optimal number of clusters in analysing data based on vertical designs.	191

List of Abbreviations

ADG	Apartment Design Guide
ATO	assemble-to-order
AR	Aspect ratio (of spatial voids)
av.sil	average silhouette of objects
CLT	Cross Laminated Timber
CNC	Computer numerical control
CTO	Configure-to-order
DP	Design parameters
FDA	Flexible Demand Assignment Problem
FR	Functional requirements
EPI	Emulsion polymer isocyanate
ETO	engineer-to-order
L	Length of spatial voids
MC	Mass Customisation
MP	Mass production
MTO	modify-to-order
MTS	make-to-stock
PRF	Phenol-resorcinol formaldehyde
PUR	Polyurethane
PW	Press waiting time
QFD	Quality Function Deployment
RPM	Revolutions per minute
SD	Standard deviation
SDD	Spanning direction dimension
SPSS	Social Sciences software
SV	Select a variant
W	Width of spatial voids
WSS	Within-cluster sum of square

List of Mathematical Notations

Symbol	Description	Unit
B_t	Billet t area	Square meter
CNC_{it}	CNC stage process time of panel i cut from billet t	Minute
C_t	Materials costs of billet type t	Dollars per billet
K	(client's financial objective) maximum structure price they desire to pay	Dollars
I $= \{1, 2, \dots, i\}$	Set of panels	-
l_i	Lower size of panel i	Square Meter
L	Building floor area	Square Meter
NP	Number of panels	-
PHC	Productive hour cost	Dollars per minute
$Press_t$	Billet t pressing stage process time	Minute
r	Recycling cost	Dollars per cubic meter
R_t	Price of a square meter of billet t	Dollars per square meter
S_{it}	Panel size i cut from billet t	Square meter
set	Coding software CNC machining estimated time	Minute
T $= \{1, 2, \dots, t\}$	Set of all billets with the option of choosing thicknesses from the following billet types: 3-layer billets thicknesses(meters): 0.085, 0.105, 0.115, 0.125, 0.135, 5-layer billets thicknesses(meters): 0.145, 0.160, 0.175, 0.195, 0.205, 0.225, 7-layer billet thicknesses(meters): 0.245, 0.265, 0.275, 0.295, 0.315	-
u_i	Upper size of panel i	Square meter
W	Waste of billet during the cutting	Square meter
X_{it}	1 If panel i assigned to billet t 0 Otherwise	-
Z_t	{ 1 If billet t selected 0 Otherwise	-

Acknowledgements

First and foremost, I am extremely grateful to my supervisors and adviser, Dr. Alireza Ahmadian and Dr. Peter Smith, and Professor Perry Forsyth, for their invaluable advice, continuous support, and patience during my Ph.D. journey. Their immense knowledge and plentiful experience have encouraged me all the time in my academic research and even in daily life. From the first day of my arrival to Sydney so far, Alireza and his family have been supporting me in such a way that I always feel that I have a family here in Sydney and never feel lonely in Australia, particularly during Covid. I will never forget Alireza's and his wife's kind favours along the journey.

I would like to express my gratitude to my lovely and caring family, my parents, my husband, and my brothers. Without their tremendous understanding, support, and encouragement over the past few years, it would be impossible for me to complete my study.

Chapter 1: Introduction

1.1 Overview

This chapter includes seven sections. After this first overview section, the second section introduces mass customisation, the necessity of mass customisation and its emergence in the manufacturing industry. The third section emphasizes on the importance of mass customisation in the residential building industry considering the problems that the building industry grapple with to respond to the current housing demand in Australia, and explaining how mass customisation can be considered as a potential solution. Also, this section discusses the potential of building elements for customisation and standardisation to prepare the scene for the research scope. The fourth section describes role of design in implementing mass customisation, and enablers of mass customisation in the design phase. The fifth section summarises the research problem and motivation, and the sixth section translates these into research objectives. The seventh section also provides the research scope and thesis structure.

1.2 What is “mass customisation” and how did it emerge and grow?

Prior to scientific management, craftsmanship was the dominant mode of production, characterised by producing low volumes and a wide variety of products (Rocha 2011) at high prices and without any standardisation (Mourtzis and Doukas 2014). With the emergence of mass production, the reduction in cost driven by economies of scale, i.e., producing large quantities of products from a limited variety, became the key competitive criterion in the market (Mourtzis and Doukas 2014; Rocha 2011). Mass production, also called serial production, was based on the standardisation of components and the systematisation of processes. These were organised so that a product was gradually assembled along a production line by groups of factory workers who performed the same operation repeatedly. In such an environment, systematic repetition of components and processes results in lower cost through economies of scale (Benros and Duarte 2009; Mourtzis and Doukas 2014). Later, manufacturing companies had to provide some degree of customisation to stay competitive while still striving to increase production as near to mass production (MP) as possible (Jensen 2020). In general, maximising production efficiency leads to generating the most cost-efficient product, but providing a degree of customisation concurrent with increasing production efficiency is a challenging mission and forms the central idea of mass customisation (MC) (Pine et al. 1993). The progress in the

development of flexible production systems and new information technologies supported the advent of MC paradigm, which delivers higher variety at lower cost (Rocha 2011).

Mass customisation was referred to by Stan Davis in his book, “Future Perfect,” in 1987 as “the same large number of clients can be reached as in mass markets... and simultaneously they can be treated individually as in the customised markets of pre-industrial economies”. Then, this concept was considered more as an industrial perspective by Pine in 1991; “providing tremendous variety and individual customisation, at prices comparable to standard goods and services to enable the production of products and services with enough variety and customisation that nearly everyone finds what they want” . In 2001, Tseng and Jiao stated that MC corresponds to the technologies and systems to deliver goods and services that meet individual clients’ needs with near mass production efficiency (Boër et al. 2013; Piller 2004). In 2002, Broekhuizen provided a similar definition of MC as the ability to provide customised products and services to an individual client by applying technology or information at optimal production efficiency and cost level (Broekhuizen and Alsem 2002).

Duray 2002 described MC as “a paradox” by combining customisation and mass production, offering unique products in a mass-produced, low-cost, high-volume production environment (Duray 2002). In 2007, the definition of MC was revised by Pine as “the low-cost, high volume, and efficient production of individually customised offerings.” Some researchers, such as Pillar, stated that MC refers to the client co-design process of products and services, which meet the needs of each individual client with regard to certain product features (Piller 2004).

MC is to accommodate the fact that client requirements are different and therefore, need to be handled by setting up the right product architecture in order to meet clients’ desires efficiently at prices near mass production (Tseng et al. 1996). In other words, in MC approach, the flexibility to meet client needs found in customised production is combined with the production efficiency found in MP (Pine 1993). Production efficiency, also known as productive efficiency and cost efficiency, identifies the conditions in which products can be produced at the lowest possible unit cost. In order to achieve cost efficiency, one should utilise resources and minimise waste, which in turn translates to higher profits. In other words, production efficiency is the ability to do something or produce something without wasting materials, time, or energy (Xu et al. 2017).

The above definitions tend to look at MC as a strategy to accommodate customisation into mass production (MP) with relatively similar principles. The principles of MC are to meet clients’ requirements and to produce in high volume and with optimal cost and production

efficiency. MC may refer to both services and products. Haverila and Feher differentiate service and product in the context of construction projects, whereby service refers to soft measures such as management and buying process, from the start to the end of the project. Product, on the other hand, has a physical nature and is delivered to the client at the end of the project. This research will place its emphasis on MC for physical products, i.e., residential buildings (Haverila and Fehr 2016).

As stated in the literature (Barlow 1999; Fogliatto et al. 2012; Jiao et al. 2007; Salvador et al. 2002), implementing MC strategies needs a systematic approach involving all the value chains. Barlow (1999) highlighted the need to integrate marketing, design, and manufacturing activities to provide customised products (Barlow 1999). Jiao et al. (2003) and Fogliatto et al. (2012) stated that there should be interdependencies among the marketing, product design, process, and supply chain for executing MC (Jiao et al. 2003). Marketing refers to product planning or definition, i.e., the activities of finding and satisfying existing or future client requirements (Wee and Aurisicchio 2018). Based on those researchers, it can be argued that implementing MC requires a systematic consideration that coordinates the decisions in the area of marketing or product planning, product design, manufacturing process, and supply chain. Considering all these areas together demands a huge amount of time and effort. Among these, design stage poses the highest potential for effective execution of MC because it can accommodate market demands, product planning and manufacturing features, and supply chain characteristics (Barlow 1999). Therefore, this dissertation will primarily focus on product design in relation to manufacturing processes, while major marketing and supply chain aspects, such as clients' desire, transportation and installation constraint will be considered in the study.

1.3 Mass customisation in the residential building industry

1.3.1 The importance of customisation in the residential building sector

Globally, the construction industry still suffers from a poor rate of productivity (Goh and Goh 2019; Hasan et al. 2018), and this problem leads to time delay and cost overrun (Hasan et al. 2018). In Australia, the building industry has a lower productivity than other industrial sectors (Alwi et al. 2002; Böhme et al. 2018; Hughes and Thorpe 2014). On the other hand, the construction industry is the fifth-largest industry in Australia and plays a vital role in Australia's economic development (Li et al. 2010). The value of new housing construction alone (not including renovations and other housing-related expenditures) exceeds four percent of the country's gross domestic product (GDP) (Dowling 2005). Given this importance, taking measures to improve construction efficiency plays a vital role in driving this sector.

Challenged by a global climate crisis, the building industry is currently seeking new orientations and strategies to cut their environmental footprint but yet stay competitive in the market. Stakeholders in the built environment are being forced at an unprecedented pace to improve a set of conflicting objectives. They are increasingly motivated to consider offsite construction as a potential solution that would maintain their profit margin and simultaneously enable them to fulfil their environmental responsibilities (Ahmadian et al. 2016). On the other hand, the Australian housing market demands for variety, not just in functional performance or comfort levels of buildings, but also in building architecture and structure (Rosewall and Shoory 2017). This apparently conflicting set of goals requires a new paradigm in the building industry that moves away from in-situ construction because achieving these goals through onsite processes has proven to be waste-prone, expensive, and sometimes associated with defective delivery of buildings (Bertram et al. 2019; Marchesi and Matt 2017). Therefore, there is a strong tendency in the market to shift towards a type of offsite manufacturing that enables customisation of prefabricated buildings. Offsite construction enables a controlled environment, allowing for precise fabrication and assembly of building components, reducing the risk of errors and ensuring higher quality construction compared to traditional on-site methods. The ability to customise building components in an offsite manufacturing offers architects the freedom to create unique structures that meet client requirements by providing aesthetic appeal and functionality of the final product (Popovic 2018). As MC paradigm has created a substantial capacity in the manufacturing sector to achieve such conflicting goals, the same principles can be adopted in the building industry to mass produce custom housings in offsite manufacturing facilities.

Moving towards MC is not just attractive for mass producers, but also for Engineer-To-Order (ETO) businesses. ETO businesses are engineering companies in which products are custom designed to meet the uniqueness expected by client-specific requirements (Haug et al. 2009; Jensen 2020). The building industry, particularly in Australia, is predominantly considered as an ETO business (Gosling and Naim 2009). Compared to the other segments of the building industry, namely institutional, commercial and specialised industrial¹ buildings, the residential building sector is subject to more customisation and at the same time, lower efficiency which leads to a significant cost burden on the shoulders of all stakeholders (Ahmadian et al. 2016). The increased demand for customisation related to residential buildings makes construction companies to constantly look for initiatives to reduce cost in order to

¹ Projects that would be classified as specialised industrial building includes manufacturing, refineries, chemical processing, power generating, mills, mining and quarrying plants.

improve their competitiveness and cost-efficiency or thus, secure a certain profit margin (Jensen 2020). Therefore, the MC approach could be one practical strategy for the residential building industry in order to improve its productivity and cost-efficiency (Haug et al. 2009; Jensen 2020)

1.3.2 . The current housing demand in Australia

In Australia, the residential building sector consists of houses, townhouses, apartments, and units, and has been one of the largest sectors of the construction industry, accounting for 26.6 % of all construction activities in 2021(IndustryEdge 2015). The residential building sector is forecasted to remain solid and stable for at least the next ten years, supported by an increasing number of house approvals in order to supply for its population forecaste to grow in the same period (ABS 2017). The primary locations of residential construction are the states with larger population size and growth, i.e., NSW and Victoria, with 56% and 50% of proportions of the total dwellings, respectively (IndustryEdge 2015). As the high cost of labour-intensive construction and diverse housing design requirements are the main predictors of a market in which MC can gain traction (Bertram et al. 2019; Wei et al. 2022), the current housing demand in Australia, particularly in its most densely populated cities, requires mass customised buildings (Wei et al. 2022).

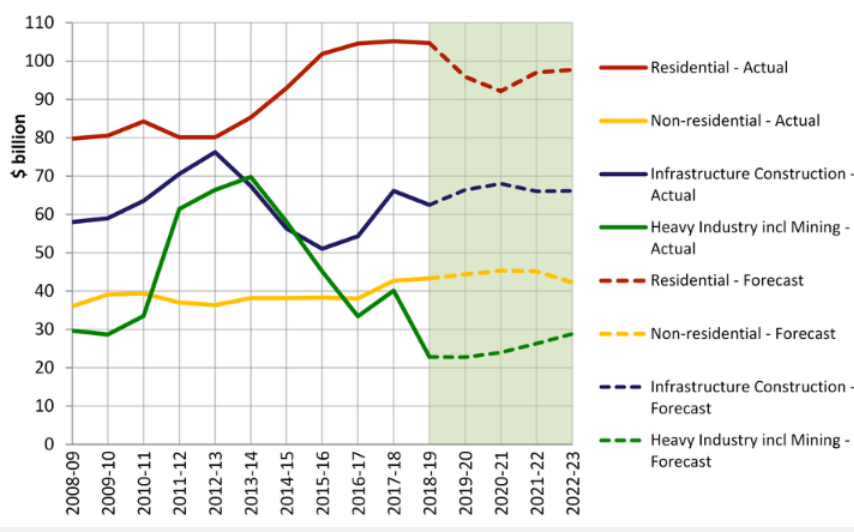


Figure 1- The share of the residential building sector within the Australian construction industry, adapted from (ACIF 2019)

Today more Australians than ever adopt apartment living (ACIF 2019). Over the past 25 years, the number of occupied apartments (including flats and units, excluding townhouses) in Australia has increased by 78%, reaching a total of 1,214,372 apartments, according to the 2016 census (ABS 2017). This growth is concentrated within Australia’s major capital cities with a prevalence of apartments in four to ten-storey apartment blocks (ABS 2017). With the gap between average annual income and the median price of dwellings continuing to rise, more

Australians (householders) are finding apartment ownership out of reach. While the dream of owning an apartment is still alive, it is becoming increasingly harder to achieve, especially for low to medium- income households. Australia’s middle-income class comprises 58% of the population, and accordingly, they could afford to buy 58 percent of dwellings. This rate is significant compared to the low and high-income classes (Toth et al. 2015; Rosewall and Shoory 2017). Therefore, it is plausible that a building developer may tend to target and build for this segment of the residential sector.

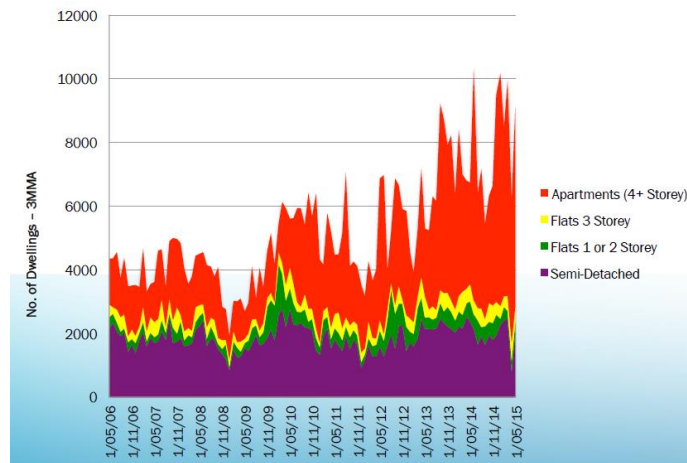


Figure 2- The growth of multi-storey apartments with more than 4 storey, adapted from (IndustryEdge 2015)

There are a number of reasons that support choosing apartment dwellings for mid-income earners as the focus of MC-oriented design in this dissertation:

- **Predictability:** the demand, particularly in terms of architectural design, is more predictable and stable in comparison to the luxurious ones; Since householders in this category are more clustered around the same demands and desires. For example, first-home buyers, in comparison to luxurious apartment householders, buy or rent a unit based on their basic necessities.
- **Repetitious nature:** compared to detached houses and semi-detached townhouses, apartments have a higher potential for MP due to their repetitive characteristics.
- **Market competition:** recent statistics show that the apartment selling rate is dropping partly due to the abundance of units available in the market. The buying tendency is mainly inclined towards apartment units that have reasonable prices but simultaneously are adequately custom designed (Barlow 1999). This is particularly important for investors who are concerned about return on investment through faster and higher lease rates because of being unique and attractive in design.

1.3.3 The potential of building elements for customisation and standardisation

There are several factors determining the decision of home buyers such as building location, environmental features, price, internal spaces and layout design (Roy and Roy 2016). Among these factors, an architect is able to influence design-related aspects such as design of internal spaces or floor layout that would impact the building price. The architect role is critical in successfully executing a MC approach because MC can be effectively achieved through design (Tseng et al. 1996). In the housing sector, studies have been carried out to investigate the desire for customisation or evaluate level of customisation expected in different building elements or spaces. Stehn and Bergstrom (2002) and Schoenwitz et al. (2017) stated that the willingness for customisation of inner design, particularly floor layout design, is strong (Stehn and Bergström 2002) (Schoenwitz et al. 2017). Hofman et al. (2006) and Veenstra et al. (2006) ranked the degree of customisability of the building elements by surveying end-users. Type and position of the kitchen, length and width of the living room, number of bedrooms, position of the bathroom and toilet, and width and length of the house are the key components of customisation in layout design based on the research conducted in Europe (Hofman et al. 2006; Schoenwitz et al. 2012). The floor layout design directly affect the building core and structure and thus, any design decision for MC should carefully weight its economic implications for the core and structure.

The building structure has conceivably the highest potential for increasing production efficiency through standardisation (Duray et al. 2000; Gilmore and Pine 1997). Although the desire for customisation of building layout can make the standardisation of the building structure difficult, building structure standardisation is strongly recommended since it has a high potential for cost saving and for causing changes in other components (Veenstra et al. 2006). Architects and building clients (i.e. developers) must act on behalf of end users who usually lack the expertise to engage in the initial stages of the design process (Augusto et al. 2012), to ensure the building structure meets both customisation and standardisation requirements.

In the context of MC, clients and manufacturers, with the aid of architects, make design decisions collaboratively by integrating the manufacturing process into the preliminary customised architectural design. The design and manufacturing integration balances production efficiency and customisation to meet an optimal building structure design.

1.4 Role of design for MC

1.4.1 Importance of the early design stages in product development

As Tseng et al. insist, MC can be effectively achieved through design (Tseng et al. 1996; Fettermann et al. 2019). In the building industry, the design process can be categorised into three major stages: conceptual design², preliminary design³, and detailed design. Conceptual design is the first stage of designing a project. It typically accounts for about 5%, in terms of value, of the design work on the entire project (Abdul-Kadir and Price 1995; Bianconi et al. 2021). At this stage, the architect establishes the size, location, and relationships between all the spaces. The basic goal of the conceptual design stage is to create some basic floor plans (Abdul-Kadir and Price 1995 ; Makstutis 2018).

Preliminary design accounts for approximately 15%, in terms of value, of the design work. At this stage, the architect and client work together to select materials, including interior finishes and products such as windows, doors, fixtures. The architect revises the basic floor plans based on the client's comments from the conceptual design stage. Preliminary engineering will start on the structure and any other specific systems. At the end of this stage, a good idea of component selection and system design should be achieved. The floor plans and space dimensions, i.e., the wall placement, are fixed based on clients' objectives and optimal design (Abdul-Kadir and Price 1995; Baghdadi et al. 2020).

In the detailed design stage, the client and architect will have settled on a final design and will begin preparing drawings and technical specifications necessary for construction. This stage is the largest of all the stages for the design and will be about 80%, in terms of value, of the design work. At this stage, the architect and engineers finalise all the technical drawings and engineering (Abdul-Kadir and Price 1995; Makstutis 2018).

Studies show that around 80% of the building construction cost can be attributed directly to decisions made at early design phase, i.e., conceptual and preliminary design stages (Marchesi and Ferrarato 2015; Tseng et al. 1996). At the early design phase, the design has more flexibility to accommodate changes to enable efficient offsite building manufacturing or onsite construction process (Baušys and Pankrašovaite 2005).

At the early design phase, a mass customiser in the building context, i.e. a manufacturer, with the aid of an architect, has to identify the product attributes along which clients' needs diverge the most. Once this is understood, the firm knows what is required to properly cover

² In some literature it is called schematic design.

³ In some literature it is called developed design.

the needs of its clients. Consequently, it can generate the so-called solution space, clearly defining what it is on offer and what it is not (Da Silveira et al. 2001; Da Rocha and Kemmer 2019).

In the MC literature, the solution space has usually been explored with conventional market research in the form of techniques and enablers (Piroozfar and Piller 2013; Piroozfar et al 2019). Conventional market research gathers data from representative clients in a chosen market sector (Jiao et al. 2007). These data are utilised to specify the customised and standardised parts of a building (Jiao et al. 2007, Jensen 2020). These specifications are then used to develop a product family and platform to enable factory production of them. The concepts of product family and platform are explained in Section 1.4.2.

1.4.2 Product family and platform design

The main emphasis of MC in the early building design stages is on setting architectural variants to enable designing a family of building products rather than only a single building (Tseng et al. 1996). A building product family refers to a set of similar building elements that yet possess unique features or functionalities to meet particular and varying requirements specified by clients (Jiao et al. 2007). Each individual building product within a family, i.e., a family member, is called a product variant or instance. All product variants share some common structures, which form a platform for that product family (Jiao et al. 2007).

The objective of family-based design for mass producers is to create variety and customisation. In construction companies, product family design aims to offer an adequate number of design options for apartments, which balance customisation with standardisation. In other words, the goal of mass customisation in building design is not an overwhelming number of choices but a thoughtfully curated set that caters to diverse needs. By making this balance, construction companies streamline offsite production, reduce complexity, and at the same time, maintain building customer satisfaction (Cuperus 2003).

Designing a product within a product family approach is not performed through a sequence of tasks. Instead, it includes integrating a set of constraints and variables across different domains, namely marketing, design, manufacturing, and supplying, to support mass customisation (Jansson 2013).

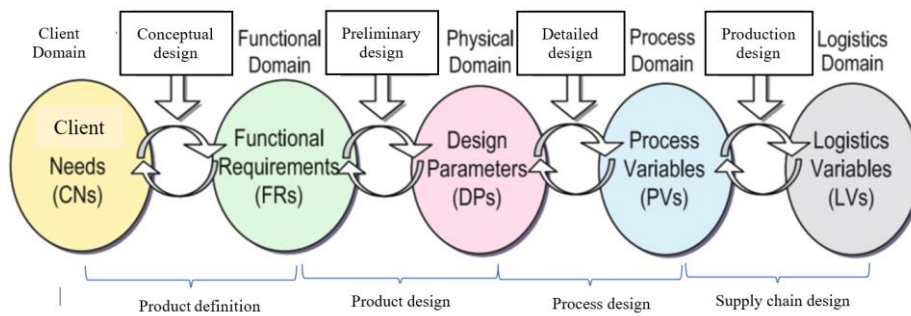


Figure 3- A holistic view of a product family and platform design and development in a MC approach, adapted from (Jiao et al. 2007).

As shown in Figure 3, the client requirements are translated into functional requirements (FRs) by designers or architects. (Jiao et al. 2007). In the building industry, research has been focused on applying tools such as Quality Function Deployment (QFD) (Gilbert III et al. 2014; Stehn and Bergström 2002; Wee and Aurisicchio 2018) and axiomatic design (Gilbert III et al. 2014; Marchesi and Ferrarato 2015; Marchesi and Matt 2017) to translate client requirements into functional requirements and constraints. In the manufacturing industry, scholars have applied clustering techniques (Dai and Scott 2007; Tseng et al. 1996) to specify FRs in clients' orders and to group design parameters based on their common denominators (de Weck et al. 2003). Clustering is a key step in finding similarities in clients' orders to enable paramterisation of the products for production process. (Jiao et al. 2007). Therefore, this step is a prerequisite for successful implementation of MC strategies.

1.4.3 Computer-aided design

Computer-aided design (CAD) is a key MC technology enablers, facilitating design model creation, modification, and optimisation. CAD-related MC studies fall into two research streams: (i) design optimisation tools for generating customised houses (Benros and Duarte 2009; Bianconi et al. 2019; Bock and Linner 2010; Duarte 2005; Juan et al. 2006; Kaiser et al. 2019; Livingstone et al. 2015; Ma and van Ameijde 2022; Monizza et al. 2017; Said et al. 2017) and (ii) product configuration systems or user-interface tools for client co-design and visualising customised options (Shin et al. 2008; Farr et al. 2014; Lee et al. 2017; Piroozfar et al. 2019). The first group employes optimisation techniques to parametrise building designs, while the second focuses on visualisation for individual clients' decisions on building configuration. Excessive complexity in building configuration negatively impacts efficiency for mass customisers in the building industry (Xu et al. 2017). Hence, this thesis does not utilise CAD systems to co-design with every individual client.

The MC topic within the context of design optimisation scope is also marginally addressed by some studies in prefabricated systems, which are dominantly focused on material

costs, energy efficiency, lighting efficiency, etc., as competitive criteria. The next section explains the design optimisation literature in prefabricated systems and the literature gap.

1.5 Gap in design optimisation for mass customised prefabrication of buildings

Figure 4 shows the gap in literature for successful implementation of MC in prefabricated buildings. Below summarises different aspects of this gap:

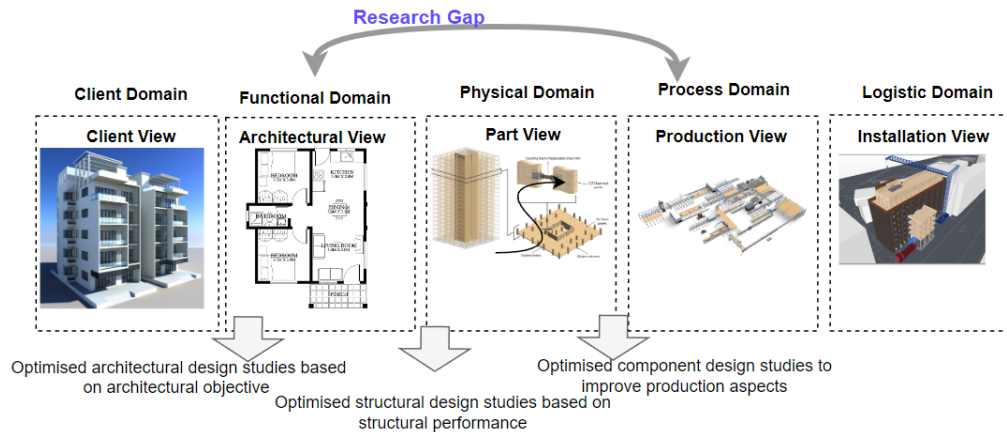


Figure 4- A schematic view of the research gap for implementing MC in the preliminary design stage

1.5.1 Lack of a two-sided view towards MC:

The MC-related literature has mainly focused on when to involve client (Cuperus 2003; Lee et al. 2017; Rocha et al. 2018; Schoenwitz et al. 2017), production strategies at a high level (Barlow 1999; Fettermann et al. 2019; Schoenwitz et al. 2012; Schoenwitz et al. 2017; Stehn and Bergström 2002), and degree of customisation (Abulfahem 2012; Hofman et al. 2006; Jensen 2014; Jonsson and Rudberg 2015). Also, past studies have mostly adopted a one-sided view to MC, neglecting simultaneous consideration of demand-side (designers and building developers) and supply-side (manufacturers) requirements (Jensen 2014; Jiao et al. 2007). Integrating client-driven design and efficient manufacturing is crucial for achieving client satisfaction and controlling product costs (Jensen 2014). This integration forms the foundation for producing customised housing at a reasonable price, facilitating a mass-customised design through optimised architecture (Jiao et al. 2007).

1.5.2 Scarcity of a quantitative approach towards design and production integration:

A lack of quantitative approach hinders effective integration of design and manufacturing process and thus, it prevents reaching a customisation in the factory that would be profitable for manufacturers and cost-efficient for building clients (Jiao et al. 2007). While a few authors, (e.g., da Rocha and Kemmer 2018) have qualitatively studied integrating design and production

processes, quantitative research about such an integration is scarce. There are a few quantitative studies that have considered production processes of prefabricated systems mainly in laborious precast concrete factories. Such studies do not parameterise production processes and variables and thus, they are not detailed enough to enable accurate measurement of cost and time savings after MC (Augusto et al. 2012; de Araujo Carneiro 2019; Petprakob 2014; Sharafi 2013; Sharafi et al. 2012; Sharafi et al. 2017).

1.5.3 Segregated architectural and structural design

Optimised layout design methods have been utilised in the literature to find either architectural or structural design solutions (Hofmeyer et al. 2006). Optimised architectural layout design usually generates various feasible layouts and evaluates them based on architectural objectives only, such as maximum living space (Arvin and House 2002; Homayouni 2007; Michalek et al. 2002; Zawidzki et al. 2011), or lighting (Baušys and Pankrašovaite 2005) and minimum geometrical complexity (Arvin and House 2002; Zawidzki et al. 2011) or energy (Bianconi et al. 2019; Michalek et al. 2002). But, the architectural objectives do not usually consider constructability or manufacturability of the designed layout.

In optimisation of structural layout design, on the other hand, “topology improvement” is set as the core objective to explore the arrangement and sizes of structural elements which are optimal in terms of weight, eccentricity, structural strength, and serviceability (Hofmeyer et al. 2006, Sharafi et al. 2015). These categories of studies neither consider architectural flexibility nor factory production processes. There are a few studies that try to integrate architectural and structural layout design but their focus is on volumetric modules with no consideration for mass customisation under the constraints of prefabrication factories (Sharafi et al. 2017, Khemlani et al. 1998).

1.5.4 Design parameterisation for MC prefabrication of buildings:

As discussed under Section 1.4.2, finding and clustering similarities in various building layouts has a key role in identification of building families and then, parameterisation of them for efficient offsite fabrication. Identifying a direct link between various layout designs and manufacturing process enables effective implementation of mass customisation in prefabrication factories (Mitchell et al. 2011). However, studies on analysing and clustering architectural designs for manufacturing are non-existent.

1.6 Research objectives

The central objective of this research is to develop a data-driven design framework for mass customisation of multistorey buildings. This objective is pursued through four sub-objectives:

- (i) To identify prevalent design patterns in residential building layouts and systematically assess their manufacturability
- (ii) To mathematically model the interrelationships between architectural and structural layout designs
- (iii) To determine the key manufacturing processes that significantly impact building layout
- (iv) To develop a comprehensive methodology for integrating identified manufacturing processes into the design of building layout, with focus on optimising factory efficiency while maintaining architectural flexibility

Corresponding to the above aim and sub-objectives, the research tries to find answer for the following questions:

- 1) What are the most common patterns in residential building layouts and how can we assess the manufacturability of these designs?
- 2) What are the key architectural and structural design interrelationships that influence building layouts?
- 3) Which manufacturing processes are the most critical in building structure cost?
- 4) How can manufacturing processes be accommodated in building layout design without compromising architectural flexibility?

The first research questions target the early investigation of MC at the conceptual design stage in order to provide an adequate number of options of manufacturable layouts. In contrast, the third and fourth questions focus on implementing MC in the preliminary design by providing a degree of standardisation while maintaining a higher degree of flexibility in building layout design.

1.7 Scope of the research:

Figure 5 indicates how the research is positioned within the building industry context. The blue field is used to describe the path from the building industry down to the focus area. The context in which the empirical studies were conducted and the model framework was developed is the multi-storey residential buildings with the panelised system and a case study in a timber building.

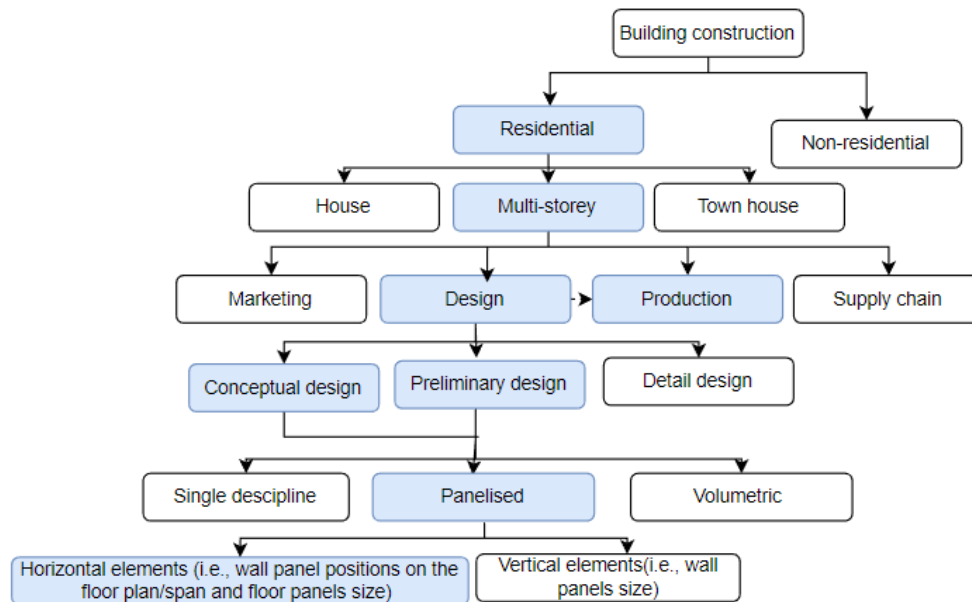


Figure 5- Overview of the research scope

This study is based on the fact that clients (i.e., developers) and manufacturers are the main stakeholders in mass customised building construction. Clients of the whole residential building with spending power become a major driving force in the housing industry and are considered as the dominant player of the demand-side. On the other hand, manufacturing costs can be controlled and reduced by the manufacturer. Hence, manufacturers are considered as the dominant player of the supply-side. In a building construction project, the architect acts on behalf of the client but has a balancing role between the client and the manufacturer by analysing the clients' design trends and the manufacturability of the design (Bonev et al. 2015).

1.7.1 Type of prefabrication:

In modular system design, different types exist, ranging from single elements clipped together (i.e. elemental prefabrication) to three-dimensional volumetric units with full fixtures (i.e., volumetric prefabrication) (Bertram et al. 2019). In the middle of this spectrum, two-dimensional panelised solutions have been created and are more suitable for customisation in residential buildings. This choice offers advantages such as easier transport, greater flexibility compared to giant volumetric modules, and higher adaptability to accommodate various design

preferences (Bertram et al. 2019). This thesis focuses on panelised prefabrication as it lends itself to mass customisation. Within this taxonomy of prefabrication, the study uses Cross-Laminated Timber (CLT) buildings as the main case because of its growing use across the globe as a sustainable material for multistorey buildings. Moreover, CLT panels are machinable and thus can be cut into diverse dimensions and configurations (de Araujo Carneiro 2019).

CLT manufacturing and construction in Australia have experienced a growth rate due to their sustainability benefits, light weight, ease of installation, and cost-effectiveness in construction. The Australian CLT market is currently at least 50,000 cubic meters per annum and is growing rapidly. On its current trajectory, it is expected the market to be more than 80,000 cubic meters by the end of 2023 because of population expansion, continued urbanisation, and sustainable housing options (IndustryEdge 2020).

1.7.2 Taxonomy of design automation

Automation plays a key role in executing mass customisation of prefabricated buildings (Bianconi et al. 2019; Michalek et al. 2002). Two types of digital tools facilitate the process of automated building customisation at design stage, data integration platforms and optimisation platforms. The first category includes any Building Information Modelling software (Bianconi et al. 2019; Michalek et al. 2002), but is outside the current research scope. This study places emphasis on optimisation as it has a higher impact than data integration on cost reduction through holistically accommodating variables and parameters related to manufacturability, architectural desirability and structural stability.

1.8 Thesis structure

This thesis comprises six chapters:

Chapter 1: Introduction

The initial chapter offers rationale for significance of MC in the building industry, the gap in the relevant research, the objectives and questions, and the scope of this research.

Chapter 2: Literature Review and Research Background

In this chapter, a thorough literature review is presented, providing essential context for the investigation. Specifically, it explores the various types of MC within the building industry, elucidating the spectrum of customisation and standardisation. Additionally, the MC design enablers and their corresponding recommendations applicable to this research are explained. Furthermore, CLT (Cross-Laminated Timber) manufacturing and prefabrication systems are a succinctly discussed.

Chapter 3: **Research Design and Methodology**

The third chapter encompasses the constructive research approach employed in this study. It outlines the data collection methods, data analysis techniques, model development process, and, crucially, the steps taken for model validation.

Chapter 4: **Analysing and Clustering Building Layouts**

The fourth chapter presents the apartment design patterns and their manufacture potential based on the statistical analysis of the building layouts in multi-story building projects located in Sydney, Australia.

Chapter 5: **Analysing and Validating MC-based Modelling of Building Layout**

The fifth chapter sheds light on the computational efficiency of the model through a case study, demonstrating its practical applicability.

Chapter 6: **Conclusions**

The final chapter consolidates the findings of the thesis, summarizing the key discoveries in relation to the research objectives, implications for research and practice, and possible avenues for future exploration.

Chapter 2: Literature Review and Research Background

2.1 Overview

This chapter presents the research background in seven sections. The second section provides the residential building procurement system and specifies the key players in implementing MC in multi-storey residential buildings. The third section illustrates the difference between construction companies and mass producers moving towards MC. This section gave the author insight into differentiating mass customisation concepts in the construction and manufacturing industries. The fourth section discusses the theory and law supporting MC. Since a part of this research is to develop a model, later in Chapter 3, the supporting theory is applied as a model validation means. The fifth section describes how to implement MC in residential buildings through three capabilities that make MC work. The position of MC enablers within each capability is summarised in this section. The level of MC in the building industry is also explained in section five to present the appropriate entry points for MC in terms of implementing customisation in residential buildings. MC enablers in the design phase, including modules, platform, and product family, are discussed to provide an approach to finding a pattern for dwellings' modular design offered to different clients. The sixth section summarises the cross-laminated timber manufacturing process and how to integrate efficient manufacturing with client-driven design. Finally, the seventh section provides a summary of this chapter and its implications for this research. The following diagram presents the flow of this section.

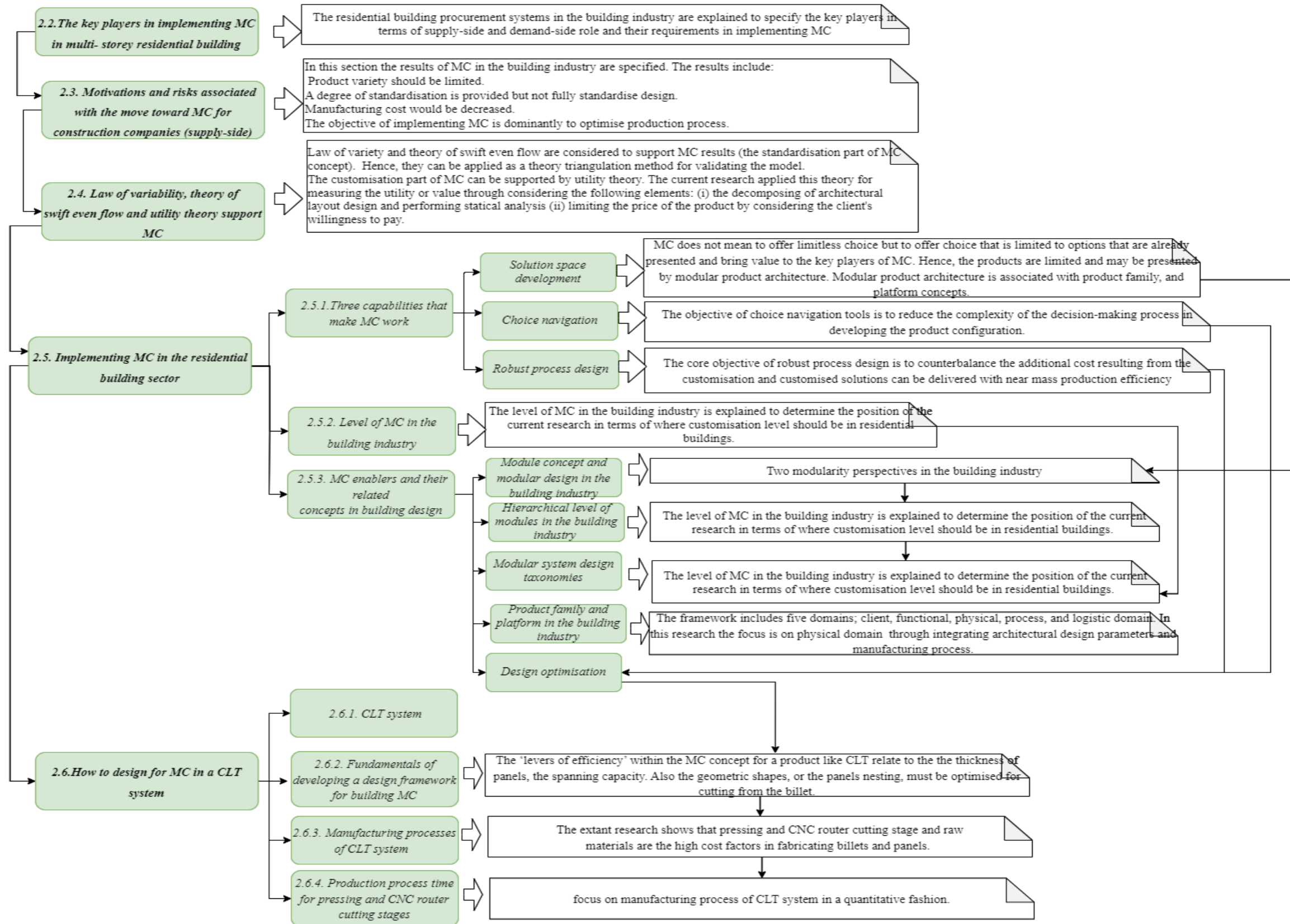


Figure 6- Flow diagram of Chapter 2

2.2 The key players in implementing MC in multi- storey residential building

According to the definitions of MC, the key factor in implementing MC is to balance demand-side and supply-side requirements. This balance pertains to achieving both customisation and production efficiency, thus encompassing the concept of solution space development. Before delving into the enablers of solution space development, it is essential to clarify the interplay between demand and supply in the realm of housing construction. Furthermore, we need to address the uncertainties surrounding the roles of housing customers during the phases of building design and construction. Various terms have been employed to describe the demand-side in residential construction, such as end-user/consumer, customer, and client. However, depending on the approach they take in order to acquire their dwelling means their position and role change. While an exhaustive exploration of the semantics of these concepts is beyond the scope of this discussion due to space limitations, their roles and positions are elucidated within the context of the prevalent procurement systems outlined in the subsequent paragraphs.

Two frequently employed procurement methods within the residential building sector are the traditional model known as Design-Bid-Build (DBB) and the Design and Construct (D&C) approach. In the traditional DBB model, a residential property buyer, acting as an investor or developer and referred to as a housing client in this scenario, engages an architect to formulate apartment designs aligned with market demands. Subsequently, the architect assumes responsibility for project management, including contractor and consultant coordination. Notably, in the DBB approach, the design phase allows for greater potential customisation and remains largely distinct from the construction phase, thereby minimising the likelihood of alterations during building (Warren-Myers and Heywood 2016).

Conversely, in the Design and Construct (D&C) method, design and construction processes are integrated, with a large firm overseeing the entire supply chain from design through manufacturing to construction. This procurement method becomes particularly relevant when optimizing efficiency is paramount, making it especially suitable for multi-story residential projects where increased modularisation is attainable. In instances where the focus of MC, for instance, is on enhancing post-construction sales and profitability, a vertically integrated design, manufacturing, and construction approach would facilitate the realisation of MC objectives (Warren-Myers and Heywood 2016).

D&C provides a single point of contact between the supply-side and the client with design (architects and engineers) either employed in-house or outsourced. Variations of D&C range from small contractors meeting localised demand to large state or national businesses (Volume builders) meeting client demand across several geographic regions. D&C contractors have several variations in how they operate and manage the process. However, generally, the majority of roles undertaken by the D&C contractor in-house include design, marketing, sales, and construction. Because of their size and dominance in the market, D&C contractors can dictate to clients, provided that they consider their clients' requirements systematically. Hence, to meet customisation requirements, they employ marketing, sales, research, and development (R&D) teams to feed architects by providing market analysis information, such as client functional requirements and their willingness to pay for the building. Then architect transfers these requirements into the design parameters. The architect, with the aid of marketing, sales, research, and development (R&D) teams, usually acts on behalf of the client, who has delegated the authority to provide them a building design (Warren-Myers and Heywood 2016).

Implementing innovation in D&C model, theoretically, may originate from demand-side requirements, i.e., client demand. But more practically, MC is dependent on the D&C contractor and their team, i.e., design and manufacturing consultants (Warren-Myers and Heywood 2016), who are on the supply-side. Therefore, this research assumed a D&C system of contracts for multi-storey residential buildings where the client as a demand-side is served by D&C contractor and their team, such as the manufacturing consultant or manufacturer of the building elements. On the supply-side, production costs can be controlled and reduced by the manufacturer. Hence, this research views the manufacturer as a key player from the supply-side. In a construction company, the architect acts on behalf of clients and has a balancing role by analysing the clients' design trends and the manufacturability of the design.

MC articles such as (Frutos et al. 2016; Hofman et al. 2006; Juan et al. 2006; Schoenwitz et al. 2012; Schoenwitz et al. 2017) tend to focus on householders (i.e., end-users) as customers in mass-customising buildings by assessing their satisfaction with the decorative elements of a building. Such a minor involvement may be a reflection of their limited power in shaping and deriving design development decisions. As a consequence, the production efficiency or cost efficiency of MC will be limited. On the contrary, this research views the developer as the client or the main player on the demand-side of a mass customised building because clients of the whole residential building with spending power become a major driving force in the housing industry. Compared to building end-users, the developer can effectively influence MC as the prime beneficiary of a constructed building. There are some other following reasons as well:

- (i) The client's needs reflect the user requirements in design since, in a MC market, the client has to listen to users in order to fit the demand. If not, the potential user may not be interested in buying the apartment.
- (ii) The client or architect has a well-defined idea about what to communicate in order to specify the user requirements. The communication has to serve a multitude of tasks, including finding a buyer, informing a potential buyer, interviewing with a potential buyer and finding out about their preferences, and following a buyer. A satisfied buyer is the client's/developer's best promoter. It is also a source of information to identify new trends in user appreciation and preference (Cuperus 2003).
- (iii) Traditionally, the construction firm is better at dealing with clients than with end-users (Cuperus 2003).
- (iv) Since each apartment unit experiences several ownerships during its life cycle, the client could be a good source to identify the market demand and, subsequently, the design parameters. Hence the user should not interface with the design and construction process.

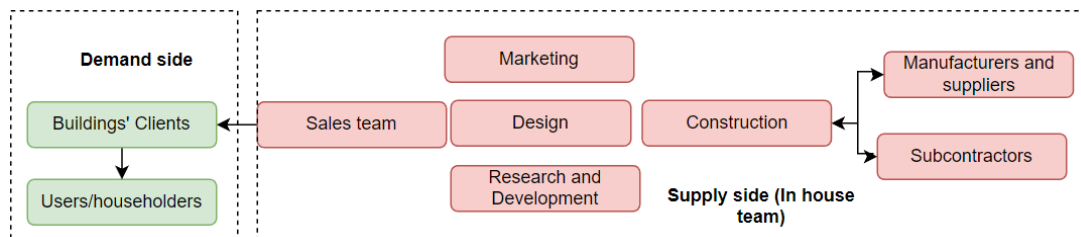


Figure 7- Demand-side and supply-side for implementing a MC strategy adopted in the thesis

2.3 Motivations and risks associated with the move toward MC for construction companies and mass producers

The motivation and risks associated with the move toward MC for the residential building industry (EOT companies) and the manufacturing industry (mass producers) are dissimilar (Haug et al. 2009). ETO businesses are engineering companies in which products are engineered to meet the client's specific requirements (Haug et al. 2009; Jensen 2020). Notably, the building industry predominantly includes ETO businesses (Gosling and Naim 2009; Noguchi and Hernández-Velasco 2005). Haug et al. (2009) highlighted six general characteristics to reveal the differences in the two paths to MC: (i) product variety, (ii) client view, (iii) engineering and manufacturing costs, (iv) business purpose, (v) configurator challenge, and (vi) efforts associated with the product redesign.

In the realm of the residential building industry, companies normally create a building as a one-of-a-kind product for each client, making the challenge in transitioning to MC the need to predetermine the constituent elements of new buildings. This naturally imposes limitation on the options available to clients (Cuperus 2003; Haug et al. 2009; Wee and Aurisicchio 2018). However, embracing MC in for the building design does not imply an exhaustive array of choices must be presented. Rather, in a mass customised apartment, an appropriate number of options can be sufficient (Cuperus 2003). Thus, mass production companies apply MC enablers, including module and product family, to generate variety. Conversely, in EOT companies, these same enablers are harnessed to enhance production efficiency, while cautiously controlling the degree of diversity. When construction companies move to MC, the creation of a predefined product solution space or design involves the risk that the solution space is not adequately large to meet all clients' requirements. On the other hand, when mass producers move to MC, from the client's perspective, the increased influence on the design of the product has to have a value; otherwise, the product varieties are just confusing or annoying (Haug et al. 2009).

Construction companies moving towards MC deal with complex products. Therefore, full standardisation of building design/ products may not be possible if to satisfy client requirements. On the other hand, mass producers tackle much simpler products compared to the first scenario, and their basis is in a standard product in which all components in the product are standardised. Therefore, for mass producers, MC can be obtained by minor product design changes, such as allowing that some components can be interchanged with others (for instance, the same component in different colours) or by offering addable components (Haug et al. 2009). Hence, from a product design point of view, a transition to MC seems to be much more complex for construction companies than for mass producers. Although the literature has emphasised product design complexity, it can be inferred that architects in construction companies should limit the design variety and supply adequate diversity in order to move towards MC. However, research is slim to provide practical insight into identifying a number of design options through finding design patterns in the residential building sector.

When construction companies move towards MC, the engineering and manufacturing process become more simplified by providing adequate variety and options, which leads to limiting the flexibility in planning, design, and manufacturing process, and eventually reducing costs per manufactured product (Haug et al. 2009; Roy et al. 2003). On the other hand, mass producers need to have more flexibility in planning, design, and manufacturing. Having more flexibility in planning, design, and manufacturing makes the production process more complex. In terms of business purpose, the main characteristic of construction companies that move

towards MC is to automate and optimise some internal processes. Although the increase in sales is not the primary purpose, the effect of optimisation, including shorter delivery times and faster manufacturing, could have a sales-increasing impact.

Residential buildings as ETO products are usually hard to standardise to a degree that allows configuration; hence the knowledge-based design⁴ generally is one of the main challenges when creating a configurator for this type of producer who becomes a standardised customiser (Haug et al. 2009). However, the design options of the clients in a scenario where a mass producer becomes a mass customiser are typically limited compared to the previous scenario. Hence, the focus of the mass producers who become mass customisers generally is to increase sales and the user interface of web configurators (Haug et al. 2009).

Table 1- Comparing the construction company and mass producers moving toward MC

General characteristics	Mass producers (manufacturing industry) move to MC	Construction companies move to MC	References
Product variety	Increase variety	Limit variety	(Barlow 1999; Cuperus 2003; Haug et al. 2009; Hofman et al. 2006; Piroozfar and Piller 2013; Popovic 2018)
Client view	Create valuable variety	Create adequate variety	(Cuperus 2003; Haug et al. 2009; Piroozfar and Piller 2013)
Product redesign	Fully standardised product	Some degree of standardisation	(Cuperus 2003; Haug et al. 2009; Popovic 2018)
Manufacturing costs	Slight increase	Decrease	(Barlow 1999; Benros and Duarte 2009; Bianconi et al. 2019; Haug et al. 2009)
Business purpose	Increase sales	Optimise production process	(Barlow 1999; Haug et al. 2009; Popovic 2018)
Configurator challenge	User interfaces	Knowledge-base	(Haug et al. 2009; Jensen 2020)

Product design and production (manufacturing) process stand out as the pivotal factors in achieving client satisfaction and constraining product costs, respectively (Jensen 2014). Therefore, integrating client-driven design and efficient manufacturing provides the ground to produce customised housing at a reasonable cost. In other words, integrating design and manufacturing are the key elements of MC-oriented design (Jiao et al. 2007). It's worth noting that design and manufacturing, when approached independently, emerge as the primary focal points within both product manufacturing and the construction industries (Jensen 2014; Jiao et al. 2007).

⁴ A knowledge-based system is a form of artificial intelligence (AI) /machine learning (ML) that aims to capture the knowledge of human experts to support decision-making in design. Machine learning is a subset of AI which allows a machine to automatically learn from past data without programming explicitly. The goal of AI is to make a smart computer system like humans to solve complex problems (Wang, and Duarte 2002).

The subsequent section presents the law and theory which support the MC in terms of product design and production process.

2.4 Law of variability, theory of swift even flow, and utility theory to support mass customisation

Considering production process optimisation during the building design is one of the key characteristics of MC for construction companies. Production process optimisation is a means for increasing cost efficiency resulting from production efficiency. The law of variability and theory of swift, even flow support production efficiency in mass customised design in residential buildings.

Theories are usually introduced when a previous study of a class of phenomena has revealed a system of uniformities that can be expressed in the form of empirical laws. Theories explore to explain those regularities and, generally, to afford a deeper and more accurate understanding of the phenomena in question. Many managerial laws have made a great impact in the construction and operations management discipline while rigorous theories remained absent, although theories exist at a higher and deeper level than laws (Schmenner and Swink 1998).

The discipline of operations management has developed a set of laws that have a bearing on the phenomenon of differential factory productivity or production efficiency. Some of these laws are deductive and derived from mathematical foundations, and some of them are probabilistic and derived from observed data, namely the law of variability, law of quality, law of bottleneck, law of factory focus, etc. Among these laws, law of variability supports production efficiency in mass customised design in residential buildings. Based on this law, the greater the random variability, either demanded of the manufacturing and construction process or inherent in the process itself or in the items processed, the less productive or production efficiency the process is. This law is consistent with the theory of swift, even flow.

Based on the theory of swift, even flow, there are two types of flow: product flow (process) and workflow (operation). Product flow represents the progress of a product along a production line, and workflow represents the individual actions performed on the product at any given workstation. Process or product flow analysis examines the flow of material or product; operation or workflow analysis examines the work performed on products by workers and machines. Process flow is improved by removing non-value-adding steps such as moving, waiting, and inspection and by minimising set-up times and rework. In construction work transforming materials or components into construction is considered value-added, while setup time and work that moves components, inspects them, counts them, or reworks them is regarded

as none value-added work. Workflow is improved by balancing the work of operators, improvements to methods and tools, etc. For prefabricated and pre-assembled elements, as in precast concrete, steel, and timber construction, the flow of fabrication (interim assemblies) off-site and assemblies on-site is comparable to product and workflow, respectively (Sacks 2016).

The theory of swift, even flow deals with both production efficiency and flow. According to the theory, production efficiency for any process, including labor, machine, materials, or total factor production efficiency increases with the speed where materials flow through the process, and it falls with the increase of variability (whether variability is associated with the demand on the process- product flow- or with steps in the process itself- workflow) (Schmenner and Swink 1998). Hence, for materials to flow more evenly, one must narrow the variability associated with either product or operation. Variability is measured by the variance, or standard deviation of the timing or quantities demanded or of the time spent in various process steps (Schmenner and Swink 1998).

The theory of swift, even flow and the law of variability provide some advice for designing and operating products. Scholars tend to use these theories in qualitative analysis (Sacks 2016). In other words, the theory and law are descriptive in nature and thus do not provide any way of making quantitative assessments of the potential impact of any change to production system design or flow control. This requires the ability to measure the quality of flow in construction, while currently, there is no such measure available (Sacks 2016). The quality of flow is often related to the continuity of the production process (Sacks 2016). Hence, instead of measuring the quality of flow, identifying the principles helping to recognise improving flow is useful. Koskela defined six principles for improving flow in production processes: reduce waste (including waiting time), reduce production or cycle time, reduce variability, minimise the number of steps, maximise flexibility and provide transparency (Sacks 2016; Koskela 2000). These principles could be useful and functional in examining the production processes by comparing production efficiency. Koskela emphasised the reduction of production time and stated that the natural unit of flow in construction is time which can be reflected in cost (Koskela 2000).

In summary, according to the above theory and law, MC strategy in the building industry narrows down the variability of product demand and process (i.e., reducing time of the production process) to improve production efficiency. These characteristics, namely variability of components and reducing process time in a mass customised design, should be compared with a fully customised design. These characteristics are discussed in chapter 5.

The customisation part or design part of MC can be supported by utility theory. Utility theory bases its beliefs upon clients' preferences. It is a theory postulated in economics to explain the behavior of clients based on the premise clients can consistently rank order their choices depending on their preferences. Utility represents the satisfaction of a client in choosing a product. Utility can be measured by observing clients' choices. Given two product options, for example, the client ranks them as to their desirability. That is, the client determines that one of the consumption bundles is strictly better than the other or decides that they are indifferent between the two options. Clients naturally make choices so as to maximise their "utility", that is, to make themselves as happy as possible (Olewnik and Lewis 2006). Utility, which is an indicator of the client's preferences, is also addressed using the term "value" in the construction-related literature.

Measuring the utility or value is complicated and requires considering several variables in building design and is out of the scope of this research. However, this research has attempted to simplify it by considering the following elements: (i) the decomposing of architectural layout design and performing statistical analysis to identify the probabilistic acceptability of the architectural design. (ii) limiting the price of the product by considering the client's willingness to pay. These elements are discussed further in Chapters 3, 4, and 5.

2.5 Implementing MC in the residential building sector

2.5.1 Three capabilities that make mass customisation work

There are three fundamental groups of capabilities that determine the ability of a firm to mass customisation:

- Solution space development:

The mass customiser must first identify the unique requirements of its clients, particularly, the product attributes along which clients' needs diverge the most. Defining the solution space includes collecting knowledge from current and past, and even future clients' order. So, the objective is to understand how client requirements are different by identifying valuable product characteristics as the base for the design and development of products in a way that effectively meets these individual requirements. Once that information is known and understood, a company can define its "solution space", which clearly delineates what it will offer and what it will not. In other words, "Solution space development is the ability to identify the product attributes along which clients' needs diverge". Solution space development is for the company to understand its client's unique requirements, and when these needs are recognised, the company can design, make and deliver the products and services accurately to

its clients. The solution space is a subset of the company's product strategy that clearly defines the boundary of what it is going to offer to the clients and what it will not offer (Piroozfar and Piller 2013; Salvador et al. 2009).

The core requirement at this stage is to access need information, i.e., information about preferences, needs, desires, satisfaction, motives, etc., of the potential clients and users of the product. However, this is not an easy task and can be a costly and complex endeavor because it is difficult to access and codify the information for the solutions provider. However, some approaches or enablers, including conventional market research techniques, the module, product family, and platform concepts, can help to define the solution space (Jensen 2020; Piroozfar and Piller 2013; Salvador et al. 2009). The conventional market research techniques apply common practices of order configuration and sales volume within an existing product portfolio (de Weck et al. 2003). In the manufacturing industry, techniques such as client surveys, conjoint analysis, and clustering (Dai and Scott 2007; Tseng et al. 1996) have been utilised to develop solution space, i.e., functional requirements (FRs) or options in a solution space.

Once the relevant options to be presented in a solution space have been identified, it has to be transferred into a product architecture that will transform these requirements into solutions for the client. It is important to note that MC does not mean to offer limitless choices but to offer choices that are limited to options already presented and bring value to the key players, i.e., the manufacturer and clients. Hence, the products are limited and may be presented by modular product architecture. Modular product architecture is associated with product family and platform concepts. Modularity is an essential part of MC. Each module serves one or more well-defined functions of the product and is available in several options that deliver a different performance level for the function(s) the product is intended to serve. This principle shows that MC demands compromise: not all notational customisation options are being offered, but only those that are consistent with the capabilities of the production processes, the given product architecture, and the given degree of variety. The product family approach has been recognised as an effective means to accommodate an increasing product variety across diverse market niches while achieving economies of scale. The backdrop of a product family is a well-planned architecture providing an overarching umbrella to capture and utilise commonality (Piroozfar and Piller 2013; Salvador et al. 2009).

- Choice navigation:

Mass customisers, i.e., D& C companies must be able to support clients in identifying their design by configuring the product that matches clients' needs with minimum effort. When

a client is exposed to many choices, the cost and complexity of evaluation easily increase. To avoid that, companies have to provide means of choice navigation to simplify the ways in which clients explore their offerings. The objective of choice navigation tools is to reduce the complexity of the decision-making process and increase user-friendliness in developing the product configuration (Piroozfar and Piller 2013). For implementing this concept technological platforms, namely computer-aided design (CAD) need to be applied.

Computer-aided design (CAD), as one of the MC design technology enablers, is the use of computers to aid in the creation, modification, or optimisation of a design. CAD as a design enabler could be classified into two research streams: (i) product configuration systems or user-interface tools such as web-based design systems to involve clients within co-design process and visualise the selected finishing items as customised options (Shin et al. 2008; Farr et al. 2014; Lee et al. 2017; Piroozfar et al. 2019), and (ii) design optimisation and automated design tools to generate customised houses (Benros and Duarte 2009; Bianconi et al. 2019; Bock and Linner 2010; Duarte 2005; Juan et al. 2006; Kaiser et al. 2019; Livingstone et al. 2015; Ma and van Ameijde 2022; Monizza et al. 2017; Said et al. 2017). These two research streams, with their corresponding techniques and software, have tried to reduce the complexity of choice in the decision-making process for clients and architects/engineers, respectively (Piroozfar and Piller 2013; Salvador et al. 2009).

Product configuration systems research has been focused on visualisation tools that help clients make a decision in terms of building configuration, for example, floor plan and facade design, etc., by considering some construction constraints. However, the optimal design is not considered in production configuration systems. Product configuration systems are also referred to as co-design toolkits. Co-design activities are performed in an action of company-to-client interaction and cooperation. The core idea of configuration systems is to engage clients in the design process. By engaging in multiple sequential experiments, clients can test the match between the available options, a particular configuration of these options, and their requirements. Although one of the most distinguished features of MC during the design process is to provide the client with the possibility to co-design products according to their preferences and interests, excess complexity in building configuration has a negative impact on performance and efficiency for mass customisers companies in the building industry (Xu et al. 2017). Hence, we did not consider this group of CAD systems in the thesis.

The second category of the research includes automation and optimisation techniques, which significantly help the designer to parametrise the design and can reduce the complexity of choice in the decision-making process for designers. Automation is supported with

integration (visualisation) and optimisation tools, in which software automatically builds configurations for designers by matching models of their needs with characteristics of existing solution spaces (i.e., sets of options). Then designers only have to evaluate the predefined configuration, which saves considerable effort and time in the search process. Integration or automation tools, including Building Information Modelling software, which provides knowledge sharing (Neelamkavil 2009), are out of the current research scope, and only optimisation tools are the current research focus. With the aid of optimisation, the manufacturability and constructability aspects of buildings can be verified prior to being built, and an optimum construction plan can be derived (Neelamkavil 2009). Design optimisation can be utilised in three major stages of an engineering design process: conceptual design, preliminary design, and detailed design (Augusto et al. 2012). Nevertheless, layout design optimisation is typically employed either in the conceptual or preliminary design stages.

- Robust process design:

A core idea of MC is to ensure that an increased variability in clients' requirements will not significantly impair the company's production efficiency. This can be achieved through robust process design. Robust process design is for the company to have the capability to reuse or combine existing organisational and value-chain resources to efficiently fulfill clients' requirements. A successful MC system is characterised by a stable but still flexible and responsive process. Value creation (for both the demand- and supply- side) within a robust process is the major differentiation of MC versus craft customisation (i.e., fully customisation). Conventional (craft) customisers reinvent not only their product but also their process for each client, which leads to a high cost. With robust process design, customised solutions can be delivered with near mass production efficiency.

The core objective of robust process design is to counterbalance the additional cost resulting from the flexibility a company needs to serve its clients individually. A higher level of product customisation requires greater product variety, which in turn entails a greater number of parts and production processes. Mass customisers use stable processes to deliver high-variety products, which allows them to achieve near mass production efficiency. This also implies that the customisation options are somehow limited. In some cases, with a lower degree of customisation, clients are being served within a list of predefined options, namely apartment design and building components called the company's solution space. In other words, in this scenario, architects offer manufacturable design patterns that are desirable for the selected clients. In other cases, a fully customised building design, i.e., a one-of-a-kind product, can be accommodated MC through integrating production processes in building design with some

adjustment in building design. In this scenario, the supply-side and demand-side agree on building design adjustments at a module or part level.

A number of different techniques can be employed to reduce the additional costs derived from customisation, or even to prevent their occurrence at all in robust process design group. The utilisation of enablers related to new technology, such as delayed product differentiation (postponement), flexible automation, process modularity, and artificial intelligence and optimisation techniques, play a significant role (Piroozfar and Piller 2013; Salvador et al. 2009). The rationale of the postponement approach is to deal with the activities that differentiate a product until information about clients' orders can be clearly identified. In other words, postponement refers to partitioning the supply chain into two stages. A standardised portion of the product is produced based on forecasts, while a differentiated portion of the product is produced based on each client's preference in the second stage. This concept seeks to increase the efficiency and effectiveness of supply chains by moving product differentiation points close to clients. It refers to the practice of postponing changes to a base product until the end of the manufacturing process. Based on this concept, the product parts that are not subject to customisation should be produced early in production processes, leaving only the customised parts to be produced after the client order is received. In this way, production efficiency is increased in manufacturing processes (Can 2008; Su et al. 2005). The economies of postponement derive from at least two factors that are closely related to product design: (i) component standardisation; prior to the point of differentiation, products parts should be common as many product variants as possible, for example, having a standardised core or product platform across the product variants and (ii) modularisation of the product design. MC requires modular product design to provide product variants (Rocha 2011). These two factors are detailed in Sections 2.5.2 and 2.5.3.

Although the words 'flexible' and 'automation' might have been contradictory in the past, that is no longer the case. Robots and automation are compatible with a high level of versatility and customisation, particularly in the automobile industry. A complementary approach to flexible automation is process modularity, which can be achieved by thinking of production and value-chain processes as segments. As such, the company can serve different clients' requirements by recombining the production process segments without the need to create costly ad-hoc modules. The objective of process modularity is to fix the overall architecture of even complex projects while retaining enough adaptability to respond to the specific requirements of a client. Artificial intelligence and optimisation algorithms are being adopted in manufacturing industries for faster and more efficient product development by choosing the appropriate

production process. These techniques can be applied for better production evaluation and identifying faster production time (i.e., product development cycles), diagnosing production bottlenecks, etc. (Salkin et al. 2018).

The next section introduces different levels of MC in multi-storey residential buildings, and then MC enablers applied in this thesis are illustrated.

2.5.2 Level of mass customisation in the building industry

A company moving towards MC should have a comprehensive view of what is the degree or level of customisation and how to implement customisation in the building industry. They also should understand how customisation can be dealt with in prefabricated buildings by understanding the level of off-site manufacturing in prefabricated systems. The next following subsections address these subjects.

Level of customisation in the building industry

The level of customisation presents the appropriate entry point for a mass customiser in terms of implementing customisation in residential buildings. The degree of customisation implemented in an apartment is determined by the production strategy that the construction company follows. Production strategy, which in some papers is known as a client order decoupling point (CODP) or type of postponement, defines when a client can be involved in the design, engineering, and manufacturing phases (Wikner and Rudberg 2005). Two slightly different approaches to classifying production strategies in the residential building context have been found in the literature. The first approach, which is the traditional strategy, classifies production strategies into engineer-to-order (ETO), modify-to-order (MTO), configure-to-order (CTO), and select a variant (SV) strategies (Bonev et al. 2015; Hvam et al. 2008). At the apartment level, ETO strategy provides a high level of customisation, since client involvement starts early in the design or engineering phase of the product specification process. MTO strategy is related to open building systems with a partly defined platform, but project-specific product differentiation is still possible. The CTO production strategy relates to closed building systems with a fully modularised platform and standard parts; hence customisation is accomplished through determining building configuration. Finally, the SV strategy is applied when a client is allowed to choose a number of fully developed and predefined apartments (Popovic 2018). There is no separation between design and manufacturing in this approach. Since both building design and manufacturing are predefined and well-developed.

In the second approach, however, the production strategy is divided into engineering and manufacturing dimensions. This concept indicates the degree to which the design process and manufacturing setup are client-dependent (i.e., order-related) and forecast-driven (i.e.,

connected to a specific sale). Within this class of research, researchers have claimed that the production strategy found in the building industry are all variations of the ETO strategy (Bonev et al. 2015). In this approach, the production strategy is divided into engineering and manufacturing dimensions. Within the engineering dimension, CODP is classified into ETO⁵, MTO⁶, CTO, and SV⁷ strategies. The manufacturing dimension is classified into make-to-order, assemble-to-order (ATO), and make-to-stock (MTS). In this approach, the traditional strategies (the first approach) are constituted by the engineering and manufacturing combination strategies (Wikner and Rudberg 2005). As this thesis focus on the design phase of the building development in the value chain, to provide consistency, the engineering dimension classification is adopted.

Construction companies are strongly concerned with engineering activities and how they are to be conducted in combination with manufacturing. To achieve the advantages of the use of platforms, they have to accept a higher degree of predefinition of the subsequent tasks in order to postpone the CODP to the later stage of the value chain. As mentioned in the previous paragraphs, postponement in construction companies can be considered from two dimensions; the engineering dimension and the production dimension. But the focus of this research is on the engineering perspective. Therefore, from the engineering perspective, supply-side, i.e., off-site manufacturers in this thesis, are traditionally characterised as being ETO. They use the majority of their engineering resources for making building specifications on individual projects while complying with industry-specific standards and norms. Hence, their building products obtain a low level of commonality, as the solutions communicated to their client contain no explicitly formulated boundaries that can be presented in the form of catalogues from the beginning. The next figure indicates the link between the degree of standardisation from a building system perspective and its potential impact on placing CODP in engineering.

As shown in this figure, the lowest level of system standardisation, i.e., formalisation, targets the part and component level. From a precast concrete manufacturing perspective, such components are, for instance, different forms and dimensions of iron bars, insulation materials, concrete recipes, etc. In a timber manufacturing system, such components represent by different sizes (length, width, and thickness) of CLT panels, insulation materials, connections, etc. In Level 2 standardisation, the engineers may define a standard set of building modules or subsystem variants, like a number of options for facades or structures design, which can be

⁵ In some literature it is called design-to-order.

⁶ Modify-to-order strategy is named as adapt-to-order as well.

⁷ Select a variant strategy is also named as engineer-to-stock in this approach.

commonly used within the off-site manufacturing design. The various modules and sub-systems would be reconfigured for each building project through a CTO approach. Finally, at level 3, the standardisation refers to the development of entire standardised buildings or building systems, for instance, a predefined set of walls or floors to an entire building. Since all product specifications for a building project are defined before the actual client order, this strategy can be characterised as SV. Companies offering houses from a type-house catalogue are a good example of this level of standardisation. The focus of using product platforms for mass customising buildings lies between ETO and SV, where the supply-side and demand-side agree on building design adjustments at a module or part level (Bonev et al. 2015).

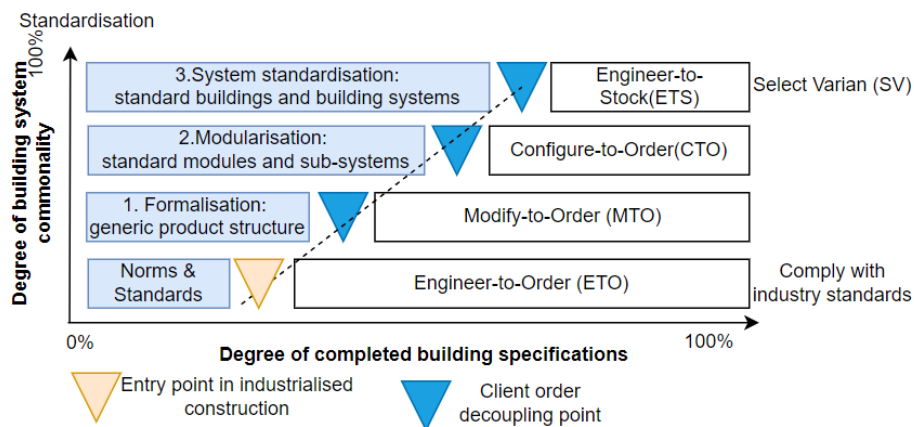


Figure 8- Leveraging customisation/ platform strategy through different decoupling points in engineering, adapted from (Bonev et al. 2015)

Level of off-site manufacturing in prefabricated system

In the literature, prefabrication has been characterised by the proportion of work carried out off-site and on-site. This characterisation is aligned with the definitions adopted in this research, such as the level of product design customisation, modular system taxonomies, and level of platform design strategy. Gib (2001) defined three degrees of off-site manufacturing or prefabrication: (i) non-volumetric preassembly, (ii) volumetric preassembly, and (iii) modular building, as detailed in Section 2.5.3 (Gibb 2001). Jonsson and Rudberg (2015) developed this categorisation further: (i) component manufacturing and sub-assembly, (ii) prefabrication and sub-assembly, (iii) prefabrication and pre-assembly, and (iv) modular buildings. Salama et al. (2016), on the other hand, distinguished between different off-site prefabricated systems: (i) processed and materials construction, (ii) prefabricated, (iii) panelised, and (iv) modular (Popovic 2018). Da Rocha et al. (2018) classified the degree of off-site manufacturing into (i) non-volumetric modules assembled on-site, (ii) non-volumetric modules produced off-site, and (iii) volumetric modules produced off-site. Bertram et al. (2019) illustrated four general classifications with more details in each level: (i) single discipline components, (ii) panels, (iii)

volumetric units, and (iv) complete structures. The off-site construction systems design are generally hybrids of those mentioned above.

The degree of off-site manufacturing systems and the level of product customisation frequently correspond. Bespoke building projects, where highly customised dwellings are built dominantly using traditional construction methods, have a small or no share of parts designed. On the other side, highly standardised buildings using the volumetric modules, which usually have a fully predefined design and are fully serviced and finished in the factory environment, are transported and installed on-site⁸. Highly standardised apartments design is derived from the need to construct affordable dwellings (Barlow and Ozaki 2003), which is very beneficial in cutting costs and achieving economies of scale. Still, it is fully standardised, or in the best case, a limited number of options is provided. On the other hand, the implementation of a full customisation strategy leads to very high production costs.

2.5.3 MC enablers and their related concepts in building design

Module concept and modular design in the building industry

The core of design for mass customisation is to develop a product platform, i.e., building structure in this research, with high-level design and manufacturing process integration. The product platform design enables the optimisation of reusability in both product design and process selection. The product platform is further associated with modules and product families. Hence, this section provides the related concepts.

A module refers to a physical or conceptual grouping of components that share some characteristics. Modules are identified in such a way that between-module (inter-module) interactions are minimal, whereas within-module (intra-module) interactions may be high (Ulrich 1995). The concepts of modules and modularity are central in constructing a mass customised design (Ulrich 1995) (Baldwin et al. 2000). Although, similar to product family and platform, a module can be viewed in marketing, design, manufacturing, and supply chain (Jiao et al. 2003), this research mainly focused on design.

Modular design can be realised by the product architecture concept. Product architecture is a conceptual representation of the physical components used for making a product, together

⁸ However, there are some examples in the building industry where customised buildings are manufactured using volumetric modules. Hence, the trade-off between production efficiency and customisation is reduced, and accordingly, this approach enables the implementation of MC.

with any interaction between them that affect the functioning of that product (Wang and Kimble 2010). Ulrich suggested three factors for figuring out product architecture. (i) the arrangement of functional elements, (ii) the mapping from functional elements to physical components, and (iii) the specification of the interfaces among interacting physical components (Ulrich 1995). Different decisions based on these three factors shape the product architecture within the continuum of architectures that a product design can assume. On one end of the architectures' continuum is modular architecture. Such design is characterised by a one-to-one correspondence between functional elements and physical parts and decoupling interfaces. The other end side of the product architecture is an integral architecture. Such design is characterised by a complex mapping from functional elements into physical components and coupled interfaces. It means that two or more physical components carry out more than one function or conversely, two or more functions are carried out by a single component. Although most products can not be classified purely as modular or integral architecture, this classification can show the overall architecture of a product design. In other words, it can be stated that the modular product is made up of modules, and the more the components of a product fit into these modules, the more modular the product is (Rocha 2011).

In the building industry, the notion of modular and traditional design approaches is an important conceptualisation presented by Gosling et al. (2016). The former is characterised by (i) a grid layout with repeatable spaces, (ii) a conceptualisation of buildings as systems rather than as collections of parts, (iii) an emphasis on repetition, standardisation, and interfaces to simplify buildings construction (Gosling et al. 2016). The main difference between the manufacturing and building industry from the modular design perspective relates to the nature of the parts that form the product itself. Most manufacturing products are simply divided into components, which have a central role in specifying modules. Hence, components are essential for performing the product's function at the highest level. In contrast, buildings need to be considered as a mix of components and spaces (spatial voids) (Rocha et al. 2015).

Regarding the building architecture and design perspectives, there are two fundamental types of functional and physical modularity, i.e., the former includes primary and secondary functions, and the latter comprises spatial voids and solid mass. Primary functions (e.g., cooking, sleeping, eating, and working) result in the form of architectural spaces that clients require an architect to design a variety of apartments based on their desire. Secondary functions (e.g., load support, enclosure, roof, and finishings) are performed by the solid mass of a building. Although spatial voids and solid mass are complementary, the residential building could be conceived as solid mass (i.e., components perspective) or spatial voids (i.e.,

architectural or spatial perspective) (Rocha et al. 2015). These two perspectives with the corresponding functional and physical modularity are indicated in Table 2.

Spatial void modularity followed by modular component coordination suggests the following benefits: (i). It creates a basis for minimising the variety of types and sizes of building components, which is the main objective of the design for MC. (ii). It also allows for the easy adoption of prefabricated components to any layout and for their interchangeability within the building. The easy adoption of prefabricated components to any layout is achieved by defining the location of each component in the building with reference to a modular grid of spatial void rather than concerning other components (Rocha et al. 2015). It is also important to distinguish between two functions of the grid. The first function is to control the disposition of components belonging to the same group of components, such as the position of load-bearing or partition walls. The second function is to coordinate the interface between different groups of components, i.e., the interface of building subsystems (Fukao 2006). For instance, with the aid of the grid, the interface between load-bearing walls and floor panels can be coordinated. (iii) Additionally, spatial void modularity facilitates the moving towards volumetric design, or moving towards CTO and SV in production strategy. This is associated with a high level of standardisation and off-site manufacturing.

Hierarchical level of modules in the building industry

The functional and physical modules that form a building can be organised into hierarchical levels. If the module is at a too low level of aggregation, such as at the bolts and nuts level, then the number of modules may be too many, and the configuration becomes difficult. On the other hand, if the modularisation is at a very high level, such as complete buildings, then the repetition may not be sufficient (Tseng et al. 1996). At the highest level, a function is provided by the whole residential building, whereas, at the lowest level, a very specific function might be provided by a single component, i.e., a wall or floor panel. The level of interest when designing a building is to define a set of sub-functions somewhere between these extremes so that each function is close to the beneficiaries' requirements and the modules devised to fulfill these functions can be combined to meet distinct requirements (Rocha et al. 2015). As mentioned before, the manufacturer from the supply-side and the client from the demand-side are the primary beneficiaries of MC.

Table 2- Two perspectives on modularity and module classification in the building industry, adapted from (Rocha et al. 2015)

Functional modularity	
Primary functions	Secondary functions

Physical modularity	Spatial voids (Architectural spaces)	Spatial perspective (Client's concern)	N/A
	Solid mass (Components)	N/A	Components perspective (Manufacturer's concern)

The supply-side, namely the manufacturer, generally deals with the building design constructability resulting from components manufacturability. In contrast, the demand-side, i.e., the client, tends to conduct spatial configuration with the aid of an architect who offers multiple ranges of apartments (as product variants) in terms of spatial variety and layout design. Hence, within the residential building design, it can be concluded that the components and spatial perspectives are associated with supply-side and demand-side concerns, respectively. While the supply-side, i.e., the manufacturer, deals with increasing production efficiency and, correspondingly, cost efficiency of the manufacturing of solid mass or building structure, the demand-side is concerned with having a variety of housing designs at a reasonable price. In other words, the client's concern can be associated with spatial configuration or layout design problems and the building structure price.

Spatial configuration or layout design problem is concerned with finding feasible and desirable dimensions and locations for a set of interrelated spaces (a family of spatial voids) that meet all design requirements within the layout. Design requirements including spaces length, width, aspect ratio, shape, connectivity, maximise design quality in terms of design preferences (Michalek et al. 2002). Layout design problems could be preliminarily achieved by predetermined sizes and limitation of variety in a systematical approach, which ensures compatibility and interchangeability of components. Dimensions of housing spaces, which indicate spatial voids characteristics, are the outcome of the architectural design analysis and are subjected to meet demand-side's requirements. Hence, based on conventional market research techniques, decomposing architectural layout design and analysing spaces is a way of indicating the expected probability of acceptable layout design based on demand-side desires (Roy and Roy 2016). This supports by the utility theory as mentioned in Section 2.4. Utility represents the satisfaction of a client in choosing a product. Utility can be measured by observing clients' choices. Clients naturally make choices so as to maximise their utility, that is, to make themselves as happy as possible (Olewnik and Lewis 2006).

As mentioned earlier, specifying the level of modules with the spatial voids approach and solid mass perspective depends on the beneficiaries' requirements, and the modules devised to fulfill these functions can be combined to meet distinct requirements (Rocha et al. 2015). Hence, based on the client and manufacturer requirements, the apartment layout and apartment

spaces from the spatial voids perspective and apartment structure and floor panel from the solid mass perspective are the levels of interest in this research. The following figure presents the two perspectives on the module classification in the multi-storey residential building and the hierarchical level of modules that are focused on in this research.

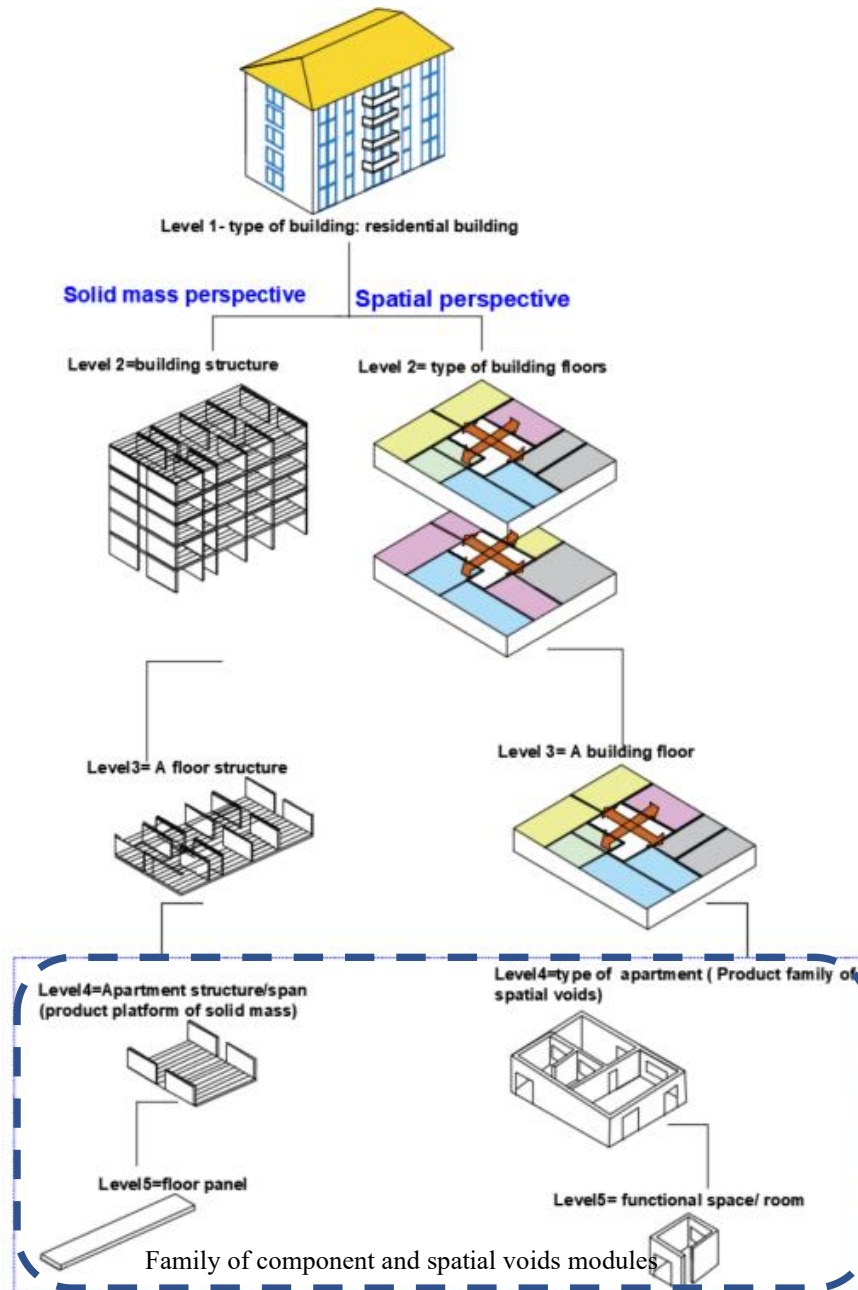


Figure 9- Components and spatial perspectives hierarchical levels

Modular system design taxonomies in prefabricated system

Modular system design lends itself to off-site manufacturing. In terms of product design perspective, modular construction involves producing standardised components in an off-site factory, then assembling them on-site. Components include a range of different systems. These systems vary depending on the complexity of the elements being brought together. Four levels of off-site manufacturing classification that Bertram et al. (2019) and Jonsson et al. (2015)

illustrated are (i) single discipline components, (ii) panels, (iii) volumetric units, and (iv) complete structures (Bertram et al. 2019; Jonsson and Rudberg 2015). The simplest are single elements that are clipped together using standard connections or interfaces. Further along the spectrum are two-dimensional panels (which can be open or closed), while three-dimensional volumetric units with full fixtures are yet more complex. Timber, concrete, and steel can be used separately or in a hybrid system in various forms (Bertram et al. 2019). As the first and fourth categories, respectively, require significant time and cost for on-site installation, panelised and volumetric systems are more appropriate to utilise in order to implement MC in the building industry.

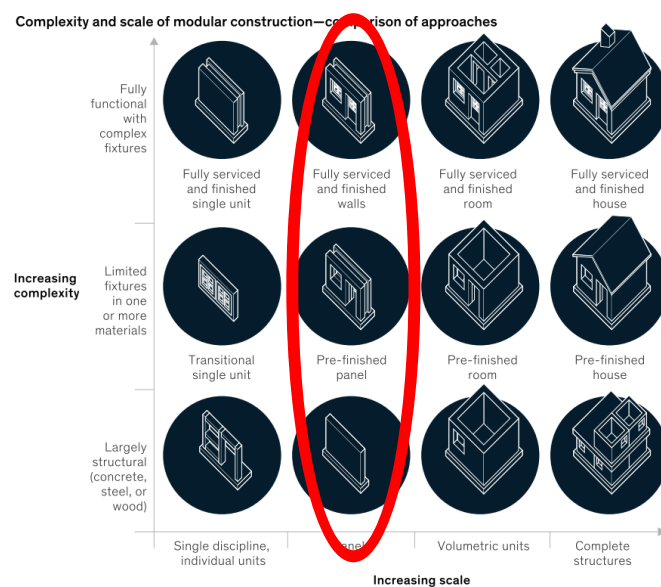


Figure 10- Different range of modular systems in terms of component perspective, adapted from (Bertram et al. 2019)

Volumetric solutions that could constitute a room or part of a room be installed on-site, like a series of Lego bricks, take advantage of maximising productivity and efficiency. Most of the work is done off-site in a factory. However, the maximum width for road transport limits the size of modules, making volumetric suitable for mass-produced housing. It is also advantageous for rooms with more intricate finishing, particularly wet rooms such as bathrooms and kitchens (Bertram et al. 2019). In contrast, panelised solution resembles a flat-pack assembly approach. The on-site installation work in panelised modules is simpler than traditional construction but more complex than volumetric modules. On the upside, it is much easier to transport panels and offers greater flexibility than giant volumetric modules. Therefore these advantages make panelised solutions appropriate for residential buildings (Bertram et al. 2019). The more optimal approach compared to the previous solutions is to use a mix of volumetric modules and panels in a project. Typically, wet areas are manufactured as bathroom

Pods and kitchens, while the remainder of the building is made from panels. This optimises the process for the two different areas of the building, bringing high-productivity improvements to the wet areas and maximum flexibility to all other spaces (Bertram et al. 2019).

Product family and platform in the building industry

The main emphasise of design for MC is to design a rational product family in order to conduct family-based design rather than design a single product. Hence, the span of the design process has to be expanded from the traditional design to include manufacturing and marketing. A product family refers to a set of similar products derived from a common platform yet possessing specific features or functionality to meet particular client requirements (Jiao et al. 2007). The essence of family-based design is to identify and exploits the similarities of design and manufacturing processes. The similarity captured is then built into a specific product family design to increase design rationalisation and manufacturing productivity and to reduce design and production costs. In mass production, each product has its unique design, process planning, production control, tooling, and inventory. However, by grouping similar products into product families based on their topologies or operation processes, it is possible to narrow down the spectrum of product designs so as to reduce design variation and optimise reusability. By this way, to satisfy customisation, design and production changes are kept at a minimum, which brings about mass production efficiency and low cost (Tseng et al. 1996).

Each individual product within a product family is called a product variant or instance. All product variants share some common structures, which form the platform of the product family (Jiao et al. 2007). Product platforms originate from the automobile industry employing a make-to-order strategy, where platforms are used to achieve efficient design and product development work (Jiao et al. 2007). A product platform can be defined as a particular kind of module that encompass a large chunk of physical or conceptual parts than the other modules and that is used in every product variant that can be generated (Rocha 2011).

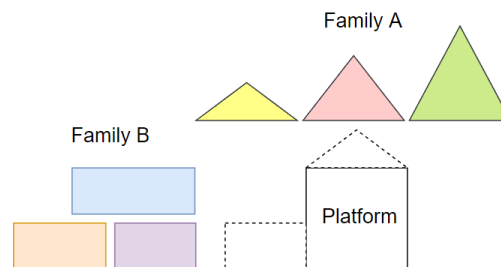


Figure 11- Product family and platform within a product variant

Based on the module, product family, and platform definition, as the essence of family-based design is to identify and exploit the similarities of design and manufacturing processes

together, it is only applicable in volumetric modules. Because in volumetric off-site construction, design and production decisions are usually integrated and jointly made. Namely, it is unlikely to have a building completely designed as a set of volumetric prefabricated pods and have a work structure that does not involve the assembly of such pods. This provides the simplest and perhaps easiest instance to implement and benefit from product modularity in construction because design and production process decisions are usually aligned. Yet, buildings are not usually erected by assembling only a set of volumetric pods produced off-site. Buildings are most often also comprised of smaller and simpler parts (da Rocha and Kemmer 2018). Therefore, only some initial concepts of product family and platform can be utilised in the building industry and in this thesis.

In a residential building, from the preliminary and secondary functional perspectives and at the lowest level based on Figure 9, the product family can be conceived as a family of spaces (living room, kitchen, bathroom, bedroom, etc.) and a family of components (floor panels with different sizes). Apartment architectural layout and apartment structure can be designed and developed based on the aforementioned family of modules. Depending on what common spaces and components all apartment or building variants share, the product platform can be specified. The platform concept supports manufacturer requirements and typically aims to reduce variety so as to increase cost efficiency. Hence, the building structure within the solid mass perspective has perhaps the highest potential for increasing production efficiency through platform concepts. Generally, product family concepts support client requirements by providing variety. However, in the building industry, with the aid of product family concepts (a family of spaces), the architect endeavors to narrow down the spectrum of apartment designs to the design with a great extent of acceptability or desirability so as to reduce design and production variation and optimise the reusability of components. This is illustrated in Section 2.3 as motivation and risks associated with the move towards MC in the building industry.

Product family and platform framework in prefabricated buildings

MC requires a robust design to meet market needs and analyse the production process in order to provide a cost-effective product. The concept of MC is commonly used by those in the residential building sector intending to increase production efficiency or cost efficiency through the appropriate design of a project for manufacturing (an off-site processing plant), transportation, and for installation (on a construction site), and simultaneously provide a customised architectural design (Kremer 2018).

The following figure illustrates a holistic approach to product platform design throughout the value chain of a building project. The framework includes five domains; client, functional,

physical, process, and logistic domain. The client scope involves the development of client insight, where marketing techniques are applied to determine client attributes (CAs), i.e., client requirements in relation to the market. Apart from requirements that directly or indirectly come from the client, a number of stakeholder requirements and governmental regulation also need to be fulfilled. Once these requirements are identified, common requirements can be grouped together to form consistent value propositions for different market segments. Then CAs are converted into a minimum set of functional requirements (FRs) in the functional domain. Here, architects develop building concepts from client information or market analysis in an architectural design based on existing industry norms, standards, and available product technologies. This stage could be a part of solution space development with the aid of conventional market research. This stage comprises the overall parameters of a building and architectural preferences on, for example, materials, shape, style, and size (Bonev et al. 2015), which are usually considered in the conceptual and preliminary design stage.

Clustering techniques or density analysis of FRs based on the previous order has been recommended to group similar designs into a family (Tseng et al. 1996). In platform terms, this mapping constitutes a number of product families (i.e., customisable items) through which common practices of order configuration and sales automation with a configuration system are performed (Bonev et al. 2015; Fettermann et al. 2019). The objective of this domain is to identify: (i) customisable items of the greater value-added capability to provide adequate variety and (ii) standardisable items in order to provide some degree of standardisation and repetition (Fettermann et al. 2019).

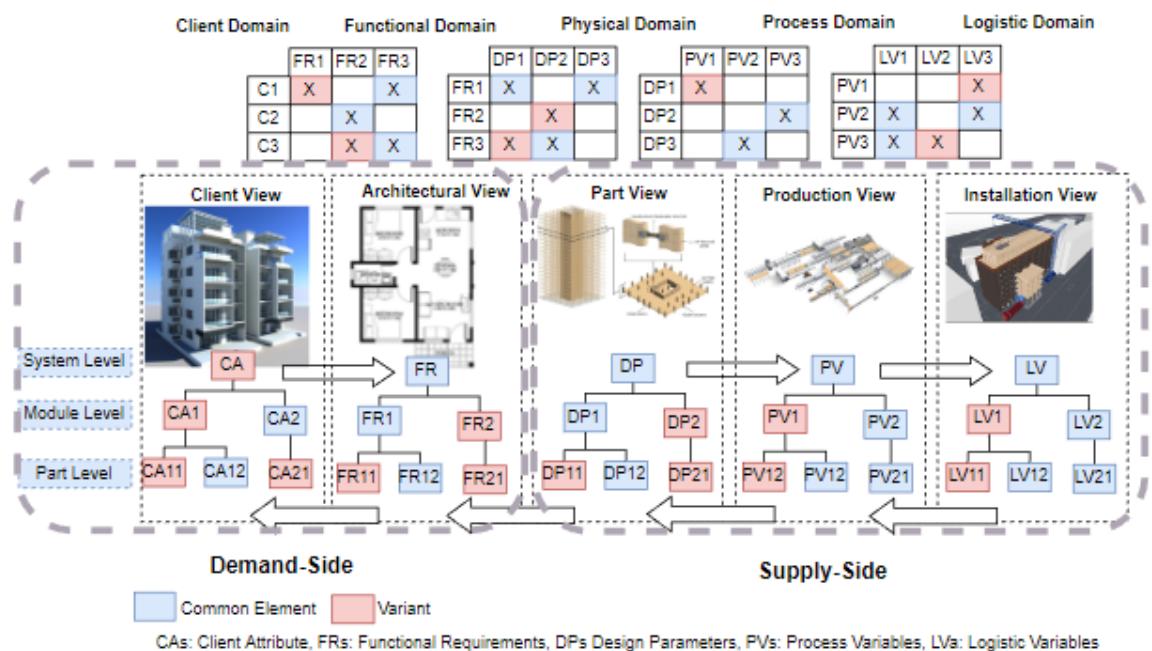


Figure 12- Holistic view of product family and platform concept in prefabricated systems, adapted from (Bonev et al. 2015).

In the physical domain, mapping the relationships and interfaces of FRs to design parameters (DPs) is done. Engineers transfer the architect's initial design into a structural model to create manufacturable structure solutions while referring to given architectural patterns and constraints. With the structural analysis and determination of the building behaviour of the preliminary design, the design focus changes from the innovative design intent of the conceptual design to a design task on a routine basis (Bonev et al. 2015). Conventionally, DPs are defined for each individual product to fulfill FRs. In design for MC, in essence, a few segments of DPs are identified to cover the same FRs that would have required a continuum of DPs (indicated in the following figure). By limiting the spread of FRs, a few selected sets of DPs would be able to fulfill diverse demand-side requirements. Therefore, the number of designs and their associated costs in engineering, manufacturing, and overheads are reduced. Clustering techniques are also applied to assist identification of clusters that match the DPs for serving the same set of FRs. The group DPs indicates the spatial voids modules (Tseng et al. 1996). The idea is illustrated in the next figure, in which product density means the utilisation of products to meet demand-side requirements (Tseng et al. 1996).

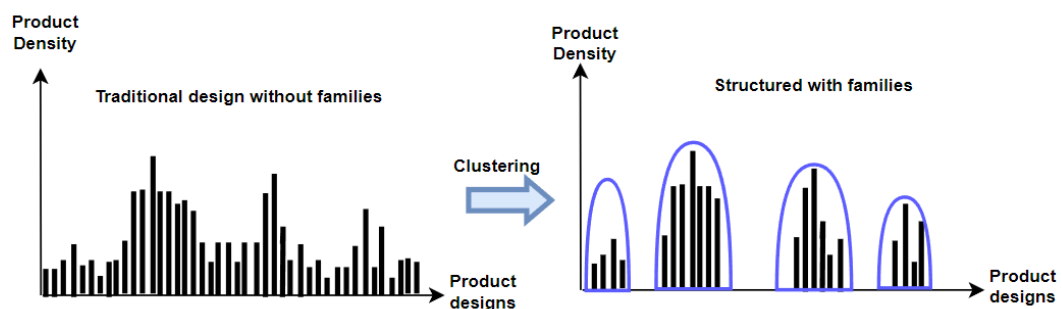


Figure 13- Clustering technique to enhance repeatability in FRs and DPs

The robust manufacturing process and logistic design deal with the delivery of customised solutions at near MP efficiency and the reuse of value chain resources for the fulfillment of different client requirements (Salvador et al. 2009). The manufacturing process can be defined accordingly as mapping DPs to process variables (PVs), and logistic⁹ variables (LVs). These two domains involve the creation of common manufacturing processes, production technologies, distribution, and supply chain networks. Common production tools, machines, transportation resources, installation methods, and optimisation techniques can be used to reduce manufacturing set-up risks and reuse proven production and installation processes.

⁹ Logistic refer to transportation of the elements and installation on-site

From the prefabricated product perspective, the main concern is the transformation of the architectural design specification of a building (FRs) into physical off-site manufacturing elements (DPs) and their subsequent on-site installation (Bonev et al. 2015). Applying optimisation techniques are facilitated trade-offs between grouped FRs and cost of production and logistic process (PVs) and (LVs) to formulate the product platform structure or prefabricate elements (DPs) (Jiao et al. 2007) (Fettermann et al. 2019; Tseng et al. 1996). The bill of material and production process should be considered in optimisation systems (Jiao et al. 2000) so that design with manufacturing is integrated, which leads to finding a cost-effective product platform and, accordingly, appropriate spatial voids modules for a given product platform. The result of these trade-offs represents the optimised DPs.

Modelling platforms from different perspectives facilitates the consideration of all five domains of a building project. As indicated in Figure 12, the modelling notations are used to represent hierarchies, commonalities, and alternative varieties. The hierarchical classification of materials, parts, components, and sub-assemblies represent the product structure and aid in providing a bill of material and production.

optimised layout design techniques

With the aid of optimisation, the manufacturability and constructability aspects of buildings can be verified prior to being built, and an optimum construction plan can be derived (Neelamkavil 2009). Design optimisation can be utilised in three major stages of an engineering design process: conceptual design, preliminary design, and detailed design (Augusto et al. 2012). Nevertheless, layout design optimisation is typically employed either in the conceptual or preliminary design stages.

Optimised layout design methods have been utilised in the literature to find either feasible architectural or structural designs, performing optimal or near-optimal in terms of a set of objectives (Hofmeyer et al. 2006). Optimised architectural layout design techniques usually generate various feasible layouts and evaluate them based on architectural objectives, such as maximum living space (Arvin and House 2002; Homayouni 2007; Michalek et al. 2002; Zawidzki et al. 2011), or lighting (Baušys and Pankrašovaite 2005) and minimum geometrical complexity (Arvin and House 2002; Zawidzki et al. 2011) or energy (Bianconi et al. 2019; Michalek et al. 2002), etc.

Optimised architectural layout design techniques have predominantly been employed in the conceptual design stage. The conceptual architectural layout problem is generally defined as the problem of 1) identifying the shape and size of the components, such as rooms and walls to be laid out, 2) identifying constraints between components, and 3) determining the relative

positions of these components that satisfy the constraints between them. Next, design objectives for optimisation are specified (Baušys and Pankrašovaite 2005). The objective functions in architectural layout design problems are usually focused on the architectural design quality of spaces but not the constructability or manufacturability of the designed layout. The reason behind it is that the studies emphasised the conceptual design stage, where the architect establishes the size, location, and relationships between all the spaces. The basic goal of the conceptual design stage is to establish the shape and size of the building with some basic floor plans of the spaces. Further research needs to be carried out to examine the constructability of the architectural design in the preliminary design stage.

There are different classes of layout problems that have been studied in the literature in terms of variety in the shape and size of components and the constraints between them. Layout components may have defined shapes (square, rectangular, etc.) or loose shapes. Loose shapes are usually undesirable in the layout design. Hence, most existing research handles rectangular components. Rectangular components may have a variable area with a fixed aspect ratio, a fixed area with (upper and lower bounded) continuously variable aspect ratio, a fixed area with a discrete allowed aspect ratio, and a variable area with (upper and lower bounded) continuously variable aspect ratio (Baušys and Pankrašovaite 2005).

On the other hand, optimised structural layout design methods defined as “topology optimisation” explore the arrangement and sizes of structural elements which are optimal in terms of structural objectives, such as structural weight, eccentricity, strength, etc. (Hofmeyer et al. 2006). These methods generally have been exploited in either the conceptual or preliminary design stages (Sharafi 2013; Sharafi et al. 2012; Tapao and Cheerarot 2017).

Some studies have already been carried out on structural layout design to optimise geometry, size, and location of different building elements (design of vertical or floor systems) (Kim et al. 2002), predominantly in precast and cast-in-place concrete systems (Augusto et al. 2012; Sahab et al. 2005). The design objectives in these studies mainly concern optimising structural performance variables (structural weight, structural strength, and serviceability) (Sharafi et al. 2015) or material cost (Baghdadi et al. 2020; Sahab et al. 2005; Tapao and Cheerarot 2017). These categories of studies rarely consider architectural designs. Also, these studies’ groups have not accounted for the structural component production processes. Nevertheless, a few studies integrate architectural and structural layout design (volumetric system) as one design system (Sharafi et al. 2017) or endeavour to fit the structural design into an architectural plan (Khemlani et al. 1998).

A number of studies have utilised optimisation methods to improve production aspects by focusing on component design. Examples include optimised design of exterior panelised walls' geometry (Gbadamosi et al. 2019; Said et al. 2017) and a precast concrete production planning model to reduce the molding process cost (Khalili and Chua 2014). However, these studies have not accounted for topology optimisation (layout optimisation). Also, production process and manufacturing constraints have not been addressed adequately, and product costs have been calculated based on predefined prices of standard components. In other words, component manufacturing processes have not been considered in cost estimation. Rather, improving production aspects has implicitly relied on standardised components.

Few studies have focused on prefabricated components production processes regarding the production time or manufacturing cost estimation (de Araujo Carneiro 2019). Because the manufacture of some typical prefabricated systems, such as precast beams and columns, is less automated and more labor-intensive leading to unknown process time. (Augusto et al. 2012; de Araujo Carneiro 2019; Petprakob 2014; Sharafi 2013; Sharafi et al. 2012; Sharafi et al. 2017). However, compared to the precast concrete system, fabricating Cross-Laminated Timber (CLT) panels is a more automated process than precast concrete elements. Then, the production process is less complicated to be measured.

2.6 How to design for mass customisation in a prefabricated system?

To develop a data-driven framework for MC, two scenarios are considered in this research. The initial scenario, detailed in Chapter 4, envisions an architect within a Design and Construct (D&C) company (volume builder) seeking modular design patterns conducive to MC. In essence, their objective is to identify design patterns that are both manufacturable and align with the preferences of selected clients. The architect's role entails striking a balance between clients' design preferences and designs that can be feasibly manufactured. Consequently, the architect undertakes an evidence-based comparison to facilitate the creation of modular design layouts founded on commonalities among clients' architectural designs. This scenario is primarily applicable during the conceptual design phase and corresponds to the identification of a set of functional requirements (FRs). The architect develops building concepts from client desires based on product analysis (i.e., architectural design), existing industry norms, standards, and available product technologies. This could be a part of solution space development with the aid of conventional market research. This stage comprises the overall parameters of a building and architectural preferences, including architectural space size, resulting in determining prefabricated component size.

In the second scenario explored in Chapter 5, the architect within a D&C firm faces the task of devising a wholly customised building layout, essentially creating a unique product. This undertaking transpires subsequent to the conceptual design stage, specifically during the preliminary design phase. In this context, the architect's scope for implementing modular design layouts is restricted. Instead, their focus shifts towards integrating production processes into the building design without compromising the adaptability of customised architectural designs. While this approach doesn't lend itself to identifying parallels in clients' architectural preferences, the architect remains responsible for optimising the design for manufacturability. The objective of this scenario revolves around transforming the architect's initial design into manufacturable solutions—namely, optimal design parameters (DPs)—all the while navigating predefined architectural patterns and constraints. This shift in design emphasis redirects from the innovative design intent characteristic of the conceptual design stage towards a design approach centred on manufacturability.

For developing the building structure as a product platform for MC, the first scenario provides a higher degree of standardisation compared to the second scenario. The first scenario primarily deals with architectural design analysis and contemporary manufacturing practices. As identifying manufacturing processes play a key role in the second scenario, this section focuses on the manufacturing processes of CLT system as a case study to develop the framework for the second scenario to implement MC.

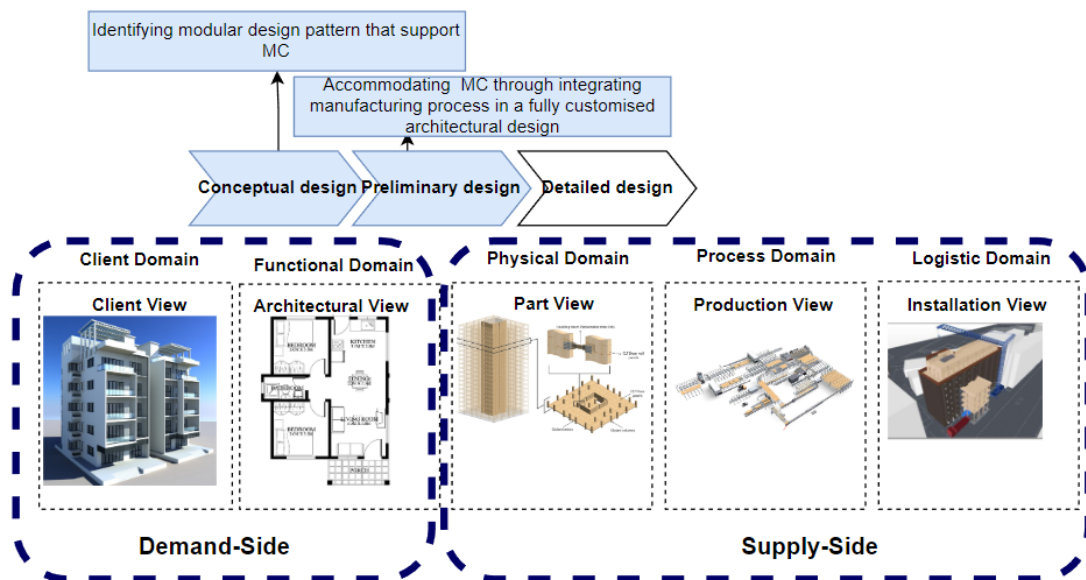


Figure 14- Two scenarios considered in this thesis for implementing MC design in a prefabricated system

2.6.1 Cross Laminated Timber (CLT)

CLT is an engineered wood product and a type of mass timber element in which each layer of timber boards is placed perpendicular to the lower layer, glue-bonded, and pressed to

form rectangular billets, typically with three-, five-, seven-layers and standard sizes (Kremer 2018; Livingstone et al. 2015; Riala and Ilola 2014). CLT is a very versatile product that can be utilised in several elements of a project, such as exterior walls, separation and partition walls, floors, and roofs. The following figure shows a schematic representation of a CLT component. Before proceeding, two main terms, called panel and billet in CLT manufacturing, need to be clarified to avoid confusion. A billet is a large standard element, while a panel is a customised one cutting from a billet.

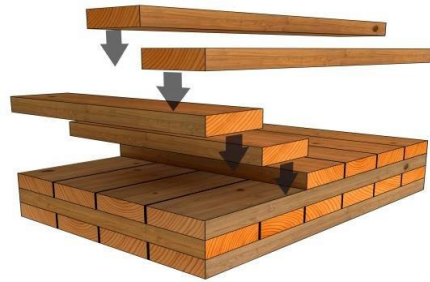


Figure 15- Schematic representation of a CLT element, adapted from (Buck et al. 2016)

CLT manufacturing and construction in Australia have experienced a growth rate due to their light weight, ease of installation, and cost-effectiveness in buildings. The Australian CLT market is currently at least 50,000 cubic meters per annum and is growing quite rapidly. On its current trajectory, it is expected the market to be more than 80,000 cubic meters by the end of 2023 because of population expansion, continued urbanisation, and sustainable housing options (IndustryEdge 2020). A US-wide survey revealed almost 70% of architecture firm professionals believe that CLT's environmental performance, structural performance, and aesthetics are excellent or good compared to other construction materials (de Araujo Carneiro 2019). The current domestic manufacturing capacity provides around 40% of the volume, with the remainder imported. Currently, two large existing plants operating CLT production lines, i.e. Xlam and Crosslam, are being enhanced to increase capacity to supply the whole country's CLT market (IndustryEdge 2020).

CLT-related applied research, particularly in Australia, has basically focused on technical or engineering aspects of the product, such as structural performance, serviceability (Brandner 2013), fire performance, and component setup variations (Buck et al. 2016; Yusof et al. 2019; Yusoh et al. 2020). Studies revealed that manufacturing issues such as optimisation of computerised cutting, perforation rates of connection, and modular fabrication are suggested research topics in CLT system (Abiri 2020; de Araujo Carneiro 2019). Customisable CLT design management regarding manufacturing processes has not yet been tackled by applied research.

2.6.2 Fundamentals of developing a design framework for building MC

In this section, the fundamentals of developing a design framework regarding manufacturing processes for building mass customisation, derived from the literature, are discussed.

Balancing increasing production efficiency through the appropriate design of a project for manufacturing and logistics on the one hand, a customised architectural design, on the other hand, requires an optimisation model to support architects' decisions. As components production costs comprise 80% of prefabricated structure costs (Forsythe and Sepasgozar 2019; Goh and Goh 2019; Hasan et al. 2018), and this percentage is significant compared to logistic costs, the current study focused on the manufacturing process of CLT elements.

Implementing MC in the building industry does not mean that an infinite number of design options have to be offered to the client, or a fully customised design can be accepted and produced by the manufacturer as a cost-effective building. Rather, in a mass customised dwelling, providing an appropriate number of design options can be sufficient. An infinitive offer of variety is the other extreme of client satisfaction. This approach causes a lot of waste, and a higher cost imposed on the client and, consequently, users (Wee and Aurisicchio 2018). The number of design options is a strategic decision that varies depending on the market segment, location, time, and how the supply side deals with manufacturing efficiency. In all cases, it is important to keep the client satisfied.

As mentioned in the previous sections, several important concepts are centered around efficiencies in the manufacturing of elements. The primary idea concern the standardisation of parts. Some literature in the manufacturing industry has recommended using 'standardised' and 'off-the-shelf' rather than custom components. Further, not only is parts standardisation important for the concept, the removal of elements and a reduction in the number of the overall parts assist in reducing time in manufacturing and increasing efficiencies. Standardisation provides 'certainty' to manufacturers of standardised products, specifically in the domain of quality control and assurance. Certainty extends to the availability of parts and to the performance of the components that constitute the end product, providing reliability through repeated manufacture and installation over time. The standardisation of parts also allows for specific tooling for machines that assemble standardised products (Kremer 2018). A company's investment in such equipment and tooling is contingent on accepting some degree of flexibility in changing customised design from the demand-side, and the control over the manufacturing process from the supply-side. By controlling over the manufacturing process, the supply-side ensures that equipment performs as expected to achieve expected efficiencies. In other words,

in mass customisation of design, the supply-side and demand-side must agree on building design adjustments at a module or part level.

In CLT elements, panels are limited to a number of specific dimensional thicknesses. However, the length is different. The following table shows the standard thicknesses of a CLT factory in Australia. Each panel and element that is cut constitutes a portion of the overall structure, often many panels will not be replicated twice. If we accept that panelised system involves a high degree of non-standardised but highly customised panels and elements uniquely produced and installed for a structure in a project, then applying MC may not be appropriate (Kremer 2018).

Table 3- The standard CLT component thickness (mm) in CLT factory, adapted from XLAM design guide

Type of panels	Panel thickness (mm)
3 Layer Panels	CL3/85
3 Layer Panels	CL3/10
3 Layer Panels	CL3/115
3 Layer Panels	CL3/125
3 Layer Panels	CL3/135
5 Layer Panels	CL5/145
5 Layer Panels	CL5/160
5 Layer Panels	CL5/175
5 Layer Panels	CL5/195
5 Layer Panels	CL5/205
5 Layer Panels	CL5/225
7 Layer Panels	CL7/245
7 Layer Panels	CL7/265
7 Layer Panels	CL7/275
7 Layer Panels	CL7/295
7 Layer Panels	CL7/315

The levers of efficiency within the MC concept for a product like CLT relate to the type of material selected, the thickness of panels, the spanning capacity. Whilst these panels are not fully standardised, they are mass customised, the ability to find commonalities between CLT thicknesses and spanning or loading capacities within the project allows for a relative degree of efficient design. Panel efficiencies, in this sense, should be considered as part of a single project only, not a comparison between different projects, because we know the majority of projects

are unique (Kaiser et al. 2019). However, it could be applicable for projects with the same characteristics.

Relative to the design and scope of the project, once the panelisation is completed, the geometric shapes or the panels nesting must be optimised for cutting from the billet. There is software that optimises panel nesting, but the software is designed for predetermined dimensions, including panel length, width, and thickness. However, anecdotally human intervention for nesting panels and selecting specified thicknesses seems to still be the preferred option (Kremer 2018). In any project, there are likely to be an assortment of panel shapes and sizes to be cut from billets. Manufacturers cannot simply just remove or reduce these parts to make efficient use of the material and production time. Nevertheless, what can be done is the arrangement of panels across multiple billets with a few changes in length to ensure efficient cutting. This scenario is usually allowed where the manufacturer's actions do not sacrifice architectural design and keep the client satisfied.

How to process production information in a quantitative way is very crucial to improving the decision support model with the objective of increasing production efficiency in an off-site manufacturing context. The next section addresses the manufacturing process of CLT system in a quantitative fashion.

2.6.3 Manufacturing processes in CLT system

Residential building design and manufacturing processes need to be integrated to provide a cost-effective building. Building design (architect view) and manufacturing process (production view) decisions are usually integrated and jointly made in volumetric off-site construction. In other words, it is unlikely to have a building completely designed as a set of volumetric prefabricated pods and have a work structure that does not involve the installation of such pods. This provides the simple and most straightforward instance to implement and benefit from modularity in construction since building design and manufacturing process decisions are usually aligned. As buildings are most often comprised of smaller and simpler parts, such as panels, this kind of product modularity can still yield MC benefits, provided that these parts are organised in such a way leading to the increased production efficiency. Hence, manufacturing process and product design decisions need to be considered simultaneously. Consequently, optimising design considering manufacturing processes becomes a key. If product design is not considered in organising the tasks to produce a building with higher production efficiency, this building is not likely to be a mass customised one.

Production efficiency of a product directly depends on the manufacturing process time. A review of the panelised structural system indicates that panel production time depends on

some characteristics, such as size and thickness (de Araujo Carneiro 2019). The industry, however, tends to disregard production time and estimates the cost of such systems based on the quantity of materials. Ignoring the production time may lead to underestimating the manufacturing process or loss of profit (Niazi et al. 2006). A handful of studies have described CLT manufacturing processes in Europe, North America, and Asia. Industry-sponsored information materials, including fact sheets, websites, booklets, and design guides, superficially and profoundly have described the production process, highlighting the production stages, panel layout and factory quality, and production control procedures. Few research, including (de Araujo Carneiro 2019) has studied CLT manufacturing process in-depth and in a quantitative way. An overview of CLT manufacturing is elucidated in this section to identify the production process stages contributing to the optimisation model development. As mentioned before, balancing increasing production efficiency through the appropriate design of a project for manufacturing and a customised architectural design requires an optimisation model to support architects' decisions.

CLT production consists in manufacturing structural- and architectural-grade CLT panels according to client requirements. Each part in the project will have specific features such as cuts, chamfers, drills, and holes, aside from its specific geometry (i.e., shape, length, width, thickness), structural grade, visual grade, etc. The general production process remains the same, but because of the differences in each panel configuration, process times, production constraints, and parameters may change from panel to panel. Understanding the production process is critical to model and simulate the manufacturing procedure and thus aids in improving production efficiency. A schematic representation of the general CLT manufacturing process is presented in the next figure, and each stage is illustrated in the following paragraphs.

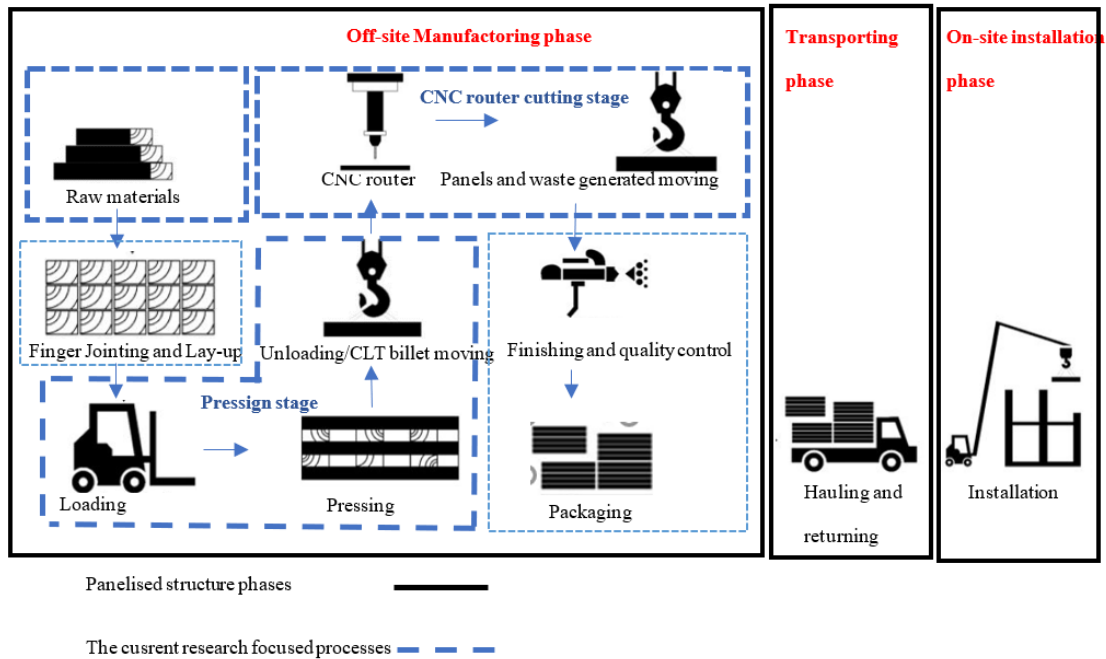


Figure 16- Overview of a CLT structure stages, adapted from (Abiri 2020)

Raw materials and preliminary stages

In the preliminary stages, raw material sorting, selection, and control are performed. Raw materials (wood board) needed for CLT production are dominantly lumber and adhesive. Lumber selection for CLT production purposes is preliminary from structural dimension lumber or boards. Species predominantly utilised in Australia's market are radiata pine and dogulas fir (FWPA 2014). Adhesives traditionally utilised for other engineered wood purposes, including PRF¹⁰, EPI¹¹, and one-component PUR¹², are usually adopted for CLT applications. Among the engineering wood adhesive, PUR adhesive is mainly utilised in Australia due to its higher safety and zero formaldehyde emission levels (IndustryEdge 2020; XLam 2017).

CLT raw materials (wood boards) are inspected, selected, planed, cut, and finger jointed. In industrial custom CLT factories, primary lumber selection, drying, and grouping are carried out directly by the wood board suppliers. After the first visual inspection of the raw materials, raw lumber boards are planed. This process includes removing a very thin layer of wood from both surfaces of the board, ensuring dimensional consistency. Then the lumber boards are cut to the desired length based on the application (longitudinal or perpendicular layers). Depending on the length of the intended panels, longitudinal finger jointing may be required (de Araujo Carneiro 2019).

¹⁰ Phenol-resorcinol formaldehyde

¹¹ Emulsion polymer isocyanate

¹² Polyurethane

Pressing stage

The next step in CLT production process is to glue the board layers together. The pressing stage is the first phase of material transformation in CLT production process, where single boards are combined with adhesive to make CLT billets (de Araujo Carneiro 2019). First, the selected adhesive is applied with parallel lines of application heads. After each layer, the adhesive application process is repeated. Then the actual panel pressing may be carried out through mechanised machines, namely, hydraulic or vacuum press equipment (de Araujo Carneiro 2019).

There are some technical constraints in the pressing stage: (i). It is impossible to press billets of different widths concurrently. While there is no constraint on pressing billets of different lengths, the same billet length is usually maintained within a certain project to increase the productivity of this stage (Abiri 2020; de Araujo Carneiro 2019). Billet production is performed with standard sizes, including 12×3 , 12×2.4 , 16×3 , and 16×2.4 meters, although producing non-standard sizes is possible and dependent on the manufacturer's machinery. Among these, 12×3 and 12×2.4 meters of billets are the most common sizes in Australia due to ease of handling across different factory stations (Abiri 2020; Guide) (ii). During billet manufacturing in the pressing stage, changing the type of billet, including the number of layers and thickness, requires the relevant settings on the press machine leading to the waiting time in this stage (de Araujo Carneiro 2019).

Computerised numerical control (CNC) router cutting stage

CLT elements are typically cut to fit. Up to the previous stage, a standard industrial CLT panel, which is named "billet", is manufactured. From this stage on, the manufacturing process includes customisable features of CLT panels. For floor panels, depending on the length of spans, the panels are cut from the standard billet. Openings and cutting the billets are usually cut out of the billets without requiring additional trimming. Cutting, drilling, and trimming are carried out by computer-aided equipment, making maximum cutting accuracy and detail. For floor panels, large openings, such as duct holes, are cut out from panels. CNC router machines incorporate large-sized CLT panels using tools, namely molding cutters, saws, chain saws, etc., with sequential instruction provided by computer code (de Araujo Carneiro 2019). The design drawings developed by the architects are converted to a command code for CNC machine to learn the pattern of the cut (Abiri 2020).

Finishing, quality control, and packaging stage

The final stage in the production line provides the final details and finishing touches to customised CLT panels. In this stage, face sanding and features that are not able to be executed

by the CNC, are performed manually. Quality control¹³, labelling¹⁴, and packaging are also carried out at this stage. Then factory wrapping is done to protect panels from moisture and light mechanical damage (de Araujo Carneiro 2019).

Material loading, unloading, and storage

During manufacturing processes, material loading, unloading procedures, and storage have significant impacts on the overall process and plant productivity. Material loading, unloading, and storage are included in each of the aforementioned stages (de Araujo Carneiro 2019).

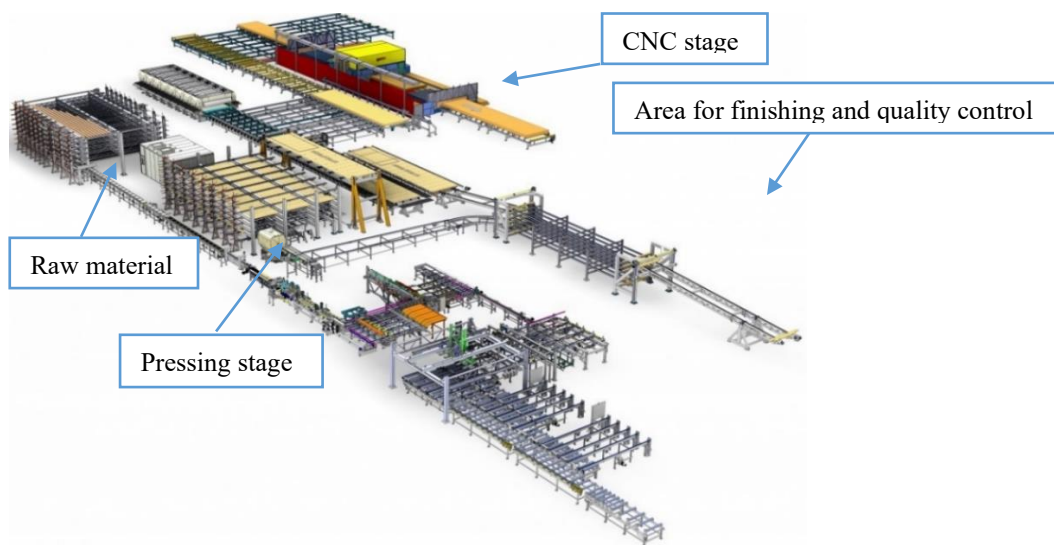


Figure 17- CLT production line and manufacturing processes, adapted from (Ledinek 2018)

CLT panel transportation and installation (logistics) constraints

Where there is off-site manufacturing, it implies that the manufactured panels should be delivered to the construction site. Transportation cost depends on the size and weight of panels, transportation method, and distance of travel. The shipping method varies depending on the infrastructure, routes, and distance. The regional types of vehicles are trucks, trains, and ships. However, it adds some limitations to the project. Truck transportation is the most feasible and common type of shipment method regionally. Truck transportation requires transportation permits for oversized loads, dimensional limitations, and road regulation restrictions. City and government permissions or truck escort add costs to the project and is not always feasible. Furthermore, the size of the hauling is limited by the regulation as well. The maximum truck

¹³ Measurable attributes, dimensional requirements and tolerances are checked, and general quality attributes such as surface finishing consistency, corner damage, among other, are inspected.

¹⁴ Labelling is important to ensure the correct panel category is being delivered and installed. It also identifies that manufacturer and indicates the quality assurance procedures have been made.

size authorised by Australia’s government is 2.5 meters wide, 4.3 meters tall, and 12.3 meters long (National Heavy Vehicle Regulator 2016).

Once the CLT panels arrive at the construction site, the installation and erection process initiates. On-site installation typically includes lifting, positioning, adjusting, and connecting the elements. As mentioned before, component production costs comprise 80% of prefabricated structure costs (Forsythe and Sepasgozar 2019; Goh and Goh 2019; Hasan et al. 2018), and this percentage is significant compared to logistic costs. Hence, the current study focuses on optimising the manufacturing process of CLT elements, but it only considers the logistic constraints. In other words, this research does not aim to optimise the logistic process and costs.

The extant research shows that pressing and CNC router cutting stage and raw materials are the high-cost factors in fabricating billets and panels (Abiri 2020; Brandt et al. 2019; de Araujo Carneiro 2019). They are presented by dashed thick lines in Figure 16. Araujo Carneiro (de Araujo Carneiro 2019) developed a relatively comprehensive CLT production time estimation model by considering billet and panel characteristics. The production time estimation model is applicable in this research since: (i) the model ties the necessary time taken to produce a panel in a particular stage with components and job characteristics. (ii) the plant layout and machine specification in Araujo Carneiro’ research are similar to the considered CLT factory, i.e., XLAM, in Australia. In the following section, the production process time of pressing and CNC stages, which are employed from the literature to develop the MC model in current dissertation, are elaborated.

2.6.4 Production process time for pressing and CNC router cutting stages

Billet characteristics, namely length, width, and thickness, significantly affect the pressing stage time (Abiri 2020; de Araujo Carneiro 2019). Referring to the time estimation model (de Araujo Carneiro 2019), for three-, five-, and seven-layers billets with 12 by 3 meters length and width, the required time of pressing stage (*Press*) for each type of billet is calculated and listed in the next table. de Araujo Carneiro developed these formulas through regression analysis to model each stage of the CLT production process. Also, the pressing stage waiting time (*PW*), which is the time considered to set up the press machine to change the billet layers number, is around 10 minutes (de Araujo Carneiro 2019).

Table 4- Pressing stage time estimated for billet 12 meters adopted from (de Araujo Carneiro 2019)

Number of layers in a CLT billet	Pressing stage time (minutes)	
3-layer	91	$Press_{three-layer\ billets}$
5-layer	102	$Press_{five-layer\ billets}$
7-layer	110	$Press_{seven-layer\ billets}$
Setup time (waiting time)	10	PW

In CNC machining stage, the production process includes cutting openings, adding customisable features and edges, and transforming long billets into smaller CLT panels. The number of panels (NP) which are cut from each billet, waste material percentage produced after cutting (W), coding software estimated process time (set) are the CNC stage time estimation indicators (de Araujo Carneiro 2019). (set) is the estimated cutting time per meter for the coded process which is provided by CNC coding software built-in feature (de Araujo Carneiro 2019). Araujo Carneiro has been extracted (set) from the software and considered based on billet fixed length and width. To adapt (set) parameter to this dissertation, the author applied CNC router catalogs for estimating cutting time per meter, for softwood as a raw material of CLT, with the speed of 10000 RPM¹⁵, and tool diameter up to 6.3 mm. The given tool diameter and machine speed are common specifications of a CNC machine in a CLT factory. Consequently, based on these specifications, (set) is approximately considered twenty seconds per meter (one-third of a minute) (3DHUBS 2021).

As an example, (set) calculation time with three different cutting patterns is illustrated in the next figure. The small rectangles with dashed lines represent cutting patterns of panels from a billet. The large rectangles with thick lines indicate billets.

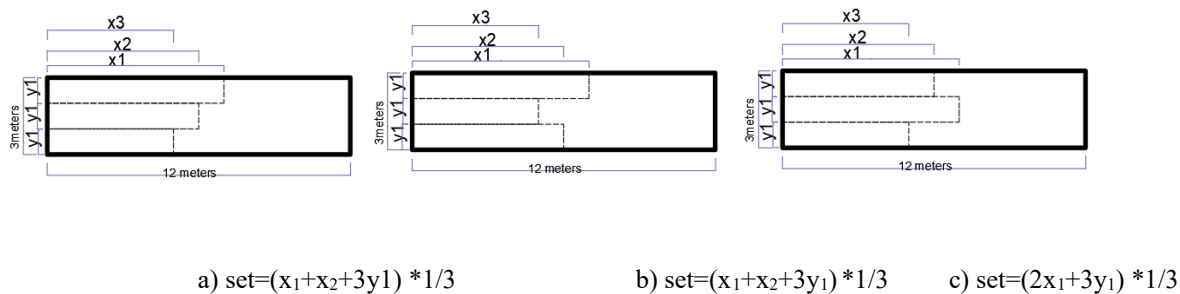


Figure 18- a), b), c). Calculation of CNC software estimation time (set) based on three different cutting patterns of panels from billet

Eventually, based on the above parameters explained, Eq (1), (2), (3) present the total CNC process time for three-, five-, and seven-layer panels, respectively (refer to Table 3)

$$Eq(1). CNC_{three-layer panels} = 1.13 + \frac{9.77NP + 0.525 W + 2.567set}{NP}$$

$$Eq(2). CNC_{five-layer panels} = 14.3 + \frac{9.77NP + 0.525 W + 2.567set}{NP}$$

¹⁵ Revolutions per minute (RPM) relates directly to the speed, or velocity, of the spindle. It represents the number of turns completed in one minute around a fixed axis. RPM maintains the same revolutions per minute throughout the entire operation.

$$Eq(3). CNC_{seven-layer\ panels} = 25.09 + \frac{9.77NP + 0.525W + 2.567set}{NP}$$

2.7 Literature review summary and its implications for this research

Within this section, residential building procurement systems in the building industry are explained to identify the key players in implementing MC and their requirements. By differentiating construction companies' and mass producers' approaches towards moving to MC concept, the importance of limiting design variety, decreasing manufacturing costs, and optimising production processes regarding design as the main characteristics of moving toward MC in the building industry are highlighted. The law of variety, theory of swift, even flow, and utility theory are considered as a law and theories that can support MC concept, hence can be applied as a theory triangulation method for validating the model. The level of MC in the building industry is explained to determine the position of the current research in terms of where customisation level should be in residential buildings. MC enablers in the design phase, including modules, platform, and product family, are discussed to provide an approach to finding a pattern for dwellings' modular design offered to different clients. These enablers also help to integrate client-driven design parameters and efficient manufacturing for floor layout. Ultimately, CLT manufacturing processes are elaborated in order to integrate with the design and support the manufacturability of the building design.

2.8 Research Gap and Innovation

The existing literature reveals several critical gaps in the successful implementation of mass customization (MC) within prefabricated building practices. Firstly, prior studies have predominantly focused on singular perspectives of MC, overlooking the essential dual consideration of both client-driven design requirements and efficient manufacturing processes. This omission impedes the integration of client satisfaction with cost-effective production strategies, crucial for achieving mass-customised designs at competitive prices.

Moreover, there is a noticeable scarcity of quantitative approaches towards integrating design and production processes, hindering the development of profitable and cost-efficient MC solutions. While qualitative insights have been explored, quantitative research in this realm remains limited, particularly in parameterising production processes during architectural design stage to quantifiably account for cost and time savings.

Furthermore, the segregation between architectural and structural design optimisation further compounds the challenge. While architectural layout optimisation often prioritises aesthetic and functional criteria without consideration for manufacturability, structural layout

optimisation typically focuses on structural efficiency, neglecting architectural flexibility and factory production constraints.

By addressing these gaps, this research aims to bridge the divide between design and manufacturing in prefabricated building practices, offering a comprehensive framework for integrating client requirements with efficient production strategies. This endeavour necessitates the development of quantitative methodologies that account for both architectural and manufacturing constraints, enabling the realisation of mass-customised designs within prefabrication factories. Additionally, by exploring the parameterisation of building layouts for efficient offsite fabrication, this research seeks to establish a direct link between architectural designs and manufacturing processes, facilitating the seamless implementation of mass customisation. Through these efforts, this study aspires to contribute significant insights into the intersection of design and manufacturing in the context of prefabricated construction, ultimately advancing the discourse on mass customisation within the residential building industry.

Chapter 3: Research Design and Methodology

3.1 Introduction

To apply product platform strategies for mass customisation of buildings, the focus must be on design specifications that lie between ETO and SV. The supply-side and demand-side agree on building design adjustments at a module or part level (Bonev et al. 2015). The integration of design and manufacturing is seen as a solution to the problem of achieving the balance between customisation and mass production efficiency in residential buildings. Dwellings' modular design aid in developing a well-defined manufacturable layout and product platform design. However, apart from some basic studies in the literature for developing frameworks for integrating design and manufacturing processes in prefabricated systems, there is a lack of comprehensive apartment design analysis to formulate the architectural design parameters (i.e., FRs and DPs) in order to find a pattern for modular design of dwellings.

To fill this gap, this research deals particularly with the two major challenges related to carrying out design for MC: (i) finding a pattern for dwellings' modular design offered to different clients and (ii) developing a framework or model to integrate architectural designs with efficient manufacturing. After conducting a literature review and discussing the state-of-the-art of MC, this dissertation aims to fill this knowledge gap with two scenarios. The first scenario includes specifying patterns for apartments' modular design, which must be executed in the conceptual design stage. This scenario assumes that an architect is looking for manufacturable design patterns that are applicable or desirable for the selected clients. As explained, there is little research in analysing the architectural design of the residential buildings in order to find common architectural space characteristics. Identifying the common architectural space characteristics is a means to find a pattern for apartments' modular design. The architect has a role to identify a balance between clients' preferred design and a manufacturable design. Apartments design analysis with spatial voids modularity approach gives architects insight into developing a well-defined practical platform for modular design scenarios (Jansson et al. 2013; Rocha et al. 2015; Roy and Roy 2016). This scenario must be executed in the conceptual design stage.

Then this research aims to fill the knowledge gap by developing a mathematical model applied in the preliminary design stage that considers the manufacturing of CLT buildings in the second scenario. The second scenario assumes that the architect has been tasked to design a fully customised building layout, i.e., a one-of-a-kind product. This task takes place after the

conceptual design stage, i.e., during the preliminary design stage. Under this scenario, the architect has little room to offer modular design layouts; instead, s/he must endeavor to accommodate MC through integrating production processes in the building design without compromising the flexibility in the customised architectural design. In other words, while this approach does not lend itself to identifying similarities in the clients' architectural design, the architect is still responsible to optimise design and determine optimal design parameters for manufacturability. How to process manufacturing information in a quantitative way is very crucial to developing the model in this scenario with the objective of increasing production efficiency in an off-site manufacturing context. For developing the building structure as a product platform for MC, the first scenario provides a higher degree of standardisation compared to the second scenario.

This chapter presents the methodological approach utilised to achieve these objectives. In this chapter, first, the general approach of the methodology and an overview of the research process are presented. Next, the research process, including data collection and data analysis techniques related to the first objective of this research, is detailed. The first objective this study is to identify prevalent design patterns in residential building layouts and systematically assess their manufacturability. At last, the details related to this study's second, third and fourth objectives, including modelling parameters, variables, and constraints, are discussed. These objectives are:

- (ii) To mathematically model the interrelationships between architectural and structural layout designs
- (iii) To determine the most critical manufacturing processes influencing building layout
- (iv) To integrate manufacturing processes in building layout design for attaining optimal factory efficiency and preserving architectural flexibility

These objectives lead to the development of a mathematical framework that can ultimately be used in the preliminary architectural design stage as a decision-making support system for increasing production efficiency and decreasing the cost of the construction operation.

3.2 The constructive research approach

The approach adopted for this dissertation is that of constructive research, also referred to as design science research. This methodology is visually depicted in Figure 19, illustrating its application within this study. The constructive research approach is a problem-solving

method that aims at producing novel solutions to both practical and theoretical problems. Solutions are often suggested through managerial problem-solving techniques through the construction of models, diagrams, and plans (Oyegoke 2011). At a practical level, project management discipline tends to adopt a problem-solving approach to projects. Problem-solving approach is categorised under the hard paradigm in project management research. The terms hard and soft paradigms are commonly used in project management literature. The soft paradigm is generally related to an interpretive epistemology, inductive reasoning, and exploratory, qualitative techniques, which emphasise contextual relevance rather than objectivity. However, the hard paradigm is typically associated with positivist epistemology, deductive reasoning, and quantitative techniques, which are often associated with rigour and objectivity. Hence, tools and techniques related to problem-solving are predominantly quantitative (Pollack 2007).

The constructive research question can be phenomenon-driven or theory-driven, or a combination of the two. The objective is to identify and solve real practical problems. Constructive research as a methodology begins with a strong grounding in identifying a practical problem from practice complemented by related literature. The identified research problems are used to propose research questions. The research questions are solved by developing or constructing a solution that will be operationalised to determine its workability. This type of approach is related to rationalise paradigm and quantitative technique (Lehtiranta et al. 2015; Oyegoke 2011; Pollack 2007).

The constructive research approach is not a new concept. There are some applied constructive studies in technical sciences, mathematics, and computer science with different solution forms, such as a conceptual or mathematical model, a physical artifact, a new product development, or even software. The constructive research approach is centered on the design of a construct or the construction of a solution. The constructive research approach is an intrinsically goal-directed problem-solving activity and usually applies the proposed construct in a case to evaluate it (Oyegoke 2011).

3.3 Overview of the research process

The next figure depicts the five phases of the constructive research approach adopted in this research. These phases are: (i) finding a practical problem, (ii) obtaining an understanding, (iii) data collection and developing a solution, (iv) validating the solution, (v) research contribution. This process is not linear but rather a dynamic and interactive process between different phases. In this thesis, it starts with Stage A by identifying practical relevance problems that have research potential and can be supported by theoretical literature review and practical

experience. This includes mass customisation epistemology, theory, and technical concerns, which provide the theoretical viewpoint as well as background and information for the investigation. This stage allows the researcher to comprehend the topic. There are three major approaches that can be used in generating problems in constructive research: (i) anecdotal evidence, (ii) evidence based on practical experience driven from practice or from practitioners, and (iii) evidence from peers' theoretical work (Oyegoke 2011). Chapters one and two of this dissertation applied evidence from peers' research to generate problems and research questions (Phases 1 and 2 of the research process).

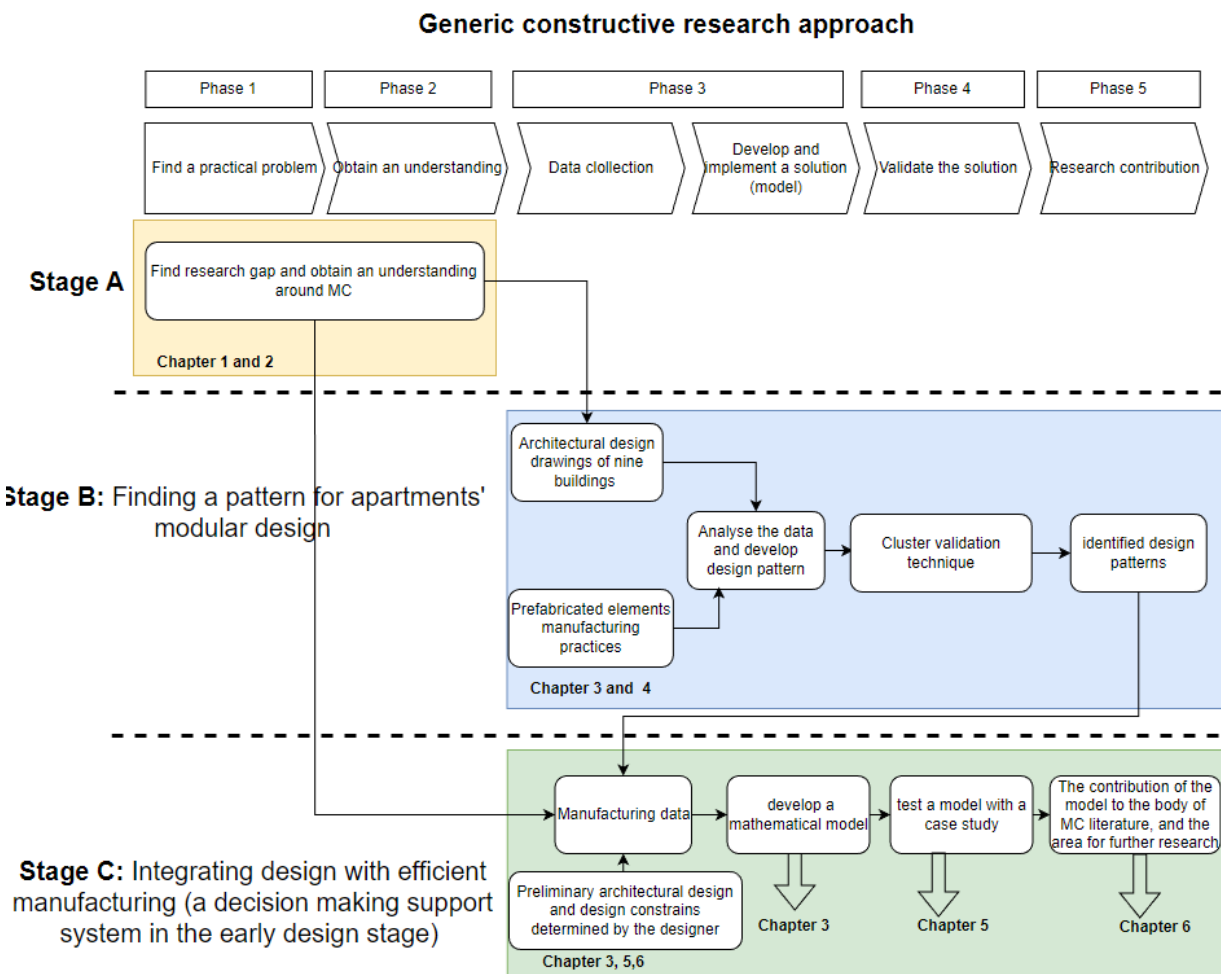


Figure 19- overview of the research process

A better design of a construct is informed by both theory-based connection and practical or real experience (Oyegoke 2011). In this thesis, the data collection is included within Stage B, and C. Stage B is related to finding patterns for apartment' modular design (as a first construct or output of this research), extracted from architectural drawings and illustrated in Chapter 4. This stage is associated with the first research objective. The architectural drawings analysis shows the real-world practice in residential building design. The methodology of this stage is further explained in Section 3.3. Stage C is associated with the second, third and fourth

objectives. This stage deals with mathematical model development (as a second output of this research), where the corresponding data was derived from the manufacturers' initial design guides, manuals, and manufacturing processes and constraints. With the aid of the literature review and collected data, the model, which is discussed in this chapter, was developed in Phase 3 of the research process. The methodology of developing the model is further explained in Section 3.4.

Depending on the work at hand, the construct, either design pattern or mathematical model, can be validated through the triangulation of different approaches (Phase 4 of the research process). To demonstrate that the solution works, testing and validation might be empirical or theoretical, quantitative or qualitative, or both. A pilot case study will be the most appropriate method to test and improve a construct. Regrettably, in construction industry research, pilot case studies are not applicable to demonstrate the workability of the construct because of the risks and costs involved. Hence, the alternative approach should be based on triangulation, where different research tools and techniques can be used to demonstrate that the construct (the framework or model in this dissertation) works and to improve on the construct.: (i) data source triangulation, when the data are expected to remain the same in different contexts, (ii) theory triangulation, where investigators with different points of view interpret the same results, (iii) investigator triangulation when the same phenomenon is examined by several investigators (Oyegoke 2011), (iv) methodological triangulation, when multiple methods are used to conduct a study. The theory triangulation has been predominantly applied in this research, where a technique for internal validation of the drawings's data analysis output, i.e., the design pattern (the construct in Stage B), has been employed in Chapter 4. Also, a case example was applied for the mathematical model validation (the construct in Stage C). The results were compared with the real-world practice in a CLT factory in addition to testing with the theory of swift, even flow and the law of variability. This includes in Chapter 5.

The construction and evaluation steps, i.e., Phases 3 and 4 (developing and implementing a solution and validating the solution), are at the heart of the constructive research approach. Nonetheless, a challenge lies in defining when a solution is completed, and the interactive activities of constructing and evaluating a solution should be terminated due to the non-linear process (Rocha 2011). Hevner et al. (2004) stated that a solution is completed and effective when it satisfies the requirements and constraints of the problem which was intended to solve. They pointed out that utility, quality, and efficacy are parameters for evaluating a solution. Bonatto (2010) and Schramma (2009) have employed utility and ease of use for assessing the proposed solutions. However, these are generic criteria. Bespoke criteria should be specified

based on the purpose of the solution to be developed and the constraint of the problem at hand (Rocha 2011).

The research's contribution to the body of cumulative knowledge (Phase 5) should be specified, and areas for further research should be highlighted. This step is illustrated in Chapter 6. It is vital to highlight that this process is not linear but rather a dynamic and interactive process between different phases.

3.4 Research roadmap for stage B

Stage B assumes that an architect in a D&C company (volume builder) is looking for modular design patterns that support MC. In other words, they look for manufacturable design patterns that are applicable or desirable for the selected clients. The architect has a role to identify a balance between the clients' preferred design and a manufacturable design. Therefore, the architect runs a fact-based comparison in order to enable modular design layouts based on the similarities in the clients' architectural designs. This scenario must be executed in the conceptual design stage. The following sub-sections are illustrated the road map for Stage B.

3.4.1 Data collection to find a pattern for apartments modular design

The first objective of this research, connected to the aforementioned scenario, encompasses two key objectives (i) to recognise the manufacturability of apartment layout designs, and (ii) to find a pattern for dwellings' modular design offered to different clients. These two facets are inherently intertwined, with the strategies for accomplishing this goal expounded upon extensively in Chapter 4.

Finding patterns for apartments' modular design might be quite complicated, demanding the consideration of a multitude of variables. These variables encompass apartment layout, apartment size, and cost, building frontage, setback, design style, etc. Identifying similarities in architectural attributes (spatial voids perspective) and structural spans (component perspective) of different apartments design can be considered as a means to find patterns for dwellings' modular design offered to different clients. The current research was implemented based on the decomposing of architectural layout design, then performing statistical analysis and a clustering technique to identify similarities. In other words, statistical analysis and a clustering technique enable the author to identify the probabilistic acceptability of spatial voids dimensions and to find modular design patterns. The first objective of this research tends to (i) identify the space dimensions (i.e., space length, width, aspect ratio) with high probabilistic acceptability in order to recognise the common design patterns, (ii) revisit contemporary manufacturing practices and compare the manufacturing practices with the existing apartment design requirements, (iii)

specify the common structural spans based on the apartment layout design and building vertical floor design.

Decomposing of architectural layout design and performing statistical analysis is a way of indicating the expected probability of acceptable architectural design as per client desires in terms of spatial voids perspective (Roy and Roy 2016). Therefore, the data has been extracted from architectural drawings of housing projects. During the data collection, the researcher focused on multi-storey middle-income class housing. These apartments have not been built or were not going to be built in high-priced areas of cities. Australia's middle-income class comprises 58% of the population, and accordingly, they could afford to buy 58 percent of dwellings, consisting a significant rate compared to the low and high-income classes (Toth et al. 2015; Rosewall and Shoory 2017). This section of data collection tried to get data to generalise to larger populations permitted by random and statistically representative samples. Therefore, the number of under-study dwellings plays a key role as the representative samples of the large populations. The following paragraph explains how to determine the number of samples.

The number of dwellings commenced in multi-storey residential buildings in Australia 2017-2018 (the latest statistics in ABS) is around 28000. Among this number, 47% are in NSW. It means NSW includes most of the market share (around 13200 per year). There is variety in the average size of apartment units (ABS 2017) in the design guidelines of different regions of Australia. Therefore, the author focused on NSW, because of the more accessible to companies and the market share it encompasses. The current apartment architectural designs that were building or built between 2017- 2020 have been examined. For the purpose of this study, the estimated sample size is 385 apartment units, in line with Cochran's formula for sizable populations. This statistical approach adheres to a confidence level of 95%, while the confidence interval and standard error are maintained at 0.05, values deemed acceptable and endorsed by the ABS and various literature sources (Kadam and Bhalerao 2010). However, to improve the level of confidence in this thesis, the sample size was considered more, i.e., 710 apartment units. Hence, within this number of apartments for analysis it can be interpreted that the sample size is representative of the population.

Within this context, this research delves into nine multi-storey housing projects featuring a total of 710 recently completed and ongoing apartment units. These projects were undertaken by six prominent clients, all oriented towards middle-income earners, and are situated in Sydney, NSW. The nine building blocks were selected based on two main criteria: a) they are mid-rise residential buildings with multiple floor levels and diverse occupancy units (i.e.

studios, 1/2/3 bedroom apartments) and b) they are located across diverse geographical areas of Sydney. The first criterion is to ensure a diverse range of building spans are included in the dataset for evaluation of offsite manufacturing. The second criterion intends to ensure buildings were strategically chosen from various regions including North¹⁶, North West¹⁷, West¹⁸, South¹⁹, and South West²⁰. This deliberate location sampling approach was adopted to observe and account for potential spatial variations as well as land size limitations and diversity within a city. By capturing a broad spectrum of buildings at different locations, the research aims to enhance the generalisability and robustness of its findings.

One of the research objective is to identify design patterns within the mid-rise residential building market that can collectively lend themselves to prefabrication, chapter 4 treats all units within nine buildings as one sample set. Therefore, individual assessment of each of the nine buildings is out of scope of investigations in this chapter. Modelling floor layouts within one building for optimum manufacture has been discussed in Chapter 5.

Of these projects, five were executed using cast-in-place reinforced concrete, while the remaining structures employed precast concrete elements. The chosen building cases were designed and constructed using concrete, the dominant structural type in the mid-rise residential context. As explained in Chapter 1, this segment of the market is the largest and therefore has the highest potential for transforming the building industry towards using sustainable prefabricated systems such as mass timber.

The building enclosure and non-load-bearing walls across all structures are composed of gib boards. These chosen projects serve as fitting exemplars for market study due to the notable and increasing population density driving the surge in multi-storey construction in Sydney. The analysis of data, which leads to finding patterns for dwellings' modular design offered to different clients, will be applicable to all geo-climatic regions of Australia with appropriate alteration as per the target population's geo-climatic condition and socio-economic status profile.

3.4.2 Statistical analysis technique to assess the data pattern and specify spatial voids dimensions

710 apartment units have been analysed to enumerate the module in terms of spatial voids and components perspectives. As mentioned in Chapter 2, there are two fundamental types of

¹⁶ Neutral Bay and Chatswood suburbs

¹⁷ Epping suburb

¹⁸ Parramatta suburb

¹⁹ Wolli Creek

²⁰ Bankstown

functional and physical modularity, i.e., the former includes primary and secondary functions, and the latter comprises spatial voids and solid mass. Primary functions (e.g., cooking, sleeping, eating, and working) result in the form of spatial voids or architectural spaces, that clients require an architect to design a variety of apartments based on their desire. These architectural spaces in this research include a living& dining room, kitchen, bedroom, study room, bathroom, ensuite, and laundry. Secondary functions (e.g., load support, enclosure, roof, and finishings) are performed by the solid mass of a building. Although spatial voids and solid mass are complementary, the residential building could be conceived as solid mass (i.e., components perspective) or spatial voids (i.e., architectural or spatial perspective) (Rocha et al. 2015).

In the 710 apartment units, all dimensions of spatial voids, including Length (L), Widths (W), and Aspect ratio (AR), were measured and analysed separately and expressed as dimensions L, W, and AR. Apartment spans, which also represent the solid mass perspective, were considered in the analysis. In structural engineering and architecture, span is the term given to the length of a structural component –floor panels in this research, that extends between two supports, that is, structural wall and column. Hence, a structural floor panel may be supported at either end, in which case it is said to span between the two points. A general engineering principle is the longer the span, the deeper the structural floor panel will have to be to safely to support the dead and live load. Thus, span plays a key role in structural and architectural design (CCAA 2003).

The next table shows the summary of the buildings’ profile. The dimensions of spatial voids (i.e., architectural spaces) and spans are clear dimensions, excluding the wall thickness (usable area in principle). All spatial voids were considered rectangular, and space arrangements were not regarded here to simplify the data analysis. Space arrangements require considering some variables in apartment layout, which complicates the data analysis.

Table 5- Buildings profile and parameters considered in the study

Number of buildings	Number of clients	Number of apartment units	Percentage of apartments type (%)		The focus of the apartment study	Spatial voids (spaces)	Parameters studied (spatial voids characteristics)
			studio	One-bedroom			
9	6	710	0.7	22.8	Apartment spatial voids and apartment spans	Bedrooms, living and dining room, kitchen, bathroom and ensuite, laundry, balcony	Space length (L), width (W), and aspect ratio (AR)-interior dimensions
			68.1	8.4			
Note: Aspect ratio= $\frac{\text{Lenth of Space}}{\text{Width of space}}$							

Then as per compiling the range of dimensions of the spatial voids and spans, the statistical analysis through programming in R studio environment and Statistical Package for the Social Sciences software (SPSS) has been employed in this research to summarise the building drawings design data. In statistical analysis, there are three measures to summarise the main features of the data, including i) the measure of frequency, ii) the measure of central tendency, i.e., mean, and iii) the measure of variation, i.e., standard deviation (Mishra et al. 2019). The measure of frequency deals with the number of occurrences and percentages in each variable within the population. Mean presents the mathematical average of a dataset to make comparisons between two or more groups. Standard deviation (SD) measures how variables spread from their mean (Mishra et al. 2019).

Statistical analysis of L, W, AR, were sorted separately by spaces and apartment types to compare the dimensions of spatial voids in different types of apartments. The statistical analysis with mean and SD does not integrate the Length and Width of each space simultaneously. Hence, the aspect ratio of spaces was also considered. The aspect ratio indicates the rate of space length to space width. Mean indicates the average of all the given dimensions (i.e., L, W, AR), while SD shows the measures of the dispersion of the given dimensions from the mean. It means how far the data values are spread out from the mean value (Mishra et al. 2019).

Statistical analysis is usually conducted based on the assumption that the data follow a normal distribution (Ghasemi and Zahediasl 2012; Mishra et al. 2019). The normal distribution described by its mean and SD indicates that extreme values in the dataset do not significantly impact the mean value. If the data are not normally distributed, the mean is not a representative value of the data. Therefore testing the normality of data is a prerequisite for analysing (Ghasemi and Zahediasl 2012; Mishra et al. 2019). Although several studies state that for sample sizes larger than 30, the violence of normality does not make a significant problem, and the data distribution can be ignored (Altman and Bland 1995; Elliott and Woodward 2007; Ghasemi and Zahediasl 2012; Mishra et al. 2019; Pallant and Manual 2007), the normality of data was assessed in this research to make cohesive and concrete results.

Quantitative methods to evaluate the normality of data include Shapiro-Wilk test, Kolmogorov-Smirnov test, skewness, kurtosis, z test, and mean with SD. SPSS software enables users to conduct all of these tests. Each numerical method is appropriate for a specific sample size. As the current study population is considered as large sample size ($n > 300$), skewness, kurtosis, and mean with SD are appropriate methods for testing normality (Mishra et al. 2019). Skewness measures symmetry, while kurtosis measures whether the data is heavy-tailed or light-tailed relative to the normal distribution (Joanes and Gill 1998). For a large sample, the

normality of data depends on the skewness and kurtosis absolute values. Either an absolute skewness value ≤ 2 or an absolute kurtosis ≤ 4 can be used to assess the normality. If the relative value of the SD with respect to the mean is less than 0.5, data is considered normal in large samples (Ghasemi and Zahediasl 2012; Mishra et al. 2019). Based on these tests attached in appendix A, the normality of the data was accepted.

For analysing span and modules from the components perspective, Australia's manufacturing design guides of some Australian manufacturers are compared with the statistical analysis of data extracted from architectural designs. The manufacturers produce the predominant residential building systems. The objective of this is to investigate the capability of the manufacturers and the manufacturability of existing designs. Finally, span patterns regarding architectural floor and vertical design are specified through cluster analysis.

3.4.3 Clustering techniques

Instead of having wide choices, the objective of modularisation is to limit the options based on their common denominators. Hence, in modular design, a technique was required to integrate and classify the characteristics of spaces (Length, Width, Aspect Ratio) and span so as to group similar spatial voids and apartments. Clustering methods are the most applicable technique to find design similarities to limit the number of options (Dai and Scott 2007). In clustering, all variables are analysed together, and the goal is to form groups or give meaning to a set of variables. Clustering techniques have been introduced as a robust technique in literature to group FRs and DPs. Hence, cluster analysis was conducted to group apartments and their spaces based on the dimensions.

Analysing the apartment layout design data by clustering results in designating a set of design dimensions of the spatial voids to reference a modular design and comply with prefabricated components manufacturing. Spatial void modularity followed by modular component coordination suggests the following benefits: (i). It creates a basis for minimising the variety of types and sizes of building components, which is the main objective of the design for MC. (ii). It also allows for the easy adoption of prefabricated components to any layout and their interchangeability within the building (Rocha et al. 2015). The easy adoption of prefabricated components to any layout is achieved by defining the location of each component in the building with reference to a modular grid of spatial void rather than concerning other components.

Clustering techniques provide the architect with an intuitive way to evaluate the expected possibility of acceptable layout designs based on client desires (Dai and Scott 2007). Cluster analysis enables the research author to put objects, here apartments' spatial voids characteristics

and spans (L, W, AR) into groups so that space characteristics within the group are similar to each other. At the same time, spatial void characteristics in any particular group are different from the characteristics in all other groups (Diday and Simon 1976; Lee 1981).

Clustering is an unsupervised machine learning technique to find similarities in data points and group similar data points together. Clustering is a powerful machine-learning tool for detecting structures or patterns in datasets. Unlike supervised methods, clustering is an unsupervised method that works on datasets in which there is no outcome (target) variable, nor is anything known about the relationship between the observations, that is, unlabeled data. Clustering itself is not one specific algorithm. Nonetheless, there are different algorithms that vary significantly in terms of recognising what constitutes a cluster and how well to track data. In general, clustering techniques can be classified into partitioning clustering, hierarchical clustering, and advanced clustering techniques. Among different clustering techniques, partitioning clustering methods are more common (Kassambara 2017; Lee 1981), which is explained in the following paragraphs.

K means Clustering

Among different clustering techniques, partitioning clustering approaches are more common and straightforward and have some features, including presenting cluster center and SD, that make them applicable to reach the objective of this thesis. Partitioning clustering techniques subdivide the data sets into a set of K groups, where K is the number of groups pre-specified by the analyst or can be estimated by some techniques. Partitioning clustering techniques include four commonly used clustering, namely K-means, K-medoids, PAM²¹, and CLARA²² algorithms. K-means clustering is one of the simplest and most commonly used unsupervised machine learning algorithms for partitioning a given unlabeled continuous data set (i.e., data without defined categories or groups) into a set of K groups (i.e., K clusters). This algorithm aims to find groups in the data, with the number of groups represented by the variable K, in which K is prespecified. It classifies objects in multiple groups, such that objects within the same cluster are as similar as possible (i.e., high intra-class similarity), whereas objects from different clusters are as dissimilar as possible (i.e., low inter-class similarity). In K-means clustering, each cluster is represented by its center (i.e., centroid), which corresponds to the mean of points assigned to the cluster (Kassambara 2017).

²¹ Partitioning Around Medoids

²² Clustering Large Applications

The basic idea behind K-means clustering is to define clusters so that the total intra-cluster variation (known as a total within-cluster variation) is minimised. There are several K-means algorithms available. The standard algorithm is the Hartigan-Wong algorithm (1979), which defines the total within-cluster variation as the sum of squared distances Euclidean²³ distances between items and the corresponding centroid:

$$\text{Eq (4). } W(C_k) = \sum_{x_i \in C_k} (x_i - \mu_k)^2$$

- x_i designs a data point belonging to the cluster C_k
- μ_k is the mean value of the points assigned to the cluster C_k

Each observation or object x_i is assigned to a given cluster such that the sum of squares distance of the observation to their assigned cluster centers μ_k is a minimum. The total within-cluster variation is designed as follow:

Eq (5).

$$\text{tot. withinss} = \sum_{k=1}^k W(C_k) = \sum_{k=1}^k \sum_{x_i \in C_k} (x_i - \mu_k)^2$$

The total within-cluster sum of square measures the compactness of the clustering, and it should be as small as possible (Kassambara 2017).

K means clustering processes

To perform a cluster analysis, generally, the data needs to prepared as follow:

- (i) Any missing values in the data are removed (Kassambara 2017). Hence, in this thesis, any missing values were pulled out from the spreadsheet before analysing the data. The missing data pertained to the dimensions of the architectural spaces, where the specific measurements were unspecified. Only less than 10 spaces in 710 units, had missing

²³ The choice of distance measures is very critical step in clustering, as it has significant impact on the results. It defines how the similarity of two elements (x,y) is calculated. The classical methods for distance measures is Euclidean or Manhattan distances. However, in most cluster analysis software, Euclidean distance, defined as follow, is more acceptable and common.

$$d_{euc}(x, y) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2}$$

Where x and y are two vectors of length n.

dimensions. Therefore, the number of missing values was minimal, and their removal did not adversely impact the validity of the data.

- (ii) The data are standardised (i.e., scaled) to make variables comparable. Standardisation consists of the transformation of the variables such that they have a mean equivalent zero and standard deviation equivalent one. This is particularly recommended when variables are measured in different scales (e.g., kilograms, meters, centimeters, etc.) or when the mean and/or standard deviation of variables are largely different (Kassambara 2017). As the L or W and AR were measured in different scales (i.e., meters compared to a ratio without any measurement scale) and the SD and mean of the variables are different to some extent, the standardisation of the data was carried out in this research.

When scaling variables, the data can be transformed as follow:

Eq (6)

$$\text{Standardisation } x_i: \frac{x_i - \text{center}(x)}{\text{scale}(x)}$$

Where *center(x)* can be the mean or the median of x values, and *scale(x)* can be the standard deviation (SD).

After standardisation, the algorithms start randomly selecting K objects from the data set to serve as the initial centers for the clusters. The optimal number of clusters (K) can be determined by leveraging some methods, namely Elbow, Average silhouette methods, and Frequency among 30 indices (Kassambara 2017). These methods are explained in the next section. The selected objects are also known as cluster means or centroids. Next, each of the remaining objects is assigned to its closest centroid, where the closest is defined using the Euclidean distance between the object and the cluster mean. This step is called “cluster assignment step.” After the assignment step, the algorithm computes the new mean value of each cluster. The term cluster “centroid update” is used to design this step. Now that the centers have been recalculated, every object is checked again to see if it might be closer to a different cluster. All the objects are reassigned again using the updated cluster means. The cluster assignment and centroid update steps are iteratively repeated until the cluster assignment stops changing (i.e., until convergence is achieved). In other words, the clusters formed in the current iteration are the same as those obtained in the previous iteration (Kassambara 2017). The algorithm works iteratively to assign each data point to one K groups with the Euclidean measuring distance method. Data points are clustered based on object similarity. One of the main features of the K-means clustering algorithm that this research leverages is the K clusters’

centroid and SD, corresponding to the mean of points and the range of variation which are assigned to the cluster. Mean, and SD can be used to label data (Diday and Simon 1976).

Estimating the optimal number of clusters

The K-means clustering requires the users to specify the number of clusters to be generated. Different methods, namely Elbow, Average silhouette methods, and Frequency among 30 indices, are available to identify the optimal number of clusters (Kassambara 2017). The following paragraph explains each method.

- Elbow method: the idea behind K-means clustering is to define clusters so that the total intra-cluster variation, i.e., the total within-cluster sum of square (WSS) is minimised. This method looks at the total WSS as a function of the number of clusters. One should choose a number of clusters so that adding another cluster does not improve the total WSS. This method computes the clustering algorithm for different values of k , usually by varying k from 1 to 10 clusters. Then for each k , the total WSS is calculated. Then the curve of WSS according to the number of cluster k is plotted. The knee (bend) location in the plot is typically considered an indicator of the appropriate number of clusters. Note that the elbow method is sometimes ambiguous; therefore, other alternative methods can be used (Kassambara 2017).
- Average silhouette method: this approach measures the quality of clustering and is also used for cluster validation statistics. Therefore, it is described comprehensively in the cluster validation section. Briefly, it determines how well each object lies within its cluster. A high average silhouette width shows good clustering. This method computes the average silhouette of objects for different values of K . The optimal number of clusters K is the one that maximises the average silhouette over a range of possible values for K . This method is similar to Elbow method. First, K-means clustering algorithm for different values of K , for example by varying K from 1 to 10 is computed. Then for each K , the average silhouette of objects (av.sil) is calculated. The curve of av.sil according to the number of clusters K is plotted. Based on the plotted curve, the maximum location is considered as the optimal number of clusters (Kassambara 2017).
- Frequency among 30 indices: as sometimes the outcomes of Elbow method and Average silhouette method are different, Frequency among 30 indices approach is used to help the optimal number of clusters as well. This approach provides 30 indices for determining the relevant number of clusters and proposes to users the best clustering scheme from the different results obtained by varying all combinations of the number of clusters, distance measures, and clustering methods (Kassambara 2017).

Cluster validation technique

Clustering results can be validated through triangulation. As mentioned in Section 3.2, there are four types of triangulation for the validation of any construct (here clustering results). These four types of triangulation include data source triangulation, theory triangulation, investigator triangulation, and methodological triangulation. Data source triangulation is attributed to a type of triangulation where the data are expected to remain the same in different contexts. Theory triangulation is a type of triangulation that investigators with different points of view interpret the same results. Investigator triangulation is attributed to a type of triangulation where the same phenomenon is examined by several investigators. Methodological triangulation is a type of triangulation in which multiple methods are used to conduct a study (Oyegoke 2011). Among four types of triangulation, theory triangulation is applied in Stage B of this research to validate the clustering results. This validation method includes using theories, laws, or hypotheses when examining a situation or phenomenon so that investigators with different points of view interpret the same results. The idea is to look at a phenomenon from different points of view, through different lenses, with different questions in mind (Denzin 2010). In other words, investigators with different points of view interpret the same results.

Silhouette method, as a law or rule, is applied as a cluster validation measure in this thesis. The cluster validation measure is a theoretical triangulation because investigators with different points of view can interpret the same results based on the rules or laws. The rules are related to the goal of clustering. As the goal of K-means clustering is to split the data set into clusters of objects such that (i) the objects in the same cluster are similar as much as possible, (ii) and the objects in different clusters are highly distinct, the average distance within a cluster should be as small as possible, while the average distance between clusters to be as large as possible. Hence, cluster validation measures reflect the compactness and separation of the cluster partitions. Compactness or cluster cohesion measures how close the objects are within the same cluster. A lower within-cluster variation is an indicator of good cluster compactness, i.e., good clustering. Separation measures how well-separated a cluster is from other clusters. Silhouette coefficient or silhouette analysis measures how well an object is clustered, and it estimates the average distance between clusters. The silhouette value is a measure of how similar an object is to its own cluster (cohesion) compared to other clusters (separation). The silhouette plot displays a measure of how close each point in one cluster is to points in the neighbouring clusters (Kassambara 2017).

For each object i , the silhouette width S_i is calculated as follows:

- (i) For each object i , calculate the average dissimilarity a_i between i and all other points of the cluster where i belongs.
- (ii) For all other cluster C , in which i does not belong, calculate the average dissimilarity $d(i, C)$ of i to all objects of C . The smallest of these $d(i, C)$ is defined as $b_i = \min_c d(i, C)$. The value of b_i can be seen as the dissimilarity between i and its “neighbour” cluster, i.e., the nearest one to which it does not belong.
- (iii) Eventually, the silhouette width of the object i is defined by the formula: $S_i = (b_i - a_i) / \max(a_i, b_i)$.

The silhouette ranges (S_i) from -1 to $+1$, where a high value indicates that the object is well-matched to its own cluster and poorly-matched to neighboring clusters. The clustering configuration is appropriate if most objects have a high value. A small S_i (i.e., around 0) means that the object lies between two clusters. If many points have a negative S_i , then objects are probably placed in the wrong cluster (Kassambara 2017).

3.4.4 R programming

Clustering has been conducted through programming in R studio environment in this research. R is a free and powerful statistical software for analysing and visualising data. R studio is an integrated development environment for R that makes using R easier. It includes a console, code editor, and tools for plotting (Kassambara 2017). Following R packages were applied in the thesis to compute clustering:

- *factorextra* for data visualisation.
- *fpc* for computing clustering validation statistics.
- *NbClust* for determining the optimal number of clusters in the data set.

3.5 Research roadmap for stage C

Stage C of the research assumes that the architect in a D&C company has been tasked to design a fully customised building layout, i.e., a one-of-a-kind product. This task takes place after the conceptual design stage, i.e., during the preliminary design stage. Under this scenario, the architect has little room to offer modular design layouts; instead, s/he must endeavor to accommodate MC through integrating production processes in the building design without compromising the flexibility in the customised architectural design. This scenario provides a higher degree of customisation compared to the first scenario. The following sub-sections are illustrated the research roadmap for this scenario.

3.5.1 Data collection to find a floor panel layout (load-bearing wall position)

Like stage B, this stage starts with finding a problem and understanding the epistemology or literature related to the problem, called layout design problems (floor panel layout) in the design optimisation scope. The main objective of this problem is to design a mass customised building with a focus on a layout design, i.e., architectural floor plan design and its related components, i.e., floor panels. In other words, the goal is to identify the manufacturability of a layout design and to find a floor panel layout with the optimal production process by integrating client-driven design and efficient manufacturing processes. In terms of modular design perspective, considering the floor plan or layout design is related to the spatial voids or architectural design perspective, while the floor panel layout is associated with the solid mass perspective.

This scenario encompasses the second, third and fourth objectives, i.e., finding and incorporating variables and parameters that address off-site manufacturing processes and integrating architectural design parameters and efficient manufacturing. This scenario is usually allowed where manufacturer's actions do not sacrifice architectural design and keep the client satisfied. Studies show that the desire for layout design customisation is strong (Hofman et al. 2006) (Veenstra et al. 2006). On the other hand, the building structure, as a building core, has perhaps the highest potential for increasing production efficiency or cost efficiency through platform concepts. The building structure has the potential for a degree of standardisation, and the architect can efficiently and effectively handle it through appropriate layout design by considering the above variables.

The following figure indicates the relation of a mass customised design and the integration of a customised design and design for manufacturability. As shown in the figure, with the aid of manufacturing data from the supply side, a customised design can be converted into a mass customised design. This conversion can be conducted by sharing and representing data in a mathematical and optimisation model.

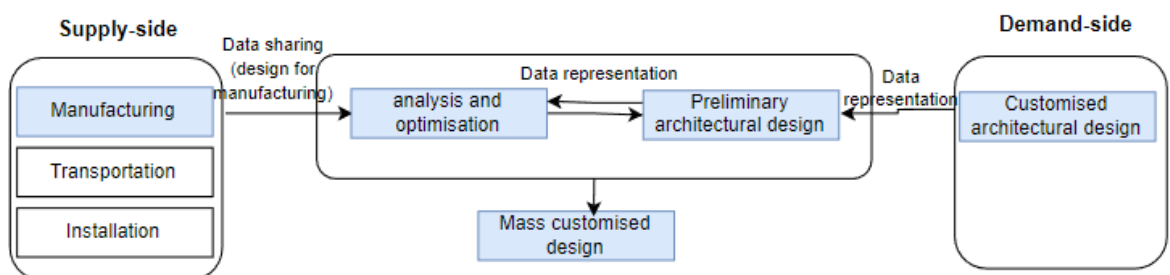


Figure 20- The framework of the scenario

Generally, mathematical models can help integrate design and manufacturing and search for the optimal solution to maximise or minimise an objective. The main variables in the current layout design problem are load-bearing wall location and floor panel dimensions. Due to some constraints in manufacturing of the billet, the billet and panel widths are usually the same. Therefore, it is considered as a parameter, but panel length and thickness are variables. The ‘levers of efficiency’ within the MC concept for CLT systems relate to the type of material selected, the thickness of panels, and the spanning capacity. Determining these factors is remarkably dependent on the load-bearing wall location. Whilst these panels are not fully standardised, they are mass customised, the ability to find commonalities between CLT thicknesses and spanning or loading capacities ‘within’ the project allows for a relative degree of efficient design. Panel efficiencies, in this sense, usually be considered as part of a single project only, not a comparison between different projects, because the majority of projects are unique (Kaiser et al. 2019).

Relative to the design and scope of the project, once the panelisation is completed the geometric shapes, or the panels nesting, must be optimised for cutting from the billet. In industry practice, there is software that optimises panel nesting. However, anecdotally, in real practice, human intervention for nesting panels and selecting specified thicknesses seems still to be the preferred option (Kremer 2018). Also, the software is designed for predetermined dimensions, including panel length, width, and thickness. In any project, there is likely to be an assortment of panel shapes and sizes to be cut from billets. Manufacturers cannot simply just ‘remove or reduce’ these parts to make efficient use of the production time, particularly CNC time, which increases production efficiency. However, what can be done is the arrangement of panels across multiple billets with a few changes in length and, consequently, in thickness to ensure efficient cutting. This scenario is usually allowed where manufacturer’s actions do not sacrifice architectural design and keep the client satisfied. The following figure visually indicates the research variables and parameters. Section 3.5.3 and Chapter 5 discuss the related objectives and the constraints of Stage C.

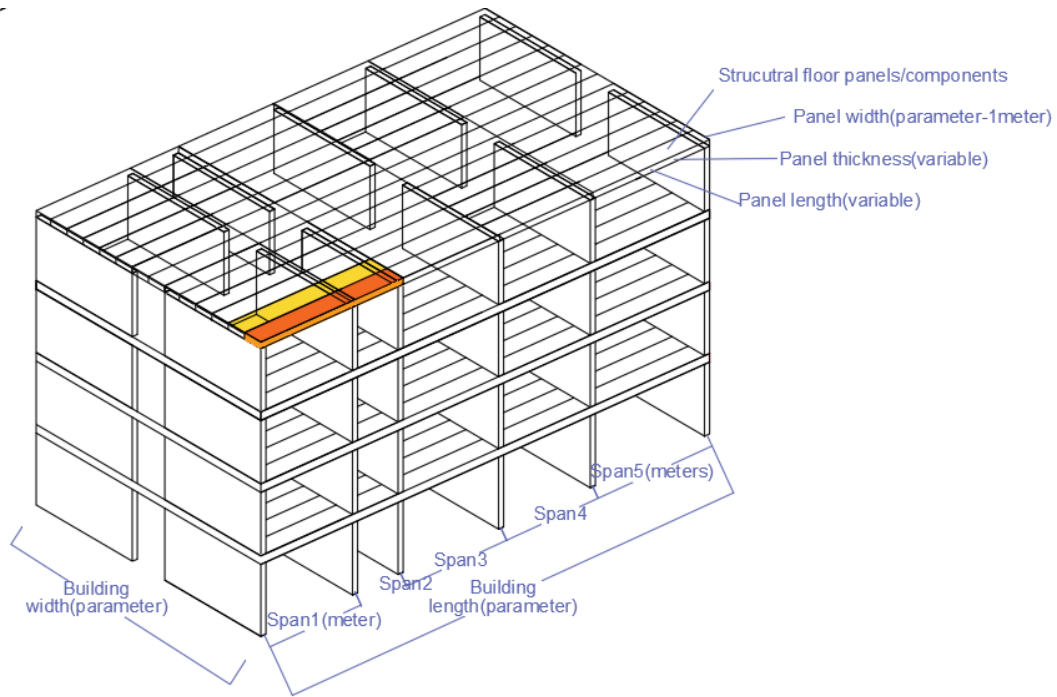


Figure 21- The variables and parameters of the layout design problem in the thesis (model parameters and variables)

The next figure presents the key parts of developing the mathematical model: i) data collection; ii) developing optimisation model based on the objective, parameters, variables, and constraints; iii) analysing of the results.

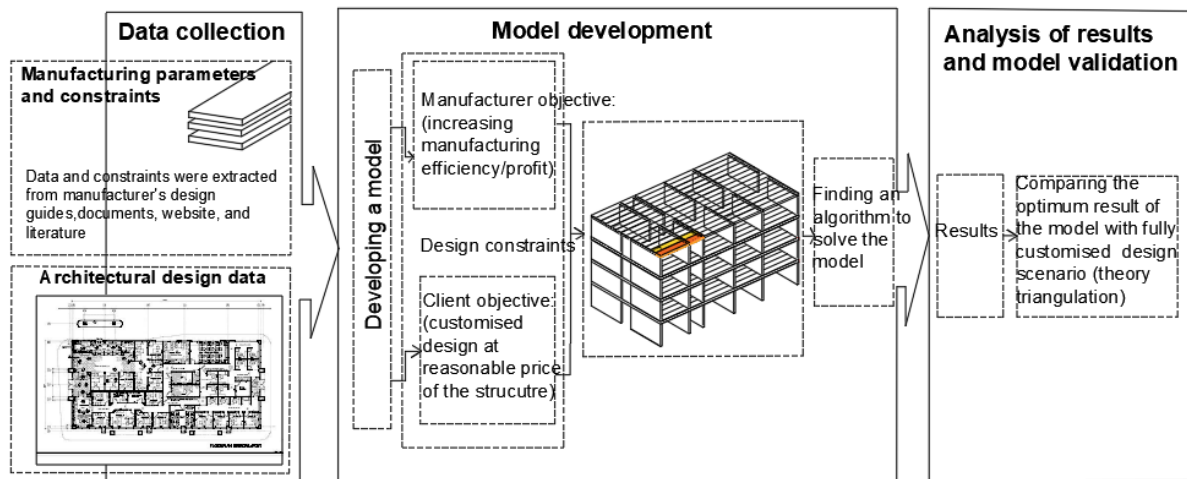


Figure 22- The key parts of developing the model

It is notable that a CLT building as a case study with simply supported floor and its corresponding structural constraints are considered. Therefore, the manufacturing data collection predominantly was focused on CLT off-site manufacturing process-related data. In general, there are two types of floor in prefabricated systems: simply supported floor and continuous floor. A simply supported floor is a floor with its ends simply supported on two

walls free to bend at the ends without any restraint, and it has only one span between two supports. On the other hand, a continuous floor is a floor extending over more than two supports or walls. The following figure shows the simple supported floor (XLam 2017) (Knaack et al. 2012).

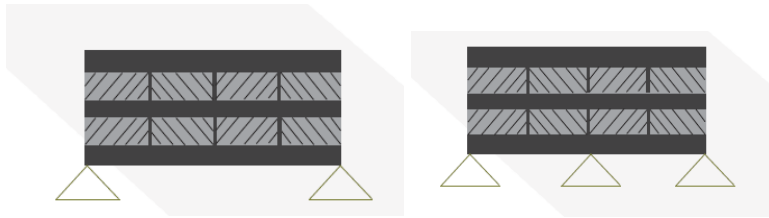


Figure 23- Simply supported floor (left) compared to the continuous floor (right), adapted from (XLam 2017)

Accounting for manufacturing process stages

As mentioned in Chapter 2, the extant research shows that pressing and CNC router cutting stage and raw materials are the high-cost factors in fabricating billets and panels (Abiri 2020; Brandt et al. 2019; de Araujo Carneiro 2019). Therefore, the off-site process-related data and design data targeting production efficiency and profit include but are not limited to: (i) average lumber and adhesive costs (raw materials) and their ratio in each billet, (ii) manufacturing process time, and productive hour cost (PHC), (iii) manufacturing constraints and typical CLT billets dimensions, (iv) architectural and structural design constraints, (v) CLT panel market price per unit.

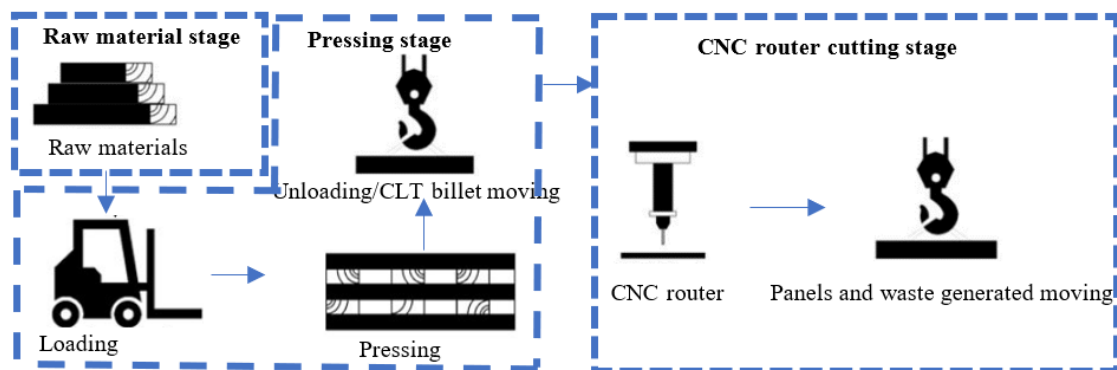


Figure 24- The stages focused in this research

Some of the information was extracted from a reputable CLT factory in Australia. The next table presents the data collected from the case factory. The factory's logistics director provided the material costs and related information. The estimated time of two main manufacturing stages, i.e., press and CNC process stages, for different billet and panel types was adapted from the research conducted by Araujo Carneiro (de Araujo Carneiro 2019) which is elucidated in Section 2.5.4. In this study, to simplify the conversion of production time into cost, only the production direct cost, which is referred to here as the productive hour cost (PHC),

is considered. The unit productive hour cost, which is the sum of standard direct labor cost, was estimated based on the average number and wages of the workers involved in the factory manufacturing process. Manufacturing constraints were identified by interviewing the director of technical service, investigating literature and manufacturers' websites, and attending webinars. CLT billets and structural design constraints presented in Table 7, were extracted from the manufacturer's preliminary design guide. Also, architectural design constraints were recognised according to an initial customised architectural design. The factory's sales and marketing supervisor presented the market price.

Table 6- Data collected from the case factory

Data	Description
Location of the factory	Melbourne, Victoria, Australia
Production floor space	Over 16,000 Sq. meter production floor space
Production capacity	Over 60,000 Cubic meter yearly production capacity
Investment	Over 54 million dollar invested in their facilities
Period of data collection	Two weeks
SMEs interviews	3 SMEs: 1. Factory's logistics director/head 2. Factory's technical service director/head 3. Factory's marketing supervisor
Types of data collected	1. Average lumber and adhesive costs (raw materials) and their ratio in each billet 2. Manufacturing process time, and productive hour cost (PHC) 3. Typical CLT billet dimensions 4. CLT panel market price per unit 5. Data regarding manufacturing constraints (i.e., the CNC cutting process constraints, pressing stage)

Accounting for transport and installation stages

The manufactured panels should be delivered to the construction site. Off-site transportation of materials has been estimated to account for 10–20% of the total project expenditure in construction projects. Transportation cost depends on the size and weight of panels, transportation method, and distance of travel. The shipping method varies depending on the infrastructure, routes, and distance (Ahmadian et al. 2016). The regional types of vehicles are trucks, trains, and ships. Truck transportation is the most feasible and common type of shipment method regionally. Truck transportation requires transportation permits for oversized

loads, dimensional limitations, and road regulation restrictions. City and government permissions or truck escort add costs to the project and is not always feasible. Furthermore, the size of the hauling is limited by the regulation as well. The maximum truck size authorised by Australia's government is 2.5 meters wide, 4.3 meters tall or high, and 12.3 meters long (National Heavy Vehicle Regulator 2016). In practice, the panel width is typically limited between 0.6 and 4.2 meters, and panel length is considered up to 12.00 meters due to the standard dimensions of the truck used to transport the element to the construction site. Payload either wider or/and higher than 2.4 and 4.2 meters or/and longer than 12.00 meters requires one pilot vehicle with some special arrangement (Sharafi et al. 2017). Therefore, the maximum floor panel width, height, and length in this research are limited to these dimensions.

Once the CLT panels arrive at the construction site, the installation and erection process initiates. On-site installation typically includes lifting, positioning, adjusting, and connecting the elements. As mentioned before, component production costs comprise 80% of prefabricated structure costs (Forsythe and Sepasgozar 2019; Goh and Goh 2019; Hasan et al. 2018), and this percentage is significant compared to transport and installation costs. Hence, the current study focuses on optimising the manufacturing process of CLT elements, but it considers the transport and installation constraints. In other words, this research does not aim to optimise the logistic process and costs.

3.5.2 Model development

The MC definitions tend to look at MC as a strategy to accommodate customisation into mass production (MP) with relatively similar principles. Those principles are to meet clients' requirements or value (i.e., generating customisation in products) and manufacturers' needs (i.e., producing products with production efficiency). In real-world production activities, companies often have to consider a variety of factors when setting a goal, such as market, production efficiency or profit, client satisfaction and loyalty, and corporate image and culture. For long-term development, companies may even sacrifice their profit due to lower production efficiency in some cases, which is not the case in this research. The concept of efficiency has a number of dimensions. Overall, economic efficiency requires the satisfaction of production efficiency. Hence, maximum production efficiency requires that products be produced at the lowest possible cost. Production efficiency is achieved when the product is produced at a minimum cost (Commission 2013), and the profit is high. Then the client would subsequently buy the customised building structure at a reasonable price. Aesthetic and other subjective aspects of design are typically ignored in optimisation models because they are difficult to model with mathematics. Hence, the subjective aspects were not modeled in this thesis.

Measuring the client requirements or value, which is supported by utility theory, is complicated and requires considering several variables in building design and is out of this research scope. However, this research has attempted to simplify it by considering the following elements: (i) considering the architect's suggestion regarding architectural design constraints and client's desires, and (ii) limiting the price of the product (i.e., building structure) by reducing client costs or considering the client's willingness to pay.

Since architectural design and building structure price, which involve the customisation part of MC strategy, are considered as a design constraint and clients requirements in mathematical modelling, the emphasis of the objective function is on the optimal production processes or on maximising profit. In order to focus on the main objective of this thesis and simplify the model, a single objective to maximise profit is set, so the preliminary objective function is noted as:

$$Eq(7). \max \pi = \sum R(S_i) - C$$

Where π means manufacture profit, which can be obtained by total revenue minus the cost. Manufacturers tend to produce a variety of components (floor panels) to meet the different needs of clients. Therefore, S_i represents the amount of i th component, and $R(S_i)$ represents the total revenue, and C represents the total cost. In order to maximise profit, the manufacturer should determine the variable related to S , including panel thickness and length. An explicit definition of the total cost part of the objective function, i.e., C , is illustrated in detail in Section 3.5.3.

The flexible demand assignment problem can be adapted to model the problem of designing load-bearing walls location in an architectural plan. The following section discusses how flexible demand assignment is adapted to develop the model.

Adapting flexible demand assignment to the floor design problem

The problem of designing each floor panel's length (i.e., building spans) and thickness, which is shown in the following figure, can be modeled as a flexible demand assignment due to their similarity of variables. In operation research, there is a well-known problem called the flexible demand assignment problem (FDA). Flexible demand assignment problem optimises the material usage when cutting a standard-size piece of material called a bin into smaller pieces with flexible sizes called item (Balakrishnan and Geunes 2003; Wang et al. 2004). This problem is motivated by one form of client or demand flexibility which is called product-specification flexibility available to a manufacturer of made-to-order specialty steel plates. Rather than specifying product dimensions precisely, some clients are willing to accept steel plates with a

specified range of sizes. For each item, the manufacturer must decide, as a part of its production plan, the size of the finished item to produce within the specified range. This choice impacts the utilisation of resources and hence manufacturing cost (Alidaee et al. 2011; Balakrishnan and Geunes 2003; Wang et al. 2004).

Supposing that the manufacturer produces I set of outputs (item) from T inputs (bin), for each item $i(i \in I)$, R_i is the constant unit revenue for item i . l_i, u_i stand for the minimum (lower) and maximum (upper) size of item i , according to the client demand range. For each bin $t(t \in T)$, C_t denotes the raw material costs while B_t means the bin size. r denotes the unit recycling cost if the capacity of a bin is not fully utilised. The objective aims to decide i) which bin (t) to use, ii) which item (i) to assign to each selected bin, and iii) for each item what item size (S_{it}) to fabricate within its specified size range. Hence, there are three sets of decision variables:

- (i) Bin selection: $Z_t = 1$ if bin t is utilised, 0 otherwise.
- (ii) Item-to-bin assignment: $X_{it} = 1$ if item i is assigned to bin t , 0 otherwise.
- (iii) Item sizing: S_{it} =size of item i assigned to bin t .

The objective of the FDA is to minimise total material waste. FDA problem is a complex problem and is typically solved with metaheuristics algorithms (Balakrishnan and Geunes 2003) such as a genetic algorithm.

In the floor panel design problem, the objective aims to decide: (i) billet selection (whether billet t is utilised), (ii) panel to billet assignment (whether panel i is assigned to billet t), (iii) panel sizing (thickness and length of panel i assigned to billet t).

The following figure shows a simple example of a hypothetical floor plan with three different panel lengths and thicknesses. The different dimensions (thickness and length) in the floor plan are shown by different colours. Each thickness should be cut out of a distinct billet. The gray colour indicates the amount of waste that could be managed by either changing the panel length or changing the cut arrangements across different billets of the same size, which is the main objective of the FDA.

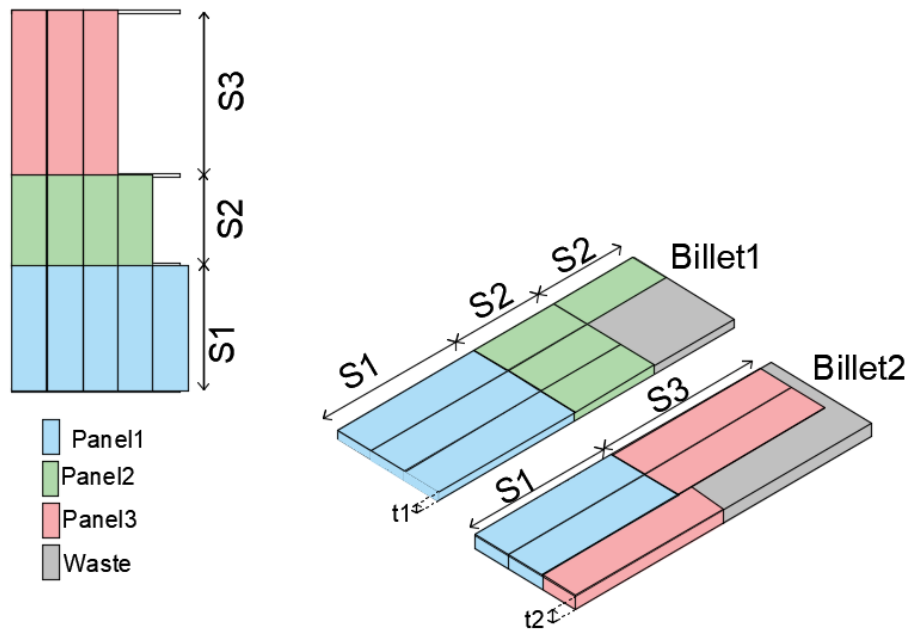


Figure 25- An illustrative example of a floor design problem in 2D plan (top left) and billet cuts based on the floor panel lengths

The differences that distinguish the current problem from the FDA are: (i) the FDA is a one-dimensional problem since it aims at finding the optimal length of items, and the item thickness is not addressed. However, the current problem looks for the optimal length and thickness of items (panels). The matter that should be discussed around this subject is how to determine the panel thickness. The answer lies within the structural constraints, leading to adopting the extant options introduced in manufacturer’s design table (Table 7).

Table 7- Preliminary structural design table, adapted from (XLam 2017)

Panel Designation	Q = 2kPa				Q = 3kPa				Q = 5kPa			
	SDL				SDL				SDL			
	0kPa	0.5kPa	1kPa	2kPa	0kPa	0.5kPa	1kPa	2kPa	0kPa	0.5kPa	1kPa	2kPa
3 Layer Panels												
CL3/85	2.8	2.8	2.5	2.2	2.7	2.6	2.4	2.1	2.3	2.3	2.1	1.9
CL3/105	3.4	3.4	3.2	2.8	3.4	3.3	3.1	2.7	2.9	2.9	2.8	2.5
CL3/115	4.1	3.8	3.5	3.1	3.9	3.5	3.3	2.9	3.2	3.2	3	2.7
CL3/125	4.2	4.2	3.8	3.4	4.2	3.9	3.6	3.2	3.5	3.5	3.3	3
CL3/135	4.9	4.4	4.1	3.6	4.5	4.1	3.9	3.4	3.8	3.7	3.5	3.2
5 Layer Panels												
CL5/145	5.1	4.6	4.3	3.8	4.7	4.4	4.1	3.7	4	3.9	3.7	3.4
CL5/160	5.4	4.9	4.5	4	5	4.6	4.3	3.9	4.3	4.1	3.9	3.6
CL5/175	5.9	5.3	4.9	4.4	5.6	5.2	4.9	4.4	4.9	4.7	4.5	4.1
CL5/195	6.2	5.6	5.2	4.7	6	5.6	5.2	4.7	5.3	5.1	4.8	4.4
CL5/205	6.4	5.8	5.4	4.9	6.2	5.8	5.4	4.9	5.6	5.3	5	4.6
CL5/225	6.6	6.1	5.7	5.1	6.6	6.1	5.7	5.1	5.9	5.6	5.4	4.9
7 Layer Panels												
CL7/245	6.8	6.2	5.9	5.3	6.8	6.2	5.9	5.3	6.2	5.8	5.6	5.2
CL7/265	7.2	6.7	6.3	5.7	7.2	6.7	6.3	5.7	6.8	6.4	6.2	5.7
CL7/275	7.4	6.8	6.4	5.8	7.4	6.8	6.4	5.8	7	6.6	6.3	5.8
CL7/295	7.6	7.1	6.7	6.1	7.6	7.1	6.7	6.1	7.4	7	6.7	6.1
CL7/315	7.8	7.3	6.9	6.3	7.8	7.3	6.9	6.3	7.6	7.3	6.9	6.3

The other difference is the nature of the objective function. As mentioned earlier in the thesis, the objective of the current study is to optimise load-bearing wall placement and floor panel layout in the preliminary design stage regarding the optimal production process through integrating client-driven design and efficient manufacturing processes. Since architectural design, which involves the customisation part of MC strategy is considered as a constraint in the mathematical modelling, the emphasis of the objective function is on the optimal production processes.

The proposed model optimises the interactions between the structural wall placement and floor panel dimensions by determining building spans, floor panel lengths, and thicknesses.

Model assumptions and design constraints

The modeling practice in this research is based on the following structural and architectural design constraints and assumptions:

1. Although each CLT manufacturer has their own distinct design guide, the structure design constraints are formulated based on the table attached in Table 7 extracted from a reputable Australian manufacturer's design manual. The table can also be replaced with any other manufacturer's design tables.

2. As typical implementation in prefabricated buildings, the width of all floor panels is the same and is considered as a parameter. Still, the panel length and thickness, representing span, are variables.
3. The wall characteristics (dimensions) and production process are not taken into consideration in this research.
4. The model aims at simulating spans of one building's floor, and it is assumed that the other floors in terms of spans or load-bearing wall placement are similar.
5. This research has not covered structural design performance and floor connections.
6. Albeit the installation order at the construction site should be considered by optimisation, for simplification, it is assumed that all CLT panels in the project are cut from billets without considering the installation priority.
7. Since floor panels are placed on the load-bearing walls, the maximum (u_i) and minimum size (l_i) of panel i is determined based on the architect's opinion.
8. Bound size constraint specifies the buildable area length and width in the model.
9. There is a restriction on panel thickness due to regulations. If the roof thickness surpasses a certain threshold, it could cause the entire building's height to exceed the permissible limit outlined in the regulations.

In the next section, the problem is presented in a mathematical form.

3.5.3 *Mathematical representation of the model*

To compare the floor design alternatives, a cost function is necessary. Aesthetic and other subjective aspects of design are typically ignored in optimisation models because they are difficult to model with mathematics. Hence, the subjective aspects were not modeled in this thesis. The objective of the floor design problem is to find the optimal production process, and the optimal production process leads to maximising manufacturer's profit and decreasing the client's cost. Therefore, maximising the manufacturer's profit is introduced as an objective function, Eq (8), while reducing client's cost appears in the form of constraint, Eq (9).

The composition of production costs is very diverse, and its accounting is very complex. It may include procurement costs of raw materials, manufacturing costs, human resource costs, transportation and installation costs, depreciation of fixed assets, marketing costs, etc. Some of its content is beyond the scope of the dissertation. Hence, this model mainly considers the main factors making up manufacturing process associated costs, including raw materials (lumber board and adhesive), pressing stage, and CNC router cutting stage, as addressed in Chapter 2,

Section 2.5. The mathematical notations of the model are listed in Table 9. For estimating raw material costs, the adhesive spread rate specifying the amount of utilised adhesive and lumber in a billet is considered 250 kilograms per square meter (Yusof et al. 2019; Yusoh et al. 2020). Pressing stage and CNC router cutting stage time (Table 8) are multiplied by productive hour cost (PHC) to convert to cost unit. PHC is calculated based on the average number of workers and their wages required for the production stage.

Table 8- Manufacturing time for producing billet with 3 meters width and 12 meters length and different sizes of panels which cut from billets, adapted from (de Araujo Carneiro 2019)

Number of layers in a CLT billet	$Press_t$ (minutes)	CNC_{it} (minutes)	PW (minutes)
3-layer	91	$1.13 + \frac{9.77NP + 0.525 W + 2.567set}{NP}$	10
5-layer	102	$14.3 + \frac{9.77NP + 0.525 W + 2.567set}{NP}$	
7layer	110	$25.09 + \frac{9.77NP + 0.525 W + 2.567set}{NP}$	

Eq (9) limits the structure price (i.e., client cost). With the aid of the architect, the client should rationally determine the intended cost based on the extant market price and the client's willingness to pay, which reflects the value they gain from optimisation of the production process. As generalising the value is out of the scope of this research, to simplify the model, it is supposed that the floor structure price per meter must be less than the average price proposed by different manufacturers.

The objective function is subject to the following constraints. The assignment constraint, i.e., Eq (10), requires assigning each panel to exactly one billet. Eq (11) shows the panel size range (minimum and maximum span) determined based on the architect's opinions or data analysis results (Chapter 4). In other words, this equation ensures that if panel i assigned to billet t , the panel size lies between its allowable minimum and maximum size; otherwise, the size of panel i assigned to billet t must be zero. The billet size constraint, Eq (12), specifies that the total size (length) of panels assigned to a given billet must not exceed that billet size. This constraint also prevents assigning panels to billets that are not chosen. Structure design constraints, Eq (13), avoid assigning panels to billets that cannot be utilised due to structural design considerations. Structure design constraints are determined based on Table 7, which is a manufacturer's initial design table indicating whether panel i with the corresponding length can be cut from billet t or not. Eq (14), the bound size constraint, represents the floor area that panels should cover. The bound size constraint specifies the buildable area length and width in the model. Eq (15) indicates nonnegativity and integrality constraints.

Objective function:

$$Eq(8). \max \sum_1^i \sum_1^t R_{it} S_{it} - \sum_1^t C_t Z_t - r \sum_1^t (B_t Z_t - \sum_1^i S_{it})$$

$$- PHC \sum_1^t Press_t Z_t - PHC \sum_1^i \sum_1^t CNC_{it}$$

$$Eq(9). \sum_1^i \sum_1^t S_{it} R_{it} \leq K$$

$$Eq(10). \sum_1^t X_{it} = 1, \text{ for all } i \in I$$

$$Eq(11). l_i X_{it} \leq S_{it} \leq u_i X_{it}$$

$$Eq(12). \sum_i S_{it} \leq B_t Z_t, \text{ for all } t \in T$$

$$Eq(13). X_{it} = 1 \text{ or } 0$$

$$Eq(14). L = \sum_i S_{it}$$

$$Eq(15). S_{it} \geq 0, X_{it} \in \{0,1\}, Z_t \in \{0,1\}$$

Table 9- Mathematical notations

Symbol	Description	Unit	Symbol	Description	Unit
B_t	Billet t area	Square meter	r	Recycling cost	Dollars per cubic meter
CNC_{it}	CNC stage process time of panel i cut from billet t	Minute	R_t	Price of a square meter of billet t	Dollars per square meter
C_t	Materials costs of billet type t	Dollars per billet	S_{it}	Panel size i cut from billet t	Square meter
K	(client's financial objective) maximum structure price they desire to pay	Dollars	set	Coding software CNC machining estimated time	Minute
$I = \{1,2,..i\}$	Set of panels	-	$T = \{1,2, ... t\}$	Set of all billets	-

				with the option of choosing thicknesses from the following billet types: 3-layer billets thicknesses(meters): 0.085,0.105,0.115,0.125, 0.135, 5-layer billets thicknesses(meters): 0.145,0.160, 0.175, 0.195, 0.205, 0.225, 7-layer billet thicknesses(meters): 0.245, 0.265, 0.275, 0.295, 0.315	
l_i	Lower size of panel i	Square Meter	u_i	Upper size of panel i	Square meter
L	Building floor area	Square Meter	W	Waste of billet during the cutting	Square meter
NP	Number of panels	-	X_{it}	1 If panel i assigned to billet t 0 Otherwise	-
PHC	Productive hour cost	Dollars per minute	Z_t	1 If billet t selected 0 Otherwise	-
$Press_t$	Billet t pressing stage process time	Minute			

3.5.4 Applying Genetic Algorithm as a solution search method of the model

The FDA is a complicated problem and has been solved by metaheuristic algorithms (Balakrishnan and Geunes 2003; Wang et al. 2004). Metaheuristic algorithms are computational intelligence paradigms especially used for sophisticated solving optimisation problems (Abdel-Basset et al. 2018). Among the metaheuristic algorithms, Genetic Algorithm (GA) is more common. Hence, it would be an appropriate method to solve the developed model. GA is a stochastic search method based on natural selection where a population is formed by individuals (Augusto et al. 2012; Hassanat et al. 2019). Each individual is a solution to the problem. If the solutions can be divided into a series of small blocks, then the steps, which are represented by genes and a series of genes (a chromosome), will encode the complete solutions (Hassanat et al. 2019).

Five phases are considered in a GA:

- i. Initial population: GAs begins with a set of individuals. An individual is characterised by a set of the model's variables known as genes. Genes are joined into a string to constitute a chromosome (Hassanat et al. 2019). In this study, based on the variables specified under Section 3.4.1, the chromosome structure should be according to the next figure. The first set of genes indicates panel sizing. The second set of genes represents allowable billet type, i.e., billet thickness. Finally, the last set shows the panel to billet assignment.

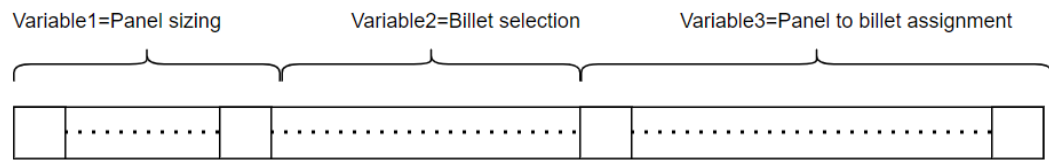


Figure 26- Chromosome structure

- ii. **Fitness:** This step computes the fitness value of each individual in the present population. Fitness classifies chromosomes in accordance with an objective function. Then, the best group of individuals is allowed to continue the process, whereas the others are rejected (Augusto et al. 2012; Hassanat et al. 2019).
- iii. **New population:** Steps 4, 5, and 6 are repeated to create a new population up to completion.
- iv. **Selection (reproduction):** The selection chooses the individuals that will participate in the cross-over. The better an individual is, the higher it has chance of being selected (Hassanat et al. 2019). There are several selection strategies; Roulette Wheel Selection, which is widely-used in Single-objective, (Hassanat et al. 2019) is adopted for selection operation.
- v. **Cross-over:** The selection process utilisation determines the individuals' uses in the cross-over to produce a new offspring (Hassanat et al. 2019). Crossover operation is used to improve the diversity of the population so as to advance global searching (Xu et al. 2017).
- vi. **Mutation:** Normally, mutation takes place after cross-over. This operator randomly applies the changes to one or more genes to produce a new offspring. Hence, it creates new adaptive solutions to avoid local optima (Hassanat et al. 2019). Mutation is different from crossover selection which is used to improve the global search by changing large part of genes of chromosomes (Hassanat et al. 2019). While the mutation operation only slightly changes the genes of a chromosome, which can protect good patterns to help convergence and avoid being trapped by local optima. A mutation point is randomly selected (Xu et al. 2017).
- vii. **Termination criteria:** GA must stop at a point to announce the best solution in hand. There are some termination conditions (Hassanat et al. 2019). In the current study, reaching a fixed number of generations is utilised as a termination strategy.

In this thesis, the designed genetic algorithm is implemented in Matlab environment, where optimisation can be conducted. Generally, four major parameters playing an important

role in gaining appropriate solutions used by GA include cross-over and mutation rate, population size, and the number of generations (Hassanat et al. 2019). The determination of these parameters is dependent on specific optimisation problems and testing of optimisation performance (Xu et al. 2017). Setting of these running parameters and the optimisation result are presented in Chapter 5.

3.5.5 Model validation techniques

Theory triangulation is the use of multiple theories, laws, rules, or hypotheses when examining a situation or phenomenon. The idea is to look at a phenomenon from different viewpoints, through different lenses, with different questions in mind (Denzin 2010). In other words, investigators with different points of view interpret the same results. Theories are usually introduced when a previous study of a class of phenomena has revealed a system of uniformities that can be expressed in the form of empirical laws. Theories explore to explain those regularities and, generally, to afford a deeper and more accurate understanding of the phenomena in question. Like many laws in natural science, many managerial laws have made a great impact while rigorous theories remained absent, although theories exist at a higher and deeper level than laws (Schmenner and Swink 1998).

The discipline of operations management has developed a set of laws that have bearing on the phenomenon of differential factory productivity or production efficiency. Some of these laws are deductive and derived from mathematical foundations, and some of them are probabilistic and derived from observed data, namely the law of variability, the law of quality, the law of bottleneck, the law of factory focus, etc. Among these laws, the law of variability was applied in the model validation section as a theory triangulation method. Based on this law, the greater the random variability, either demanded of the process or inherent in the process itself or in the items processed, the less productive the process is or, the less production efficiency the process has. This law derives from the theory of swift even flow and can be verified by simulation. The more variable the timing or the nature of the jobs to be done by the process, and the more variable the processing steps themselves or the items processed, the less output there will be formed the process, as captured by labour production efficiency measures, machine production efficiency measures, material production efficiency measures, or total factor production efficiency measures (Schmenner and Swink 1998).

3.6 Research design summary and its implications for this thesis

To develop a data-driven framework for MC, two scenarios are considered in this research. Therefore, the research methodology and stages, including data collection, data

analysis, and model validation, for each scenario are discussed in this chapter. The first scenario, which is discussed in Chapter 4, assumes that an architect is looking for modular design patterns that support MC. In other words, they look for manufacturable design patterns that are applicable or desirable for the selected clients. Therefore, the architect runs a fact-based comparison in order to enable modular design layouts based on the similarities in the clients' architectural designs. This scenario must be executed in the conceptual design stage. This scenario aims at meeting the first objective of this research. The first objective of this research include (i) recognising the manufacturability of layout design and (ii) identifying similarities in architectural design and structural spans of different apartments. These can be considered as a means to find a pattern for dwellings' modular design offered to different clients. In other words, this objective identify the common architectural space characteristics (i.e., space length, width, aspect ratio) and structural spans. The clustering technique was considered as a method to find a pattern for apartments' modular design. Among four types of triangulations, theory triangulation is considered in this research to validate the clustering results.

The second scenario discussed in Chapter 5 assumes that the architect has been tasked to design a fully customised building layout. This task takes place during the preliminary design stage. Under this scenario, the architect has little room to offer modular design layouts; instead, s/he must endeavor to accommodate MC through integrating production processes in the building design without compromising the flexibility in the customised architectural design. This scenario aims at achieving the second, third and fourth objectives. These objectives are (i) to mathematically model the interrelationships between architectural and structural layout designs, (ii) to determine the most critical manufacturing processes influencing building layout, (iii) to integrate manufacturing processes in building layout design for attaining optimal factory efficiency and preserving architectural flexibility. In other words, these objectives lead to finding a wall and floor panel layout with the optimal production process. A mathematical model is proposed. The proposed model optimises the interactions between the structural wall placement and floor panel dimensions by determining building spans, floor panel lengths, and thicknesses. Every option is measured against the available budget, and the client wants to know the cost implication of every combination of options. Theory triangulation is also considered in this scenario to validate the mathematical model results.

Chapter 4: Analysing and Clustering Building Layouts

4.1 Introduction

To apply product platform strategies for mass customisation of buildings, the focus must be on design specifications that lie between ETO and SV (Bonev et al. 2015). As elaborated upon in Chapter 2, this intermediary realm allows for alignment between supply-side and demand-side stakeholders to collaborate on building design refinements at the module or component level, thereby facilitating a degree of standardisation. MC for the building design does not mean that an infinite number of options have to be offered. Instead, in a mass customised apartment, an appropriate number of options can be sufficient (Cuperus 2003). This is where the role of Mass Customisation (MC) enablers such as modules, platforms, and product families comes to the fore, effectively serving as mechanisms to provide a diverse yet manageable range of choices. Yet, the existing literature reveals a scarcity in comprehensive analyses of apartment designs, particularly in formulating architectural design parameters. This gap impedes the process of focusing on high-demand options and subsequently developing a coherent pattern for modular building design, akin to a product platform. Within this context, the present chapter postulates a scenario in which an architect endeavours to find modular design patterns that support MC through product platform concepts. In other words, they look for manufacturable design patterns that are applicable or desirable for the selected clients. As one of the research objectives is to identify design patterns within the mid-rise residential building market that can collectively lend themselves to prefabrication, this chapter treats all units within nine buildings as one sample set. Therefore, individual assessment of each of the nine buildings is out of scope of investigations in this chapter. Modelling floor layouts within one building for optimum manufacture has been discussed in Chapter 5.

The architect has a role to identify a balance between the clients' preferred design and efficient manufacturing process. Therefore, the architect runs a fact-based comparison in order to enable modular design layouts based on the similarities in the clients' architectural designs. This method is best executed during the conceptual design phase, facilitating a comprehensive exploration of design possibilities. Instead of having wide choices, the objective of modularisation in building design is to limit the options based on the expected probability of acceptable layout design. Apartments design analysis with spatial voids modularity approach gives architects insight into developing a well-defined practical platform. In addition, the

modular design patterns in this chapter lead to parametrising architectural design and providing an appropriate number of design options. Modular design scenarios are identified according to finding similarities in architectural design (spatial voids module perspective) and structural spans of nine multi-storey housing projects, considering the contemporary manufacturing practices (components module perspective) in Australia. The projects include 710 recently completed and ongoing apartment units for middle-income earners, which have been built by six well-known developers in Sydney, NSW.

As discussed in Chapter 2, two distinct perspectives—architectural and manufacturing—are instrumental in shaping modularity within building design. The former, rooted in spatial voids, and the latter, centred around solid mass modules, serve as the cornerstones of this discussion. Consequently, this chapter unfolds with a dichotomous structure, divided into two key sections.

The first section carries out architectural design analysis to address spatial voids of apartments' modular design and to generate a number of design options with considering architectural design patterns. To achieve this, Section 4.2 commences by delineating a comprehensive overview of the profile of the examined buildings. It proceeds to define the sample size and the methodology deployed for quantifying the parameters of architectural drawings. Subsequently, a synthesis of statistical analysis outcomes pertaining to architectural designs—including average spatial void dimensions and the extent of spatial void variability—is presented. A pivotal facet, spatial void configuration (referred to as spatial voids modules), is then elucidated through the lens of cluster analysis. The subsequent exploration, detailed in Section 4.3, delves into the realm of layout design manufacturability. This is pursued through a twofold approach: Section 4.3.1 delves into statistical analysis regarding apartment spans, while Section 4.3.2 focuses on delving into component manufacturing practices. The objective is to ascertain the capabilities of Australian prefabricated system manufacturers. This entails a comparison between the outcomes of statistical analysis concerning apartment spans and real-world component manufacturing practices. By weaving insights from Sections 4.3.2 and 4.3.3, this section culminates in the presentation of modular design scenarios and span patterns within architectural floor plans and vertical designs. This is achieved through the prism of cluster analysis. The modular design scenarios presented in this chapter could be equal to CTO approach, where the architect define a standard set of building modules or subsystem variants, like a number of options for structures design, which can be commonly used within the off-site manufacturing design. The next figure shows the Stage B research roadmap which is related to this chapter.

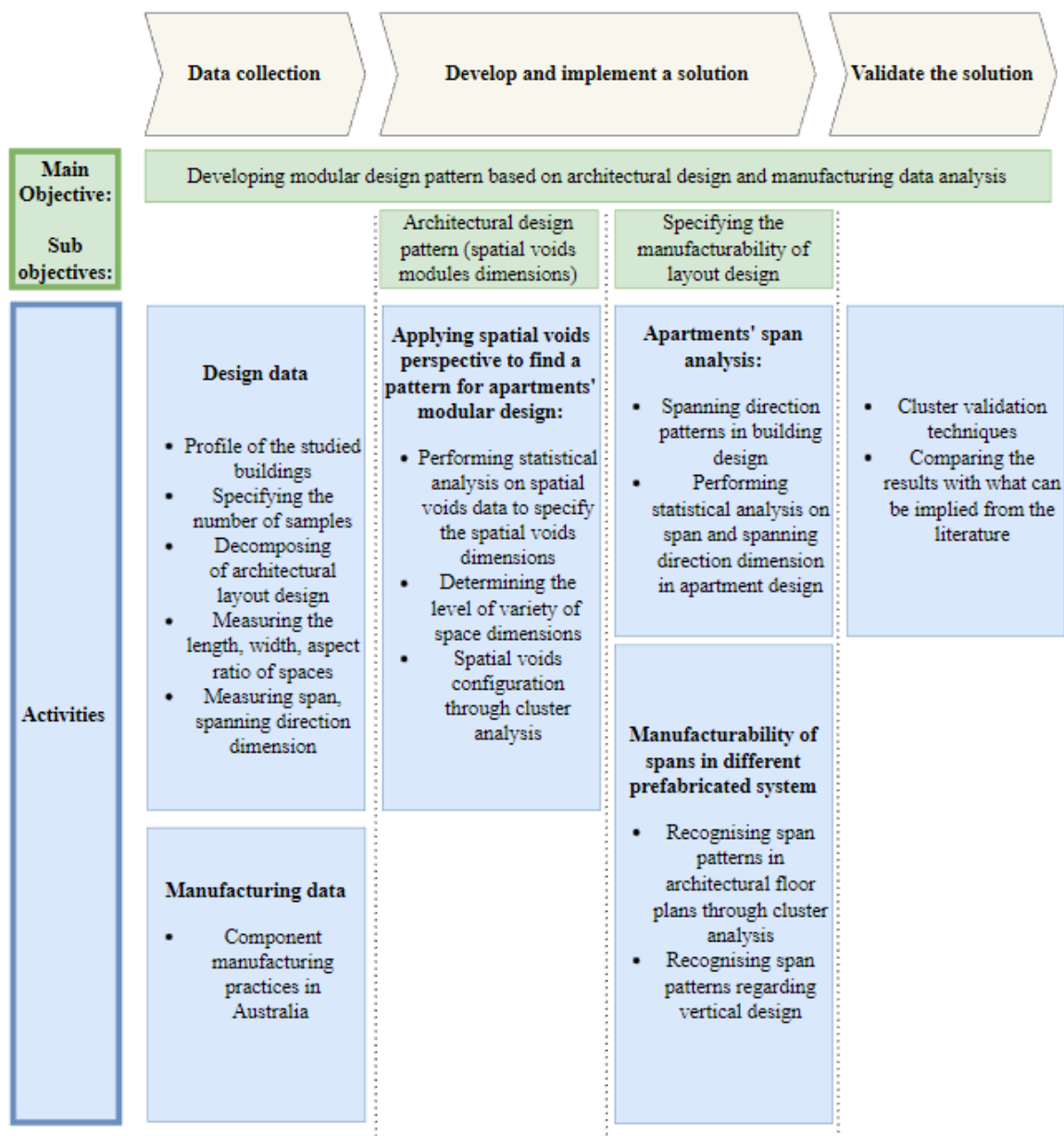


Figure 27- Research roadmap for Stage B

4.2 Applying spatial voids perspective to find a pattern for apartments' modular design

Because of their size and dominance in the market, D&C contractors can dictate to clients, provided that they consider their clients' requirements systematically. Hence, to meet customisation requirements, they employ marketing, sales, research, and development (R&D) teams to feed architects by providing market analysis information, such as client functional requirements and their willingness to pay for the building. Subsequently, architects translate these requisites into design parameters. Acting as intermediaries, architects, with the collaboration of marketing, sales, research, and development (R&D) teams, generally represent the client's interests. The client, having vested authority, entrusts the architect with the responsibility of providing them with a dwelling (Warren-Myers and Heywood 2016)

The manufacturer generally deals with the building design constructability resulting from components manufacturability. In contrast, the client tends to conduct spatial configuration with the aid of an architect who offers multiple ranges of apartments in terms of spatial variety and layout design. Multiple ranges of apartments are similar to the product variants concept in the product design industry. Hence, within the residential building design, it can be concluded that the components (solid mass modules) and spatial perspectives are associated with supply-side and demand-side concerns, respectively. While the supply-side deals with increasing cost efficiency through the production efficiency of components manufacturing, the demand-side is concerned with having a variety of housing designs (i.e., spatial configuration or architectural layout design) at a reasonable price.

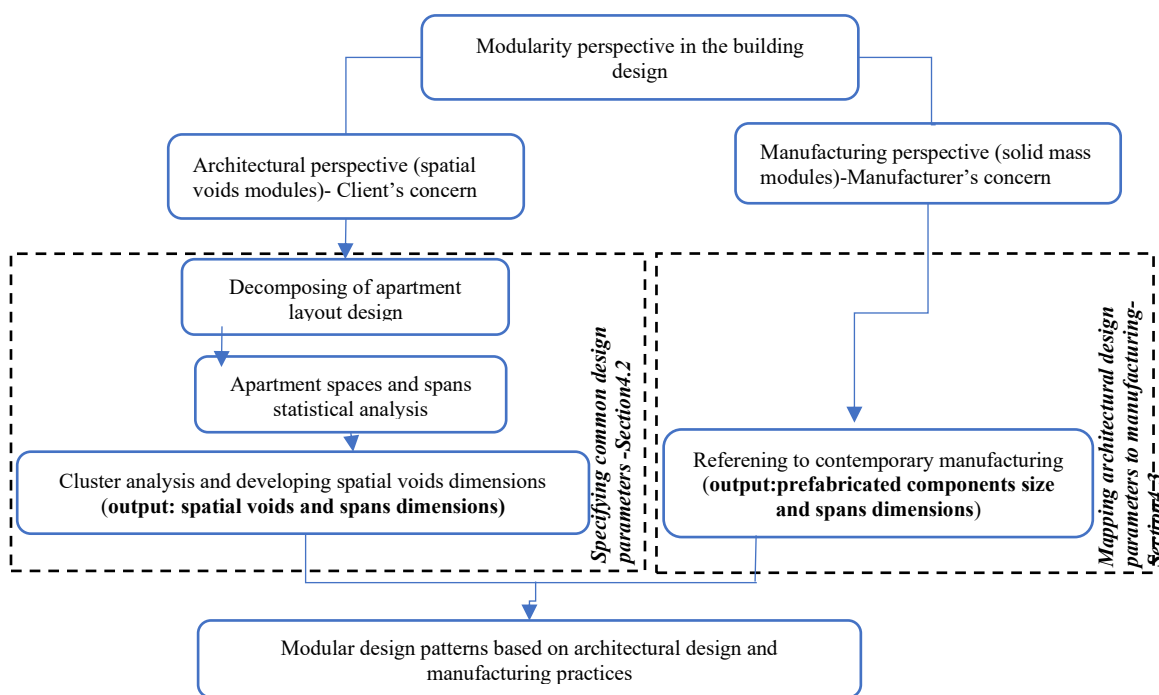


Figure 28- The chapter framework to find some modular design scenarios for apartments design

Instead of having a wide range of choices, the objective of finding a pattern for apartments' modular design is to provide appropriate number of options according to the clients'/ designers' expected probability of acceptable layout design. Finding a pattern for apartments' modular design might be quite complicated, which requires considering several variables, such as apartment layout, size, cost, building frontage, setback, design style, etc. A pattern for apartments' modular design is generally achieved by predetermined sizes (dimensions) and limitation of variety in a systematic approach (Roy and Roy 2016). The current research was implemented based on the decomposing of architectural layout design and analysing of spaces in a statistical manner. Statistical analysis and a clustering technique were performed to find the probabilistic acceptability of the spatial voids dimensions. Architectural layout components, i.e., spatial voids, may have defined shapes (square, rectangular, etc.) or

loose shapes. Loose shapes are usually undesirable in the layout stage. Special voids in floor plans usually include rectangular or square shapes (Michalek et al. 2002).

Spatial void modularity followed by modular component coordination suggests the following benefits: (i). It creates a basis for minimising the variety of types and sizes of building components, which is the main objective of the design for MC. (ii). It also allows for the easy adoption of prefabricated components to any layout and for their interchangeability within the building (Rocha et al. 2015). The easy adoption of prefabricated components to any layout is achieved by defining the location of each component in the building with reference to a modular grid of spatial void rather than concerning other components.

In summary, this section, with its following subsections, aids in achieving a part of identifying modular design scenarios based on recognising similarities of architectural design.

4.2.1 Apartments architectural design with a view of spatial voids

Profile of studied buildings

Deriving spatial voids dimensions based on clients' desires has not been extensively explored within the prevailing literature, primarily due to reasons such as the limited robustness of the study volume. Recognizing that decomposing architectural layout design and conducting statistical analysis offer a means of gauging the anticipated likelihood of acceptable architectural layout design parameters in line with client preferences, this section embarks on data analysis within housing projects, focusing on the architectural spaces within apartments. To facilitate this endeavor, a selection of nine recently completed and ongoing projects encompassing a total of 710 apartment units in Sydney, NSW has been meticulously chosen and dissected to ascertain the essence of the module from a spatial voids perspective. It's worth noting that Sydney, NSW accounts for a significant portion of the market share, representing approximately 13,200 apartment constructions annually, as per ABS 2017 and ACIF 2019.

Design and production decisions are usually integrated and jointly made in volumetric off-site construction. Namely, it is unlikely to have a building completely designed as a set of volumetric prefabricated pods and have a work structure that does not involve the assembly of such pods. This provides the simplest and perhaps easiest instance to implement and benefit from product modularity in construction because design and production process decisions are usually aligned. Yet, buildings are not usually erected by assembling only a set of volumetric pods produced off-site. Buildings are most often also comprised of smaller and simpler parts (da Rocha and Kemmer 2018), such as wall panels, beams, and columns. These nine buildings have concrete structures, either precast or cast in place walls and columns. The enclosure and none load-bearing walls of all buildings are gib boards. The data analysis of drawings leads to

specifying (i) the spaces which require a higher level of standardisation and have similar architectural characteristics (i.e., space length, width, aspect ratio) in order to recognise the common architectural design, and (ii) a number of design options based on the expected probability of acceptable architectural layout design. The analysis of data will be applicable to all geo-climatic regions of Australia with appropriate alteration as per the target population's geo-climatic condition and socio-economic status profile.

Finding from statistical analysis of apartment architectural design

The primary aim of this section is to delineate the specific spaces necessitating either a heightened level of variety or standardized design. In essence, the objective here is to pinpoint prevalent spatial void dimensions for various functional areas within apartments. The analysis of apartment designs serves to equip architects with a profound understanding, facilitating the provision of well-defined design and building platform.

The subsequent histogram, illustrating the frequency distribution of each apartment unit, vividly portrays the dominance of two-bedroom apartments as the most sought-after dwelling type in Sydney. This observation resonates with the assertion by Domain Group: "two-bedroom apartments cost an average of 13 percent more than one-bedroom units across Sydney". Furthermore, it's pertinent to highlight that "comparing the apartments' prices and their resale value indicates that two-bedroom apartments offer greater resale value in the future" (Frost 2018). On the flip side, the number of studio units pales in comparison to other unit types, thereby rendering them excluded from the ensuing data analysis.

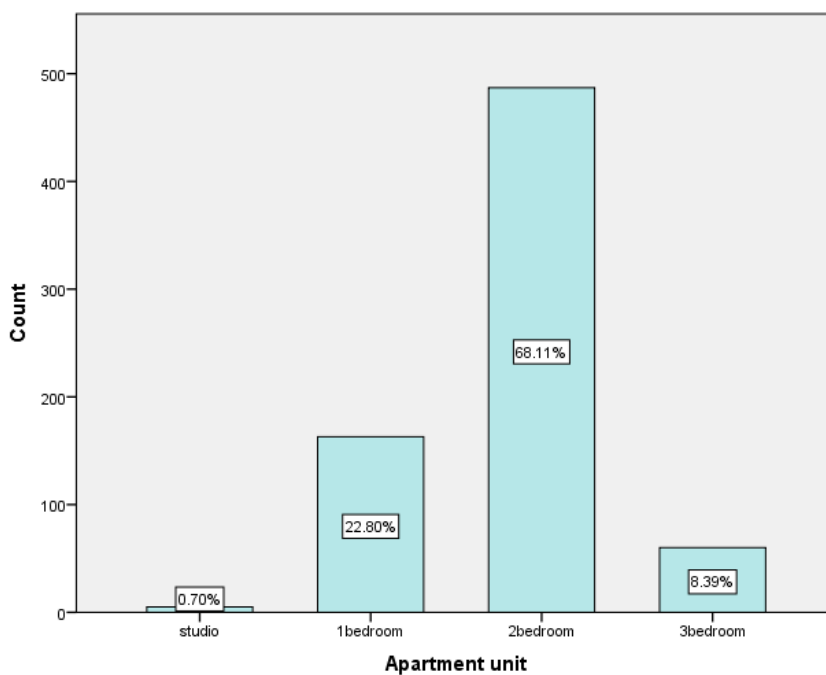


Figure 29- Apartment unit frequencies

Referencing the Apartment Design Guide, which offers a prescriptive guideline for NSW multi-storey residential buildings, the minimum area of one-, two- and three-bedroom units should be at least 50, 70, and 90 square meters, respectively (NSW Department of Planning Environmen 2015). Accordingly, there was an expectation for unit sizes to increase at the proposed minimum area. However, the ensuing data analysis, succinctly outlined in the subsequent table, refutes this assumption. To elaborate, the table reveals that the average area of each apartment type is in fact greater than the specified sizes delineated in the Apartment Design Guide. This underscores the comprehensive range of apartment designs encompassing varying dimensions within the residential building market.

Table 10- Summary of apartment design

Apartment type	Number of units	ADG recommended minimum area	Actual minimum area (square meter)	Actual Maximum area of data (square meter)	Average area of data (square meter)	Difference between the size in ADG and average area of data (square meter)	Average lengths of unit (meter)	Most common length range of unit (68% of the sample-meter)	Average widths of unit (meter)	Most common width range of unit (68% of the sample-meter)
Studio	5	30	44	49.9	48.2	18.2	13.1	12.1-14.2	3.5	3.4-4.1
One-bedroom	163	50	59	93.7	73.6	23.6	10.5	8-13	7.1	5.8-8.4
Two-bedroom	487	70	76.8	145.9	103.8	33.5	12.5	10.3-14.7	8.35	6.8-9.8
Three-bedroom	65	90	114.3	211	131.8	41.8	15	11.6-18.4	8.6	7.3-9.9
*ADG: Apartment Design Guid, (NSW Department of Planning Environmen 2015)										

Given the research’s primary focus on apartment spatial voids—encompassing living and dining areas, kitchen, bedroom, study room, bathroom, ensuite, laundry, and balcony—the length, width, and aspect ratio of all these spatial voids were meticulously gauged, analysed, and represented as L, W, and AR, respectively. The resultant analysis findings of spatial void dimensions offer architects invaluable insights into identifying two key aspects: (i) spaces demanding diversity, and (ii) spaces conducive to standardisation in terms of dimensions. The ensuing paragraphs delve into the discussion of these analytical outcomes and their implications.

Table 6 in Chapter 3 provides a concise overview of the profiles of the buildings under consideration. The dimensions of parameters are clear dimensions, excluding the wall thickness

(usable area in principle). All numeric data adhere to the Australian standard units of measurement system. It's important to note that, for the sake of simplifying data analysis, this thesis treats all spatial voids as rectangular shapes, without accounting for spatial arrangement or proximity. For instance, living and dining rooms were amalgamated into a single rectangular space. In cases where living and dining areas don't possess a uniform rectangular shape, the equivalent area was computed by summing the areas of two or more rectangles based on their average width and length.

Upon compiling the range of parameter dimensions, the arithmetic mean and standard deviation (SD) of spatial void dimensions were calculated. This step aimed to review the range of variation within the dimensions. Mean indicates the average of all the given dimensions (i.e., L, W, AR), while SD shows the measures of the dispersion of the given dimensions from the mean. It means how far the data values are spread out from the mean value. The mean of each spatial void dimension (i.e., the mean of L, W, AR) and their level of variation in terms of size (SD) were sorted out (i) separately by spaces and based on apartment type in the next table, (ii) separately by space without considering the type of apartments in Table 12. The latter indicates the arithmetic average dimensions available within all apartments, while the former presents the average dimensions available within each apartment type. The statistical analysis with mean and SD does not integrate the Length and Width of each space simultaneously. In this context, AR plays a crucial role in determining the ratio between Length and Width for each space.

An independent analysis revealed that there exists no significant distinction between the dimensions of the bathroom and ensuite spaces. Given their comparable functions from a spatial void perspective, these two spaces were amalgamated and considered as a single entity or function. A similar approach was adopted for bedrooms other than the main bedroom (often referred to as the master bedroom). Consequently, bedrooms excluding the master bedroom were categorized under the label "extra bedrooms" in both Tables 11 and 12. The master bedroom, on the other hand, was discerned from other bedrooms through a distinction: it was treated as the sole bedroom in one-bedroom apartments and as the master room in two- and three-bedroom apartments. The results derived from spatial void dimensions, presented in Tables 11 and 12, encapsulate the average clear dimensions, excluding wall thickness.

Table 11-Average dimensions and SD sorted separately by spatial voids and apartments typ

Apartment Type Spatial voids	One bedroom (Average apartment area=72.7, SD=11.7 square meters)							Two bedroom (Average apartment area=103.7,SD=15.3 square meters)						Three bedroom (Average apartment area=130.7,SD=19.6 square meters)							
	Number of case	Average Length (meters)	SD (meters)	Average Width (meters)	SD (meters)	Average AR	SD (meters)	Number of case	Average Length (meters)	SD (meter)	Average Width (meters)	SD (meters)	Average AR	SD (meters)	Number of cases	Average Length (meters)	SD (meters)	Average Width (meters)	SD (meters)	Average AR	SD (meters)
Living room	164	5.6	1.2	3.9	.4	1.4	0.2	489	6.1	0.7	4.1	.4	1.5	0.2	56	5.9	0.7	4.4	0.6	1.4	0.2
Kitchen	164	3.1	0.5	2	0.8	2.2	1.8	489	3.4	0.8	2.4	0.5	1.7	1.4	56	3.4	0.5	2.5	0.3	1.4	0.3
Main bedroom	164	4.2	0.6	3.2	0.2	1.3	0.2	489	4.4	0.6	3.2	0.3	1.4	0.2	56	4.9	0.6	3.3	0.3	1.5	0.2
Bedroom 2	-	-	-	-	-	-	-	489	3.8	0.3	3.1	0.2	1.2	0.1	56	3.9	0.3	3.1	0.2	1.3	0.1
Bedroom 3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	56	3.7	0.3	3.2	0.3	1.2	0.1
Study room	27	2.6	0.5	2.1	0.5	1.3	0.2	59	2.9	0.7	1.9	0.4	1.6	0.4	20	2.1	0.4	1.6	0.3	1.4	0.4
Bathroom	164	2.6	0.3	1.8	0.3	1.4	0.2	489	2.5	0.3	1.8	0.3	1.4	0.2	56	2.7	0.3	1.8	0.2	1.5	0.2
En suite	36	2.6	0.1	1.9	0.3	1.4	0.2	453	2.5	0.4	1.7	0.3	1.5	0.3	56	2.7	0.3	1.8	0.3	1.5	0.3
Laundry	155	1.3	0.2	0.8	0.1	1.7	0.3	424	1.4	0.2	0.9	0.2	1.6	0.3	45	1.5	0.3	0.9	0.2	1.6	0.3
Balcony 1	164	4.3	1.3	2.5	0.6	1.8	0.8	489	5.3	2.1	2.7	0.6	2.1	1.1	56	5.5	2.8	3.0	0.9	2.0	1.3
Balcony 2	9	2.5	0	1.2	0	2.0	0	199	5.8	3.6	1.6	0.7	4.4	3.8	30	4.0	1.2	1.8	0.6	2.6	1.5

In a few apartments, laundries were located in the kitchen. In those cases, the laundry dimensions were not measured separately, instead, the kitchen was considered as a kitchen including laundry.

Generally, the size of apartments significantly varies across the projects. One-, two-, and three-bedroom apartments have a rounded average area of 73, 104, and 131 square meters, respectively. Accordingly, a wide range of various dimensions of spaces is observed across the examined projects. Within the domain of the same client, the dimensions vary from project to project, and even in some cases, within the same project or building, it differs within apartment types. It appears that space dimensions have evolved from the maximum use of the available land and buildable area, and no remarkable space modularity has been reflected. Modularity in design and space dimensions is followed within the same apartment type in a few projects. This kind of modularity is specific to the project and apartment type itself. The comparison of the average dimensions of each spatial void in Table 11 also demonstrates that there is no correlation between the type of apartment and spatial void dimensions. Therefore, all apartment types are accounted together for further actions (Table 12).

Table 12- Average dimensions and SD sorted separately by spaces in all types of apartments

Space	Number of cases	Average Length (meters)	SD (meters)	Average Width (meters)	SD (meters)	Average AR	SD (meters)
Living room	710	6.0	0.9	4.1	0.5	1.5	0.2
Kitchen	710	3.3	0.7	2.3	0.6	1.8	1.5
Main bedroom	710	4.4	0.6	3.2	0.3	1.4	0.2
Extra bedroom	545	3.7	0.3	3.1	0.2	1.2	1.2
Study room	106	2.7	0.7	1.9	0.5	1.5	0.4
Bathroom	125 8	2.5	0.3	1.8	0.3	1.4	0.3
Laundry	627	1.4	0.2	0.9	0.2	1.6	0.3
Balcony	946	5.3	2.5	2.5	0.8	2.6	2.3

The frequency histograms depicting spatial voids dimensions (Figures 30 to 35), obtained from the statistical analysis, reveal that certain spaces exhibit a narrow range of Length and Width variations, while others encompass a broader spectrum of dimensions across different projects. A schematic representation of all spatial voids dimensions, based on their minimum and maximum values, is illustrated in Figure 37. The limited range of dimension variability signifies that these

spaces lend themselves to standardisation, offering fewer options for dimension customisation. Essentially, it indicates that clients need not contend with extensive size diversity within these spaces. Excluding the balcony, the Standard Deviation (SD) of spatial voids dimensions falls within the range of 0.1 to 0.9 meters. Consequently, to categorise the variety of spatial voids, dimensions less than 0.3 meters, between 0.3 and 0.6, and exceeding 0.6 meters are classified as representing low, medium, and high levels of variety, respectively. In this study, the combined variety levels for each spatial void side determine the overall potential for space standardisation. These combinations and their corresponding outcomes are delineated in Table 13. Spaces such as extra bedrooms, bathrooms, and laundries exhibit narrow SD across diverse projects and apartment types, indicating a propensity for standardisation. Conversely, spaces like the balcony, living and dining rooms, and kitchen demonstrate larger SD, implying a substantial diversity desired by clients seeking customised apartments. These analytical findings, encompassing all projects and apartment types, are consolidated in Table 13.

It's worth noting that Figure 31 underscores the non-normal distribution of kitchen dimensions, characterised by a significant gap between the minimum dimensions and the rest. This gap highlights the two distinctly different types of kitchens: the one-wall kitchen and the rectangular kitchen. By distinguishing these two kitchen types, there is negligible impact on the average length, width, and SD (Appendix A), and the results in Table 13 remain unaffected.

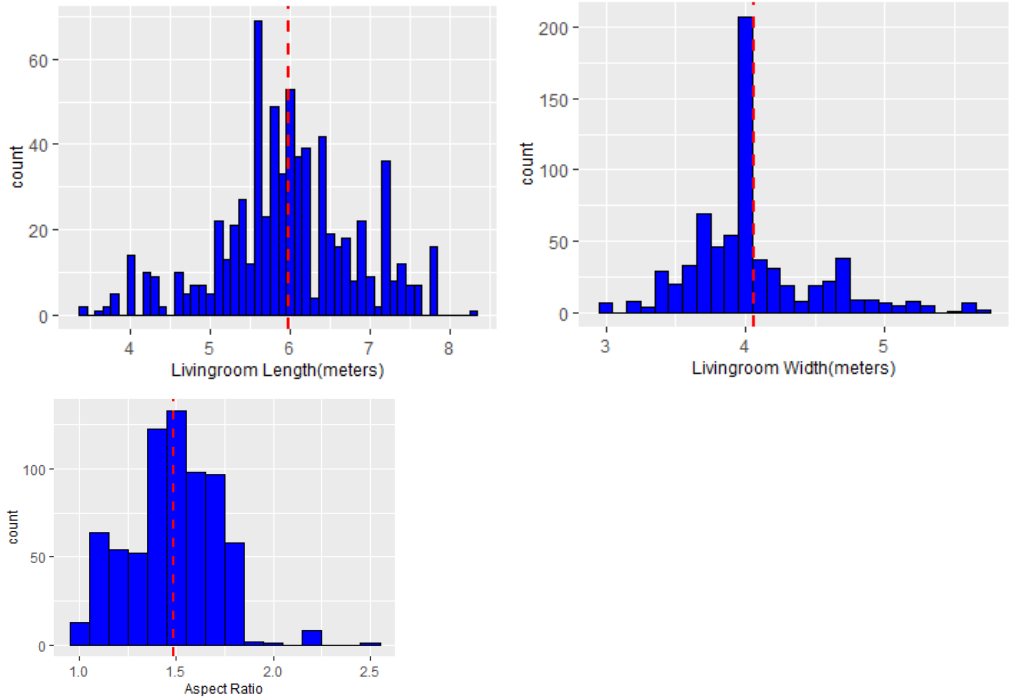


Figure 30- Frequency histograms of living& dining room dimensions

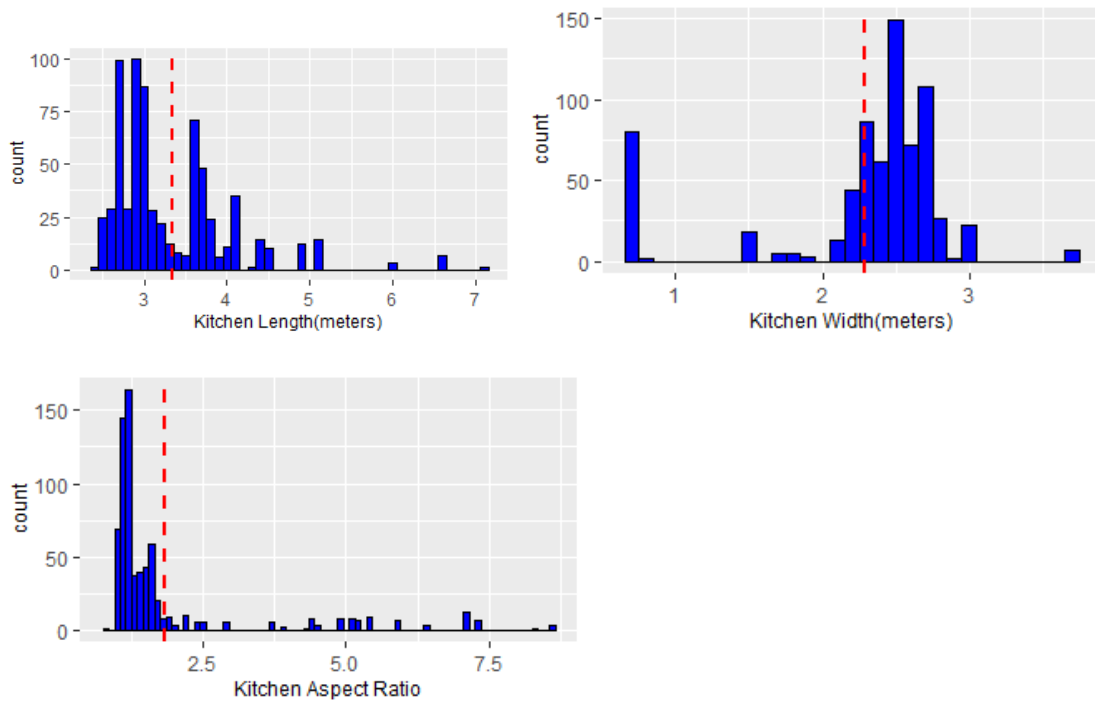


Figure 31- Frequency histograms of kitchen dimensions

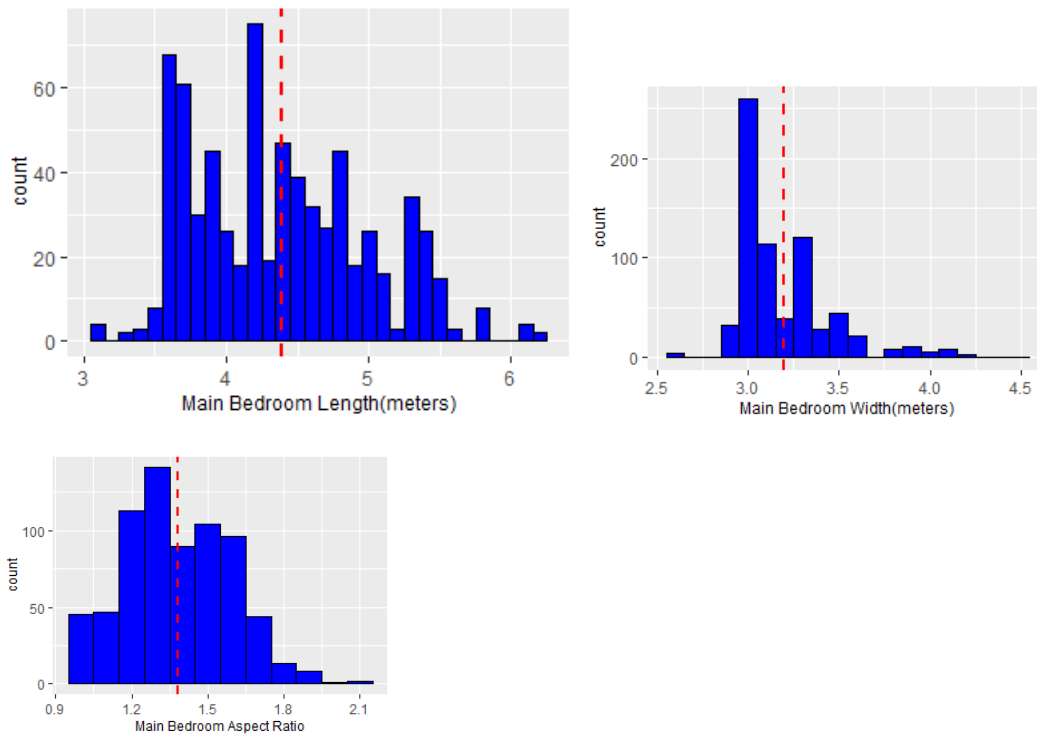


Figure 32- Frequency histograms of main bedroom dimensions

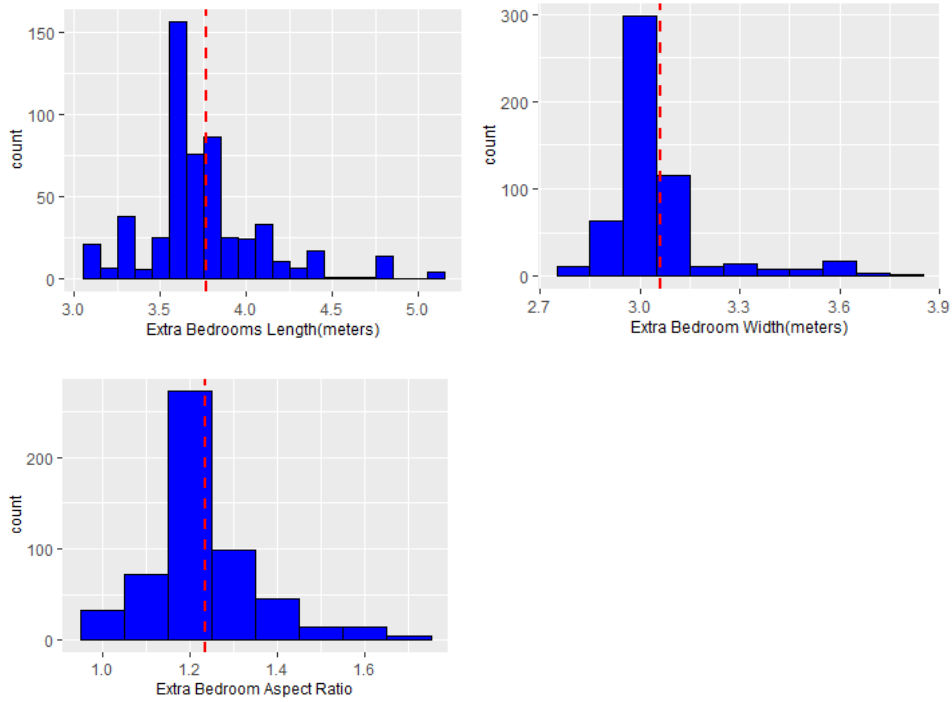


Figure 33- Frequency histograms of additional bedroom dimensions

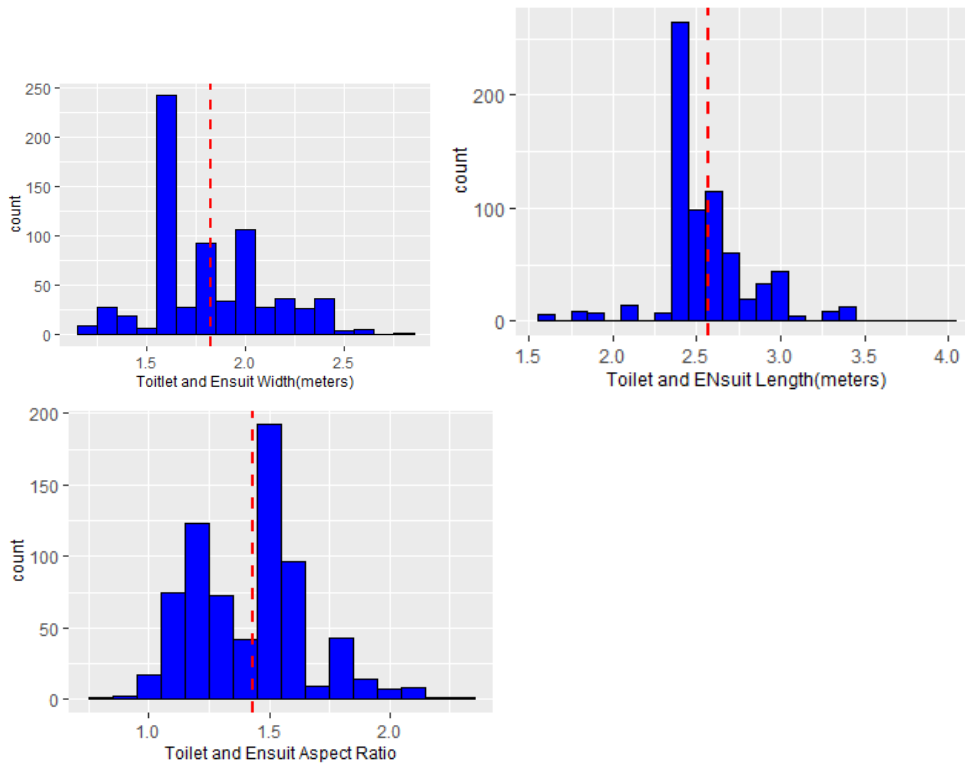


Figure 34- Frequency histograms of bathroom dimensions

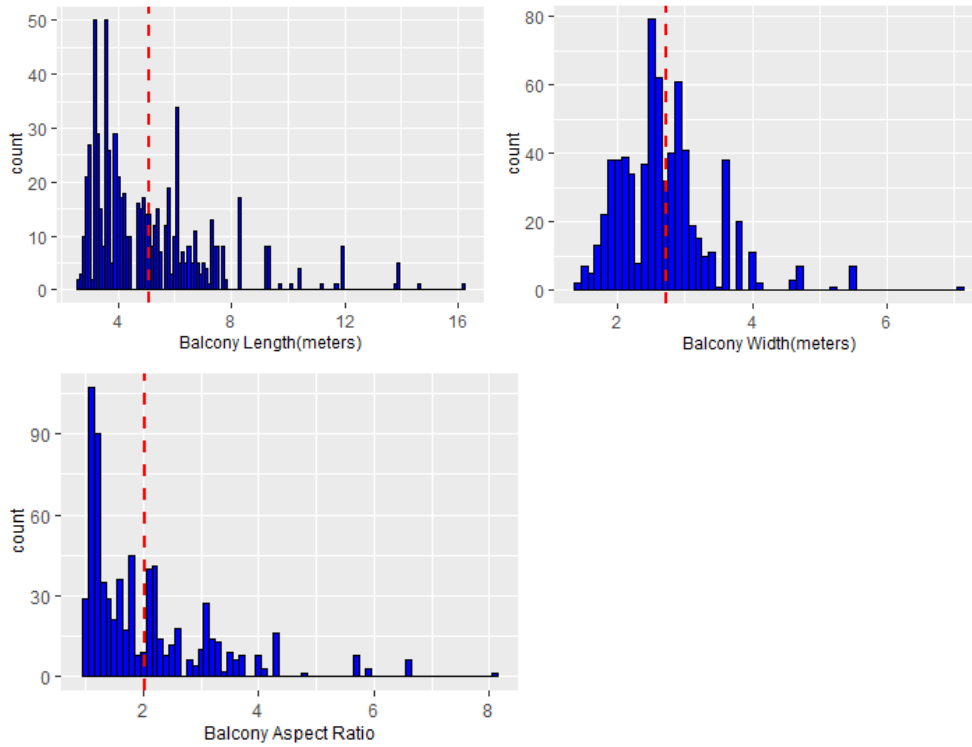


Figure 35- Frequency histograms of balcony dimensions

Table 13- Level of variety of spaces

Spaces	Level of variety in space length (number of options)	Level of variety in space width (number of options)	Potential for space standardisation
Living room	High	Medium	Low
Kitchen	High	Medium	Low
Main bedroom	Medium	Low	High
Extra bedroom (s)	Low	Low	High
Study room	High	Medium	Low
Bathroom/Ensuite	Low	Low	High
Laundry	Low	Low	High
Balcony	High	High	Low

Notes:

- High variety: $0.6 < SD$
- Medium Variety: $0.3 < SD \leq 0.6$
- Low variety: $0 \leq SD \leq 0.3$

The potential level of standardisation of each space is the result of the following combination: High+High= Low, High+Low= Medium, Low+Low= High, Medium+High= Low, Medium+Low= High

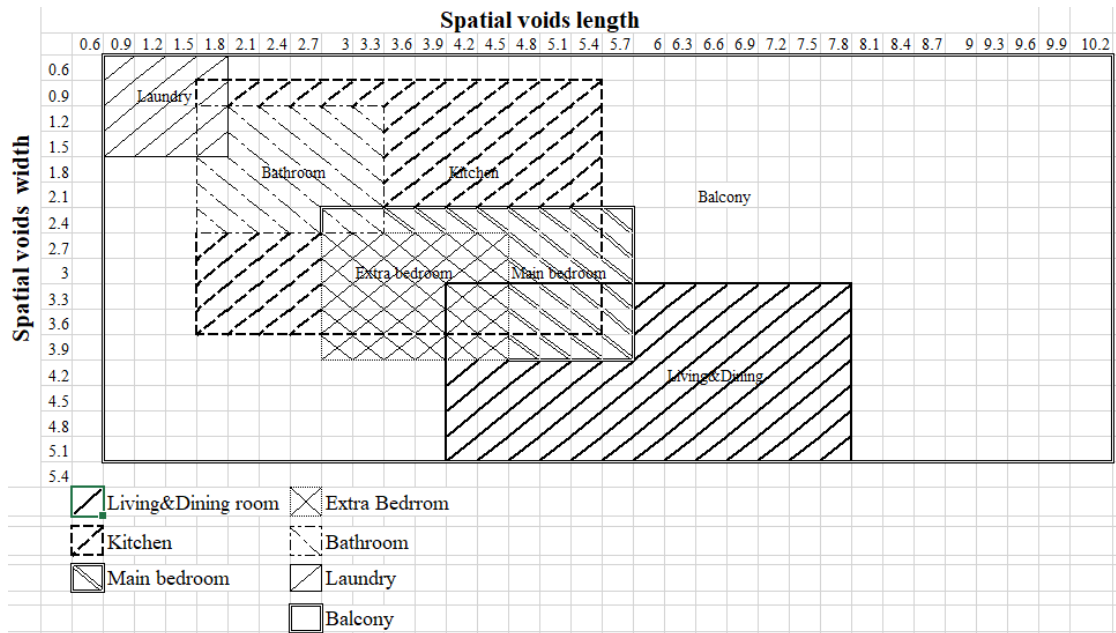


Figure 36- Schematic view of minimum and maximum dimensions of spatial voids

4.2.2 Spatial voids configuration (apartments spaces dimensions) through cluster analysis

In the residential building industry, companies normally create a building as a one-of-a-kind product for each client, and the challenge when moving to MC is to predefine the elements of which the new buildings can consist, which obviously limits the options for the client. MC for the building design does not mean that an infinite number of options have to be offered. Instead, in a mass customised apartment, an appropriate number of options can be sufficient (Cuperus 2003). In other words, conventionally, DPs are defined for each individual product to fulfill FRs. In design for MC, in essence, a few segments of DPs are identified to cover the same FRs that would have required a continuum of DPs. By limiting the spread of FRs, a few selected sets of DPs would be able to fulfill diverse demand-side requirements. Therefore, the number of designs and their associated costs in engineering, manufacturing, and overheads are reduced (Tseng et al. 1996). Hence, in construction companies, the MC enablers, including modules and product families, are utilised as a means to limit variety. When construction companies move to MC, the creation of a predefined product solution space or design involves the risk that the solution space is not adequately large to meet all clients' requirements. Instead of having wide choices, the objective of modularisation is to limit the options based on their expected probability of acceptable layout design.

Spatial void modularity followed by modular component coordination suggests the following benefits: (i). It creates a basis for minimising the variety of types and sizes of building components, which is the main objective of the design for MC (Cuperus 2003) (Rocha et al. 2015).

(ii). It also allows for the easy adoption of prefabricated components to any layout and for their interchangeability within the building (Rocha et al. 2015). In modular design, a technique is required to integrate and classify the characteristics of spaces (Length, Width, Aspect Ratio) so as to group similar ones. In the literature, clustering techniques are applied to assist identification of clusters that match the DPs for serving the same set of FRs. The group DPs indicates the spatial voids modules (Tseng et al. 1996). As clustering techniques have been introduced as a robust technique in literature to group FRs and DPs, cluster analysis was conducted to group spaces based on their dimensions. Analysing the apartment layout design data by clustering results in designating a set of architectural design parameters of the spatial voids to reference a modular grid and comply with prefabricated components manufacturing.

As an outstanding method, K-means clustering groups architectural spaces as per their characteristics (dimensions and AR) to limit options in a wide spectrum of designs and enhance the repeatability of design. To perform a cluster analysis, the following steps were carried out.

- (i) Any missing values were pulled out from the spreadsheet before analysing the data.
- (ii) The data were standardised (i.e., scaled) to make variables comparable. Standardisation consists of the transformation of the variables such that they have a mean equivalent zero and standard deviation equivalent one. Standardisation is particularly recommended when variables are measured in different scales or when the mean and/or standard deviation of variables are largely different (Kassambara 2017). As the L or W and AR were measured in different scales (i.e., meters compared to a ratio without any measurement scale) and the SD and mean of the variables are different to some extent, the standardisation of the data was carried out.

When scaling variables, the data can be transformed as follow:

$$\text{Standardisation } x_i: \frac{x_i - \text{center}(x)}{\text{scale}(x)}$$

Where *center(x)* can be the mean or the median of x values, and *scale(x)* can be the standard deviation (SD) (Kassambara 2017).

The optimal number of clusters (K) was determined by the frequency of the (K) proposed by Elbow, Average silhouette, and Frequency among 30 indices methods (Kassambara 2017). The most repetitive number of clusters proposed by these three methods was selected for each space. In

the case each of the methods proposed a different number of clusters, the median was selected. The number of clusters proposed by each method is illustrated in Figures 37 to 43, and the results are listed in the next table.

Table 14- Optimum number of clusters for each space

Name of method	Elbow method	Average silhouette	Frequency among 30 indices	Number of final clusters
Living&Dinning room	6	6	4	6
Kitchen	5	2	8	5
Bedroom l	5	3	3	3
Additional bedroom	4	3	3	3
Bathroom	4	4	8	4
Laundry	3	2	3	3
Study room	4	8	4	4
Balcony	5	3	3	3

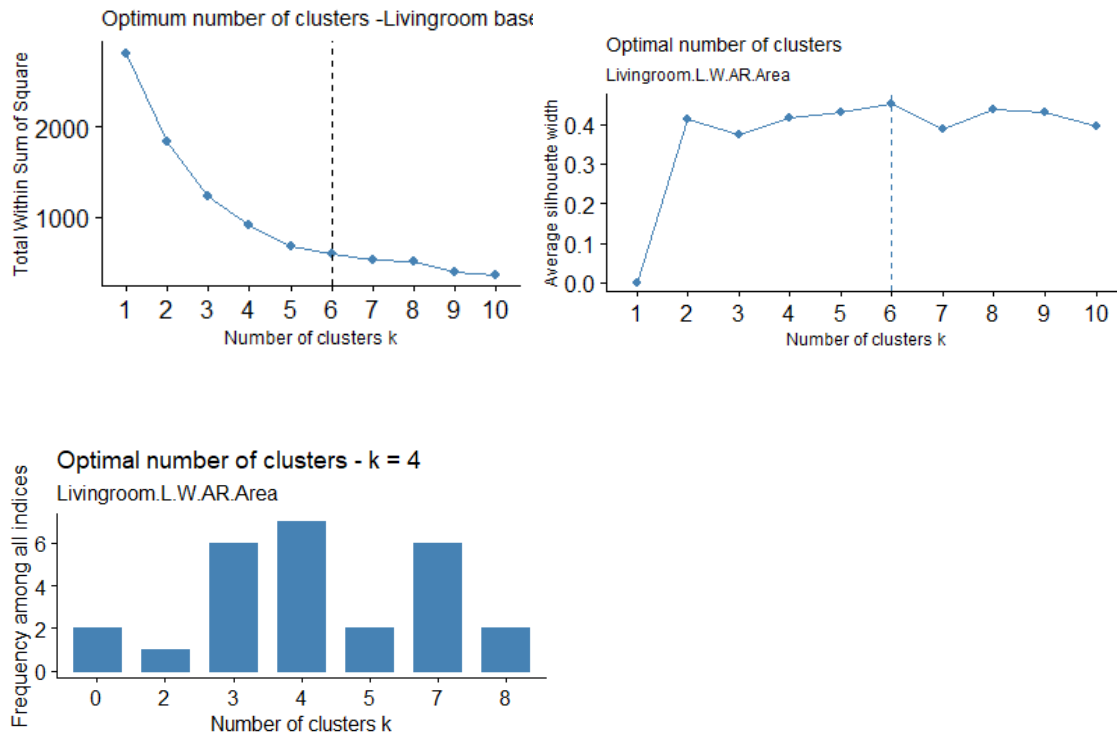


Figure 37- Number of clusters for living& dining room- left to right Elbow, Silhouette, Frequency among 30 indices methods

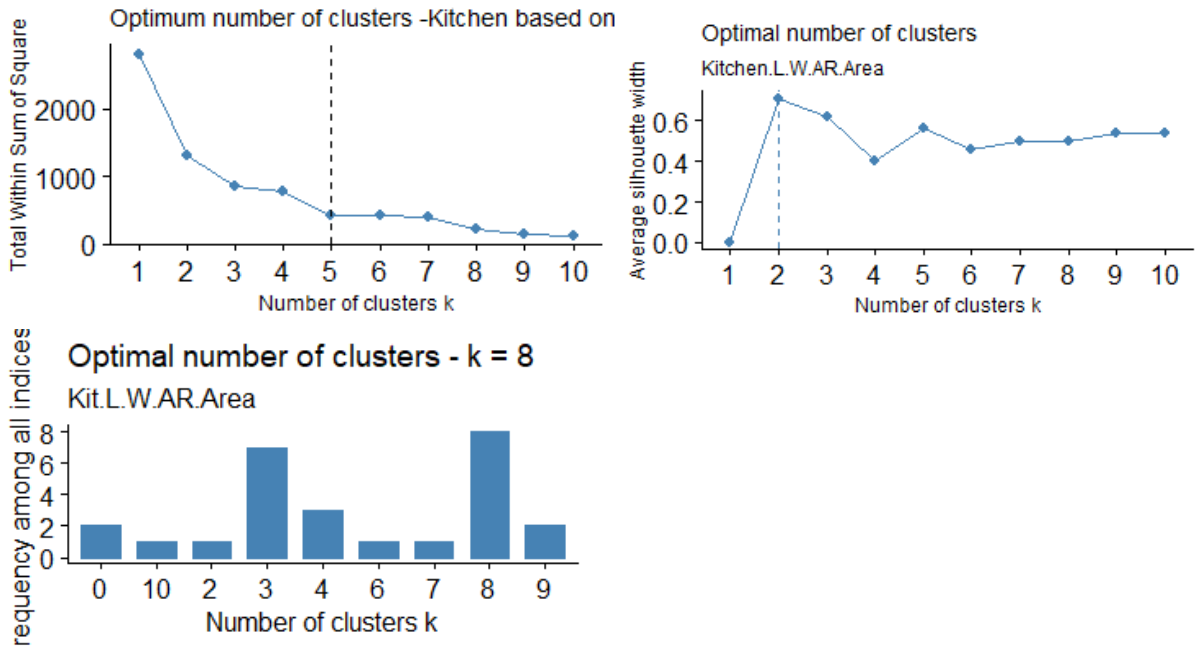


Figure 38- Number of clusters for kitchen- left to right Elbow, Silhouette, Frequency among30 indices methods

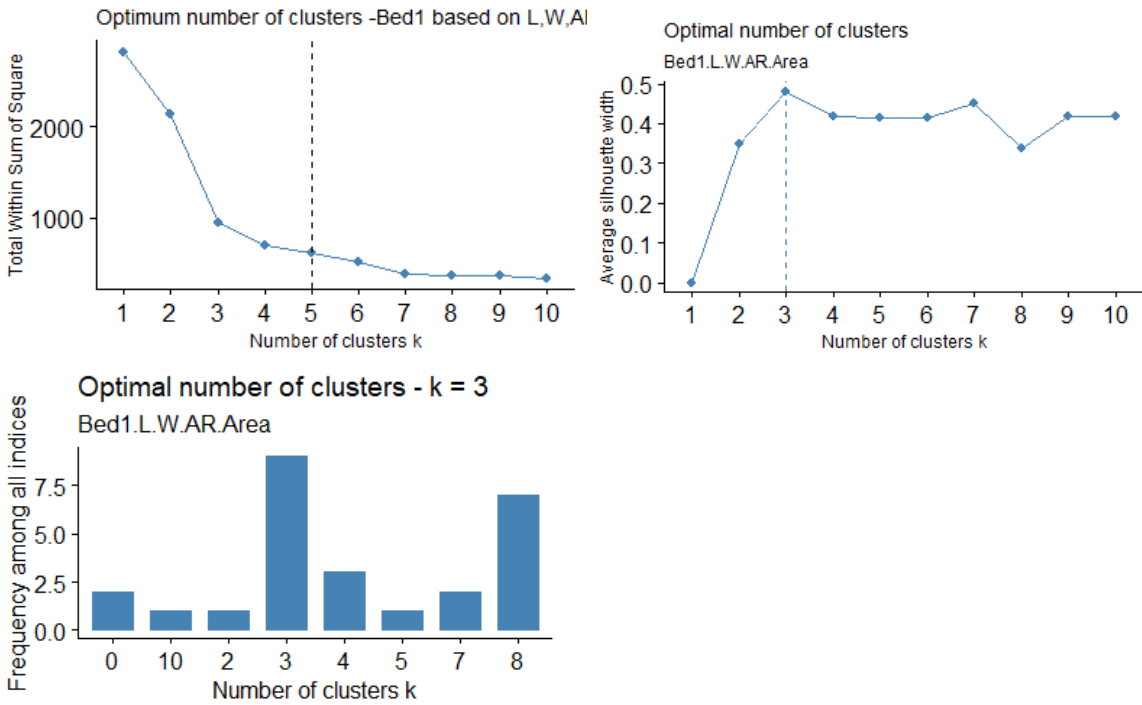


Figure 39- Number of clusters for the main bedroom- left to right Elbow, Silhouette, Frequency among30 indices methods

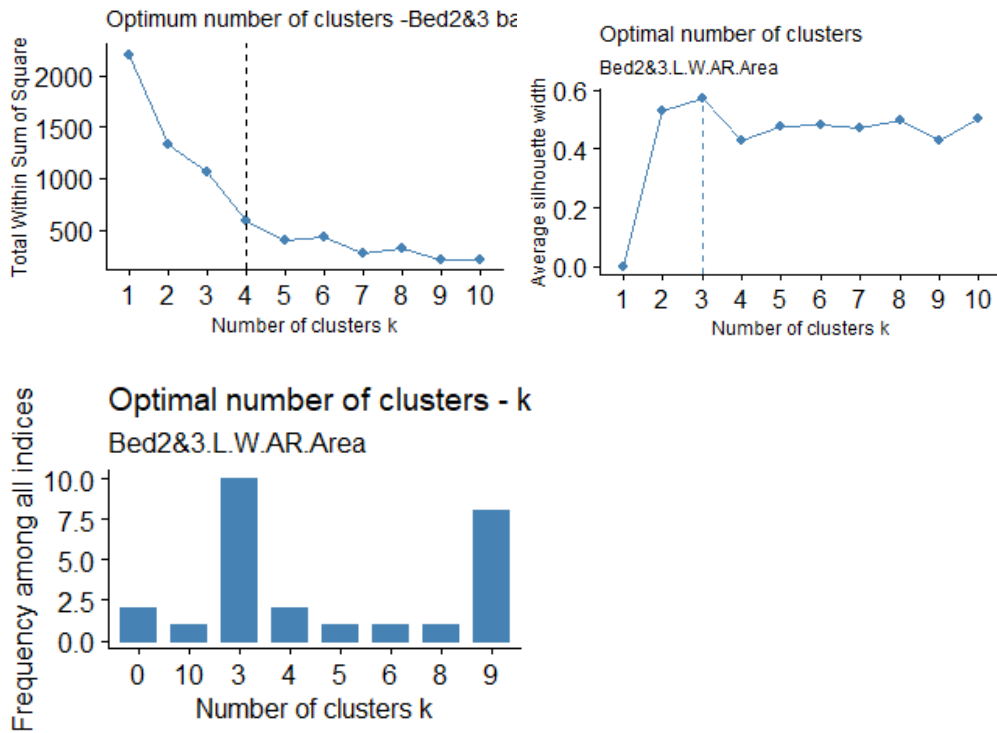


Figure 40- Number of clusters for extra bedroom- left to right Elbow, Silhouette, Frequency among30 indices methods

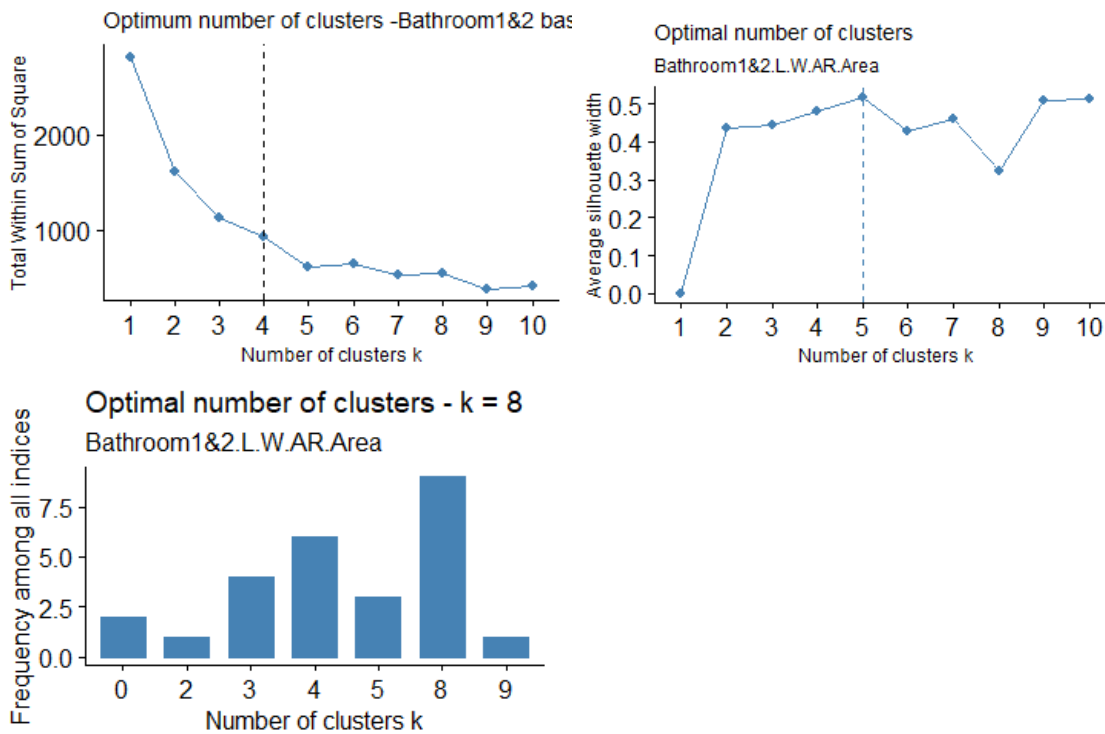


Figure 41- Number of clusters for bathroom- left to right Elbow, Silhouette, Frequency among30 indices methods

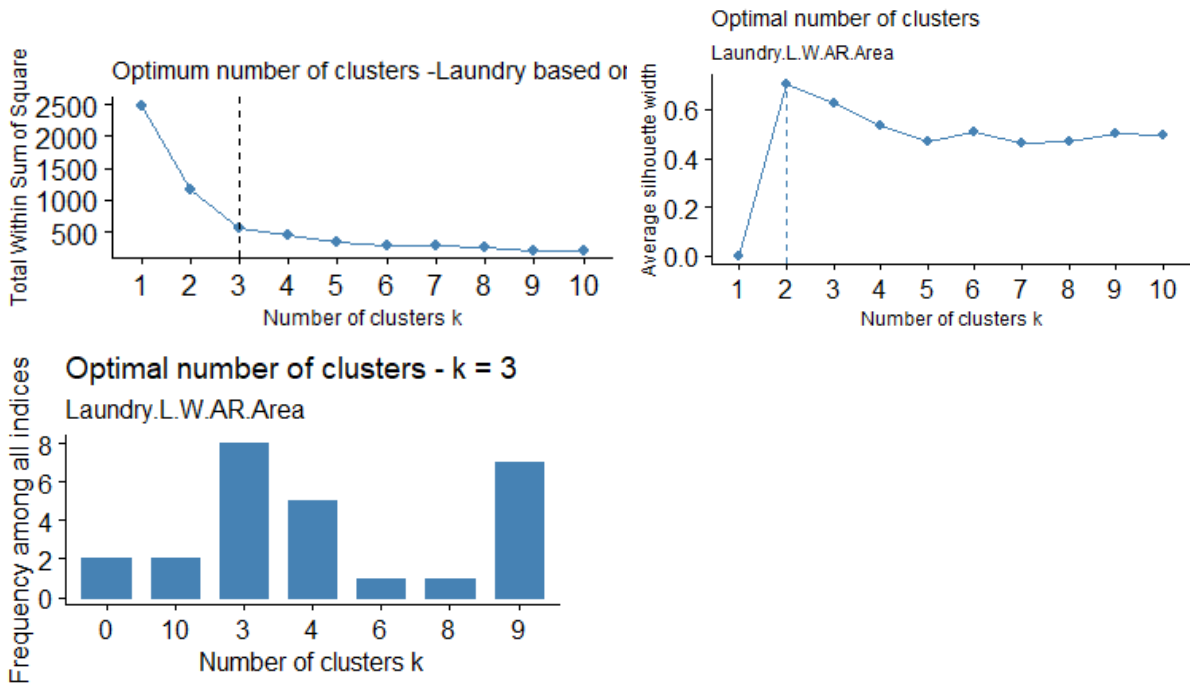


Figure 42- Number of clusters for laundry- left to right Elbow, Silhouette, Frequency among30 indices methods

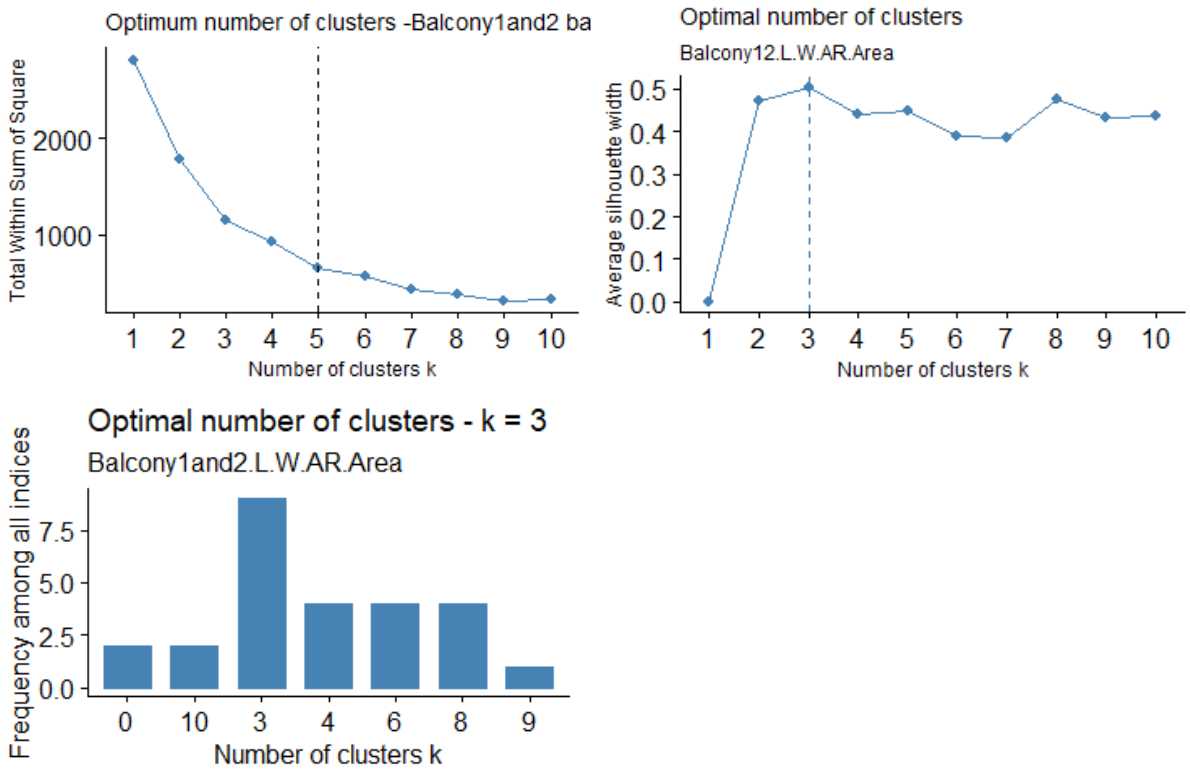
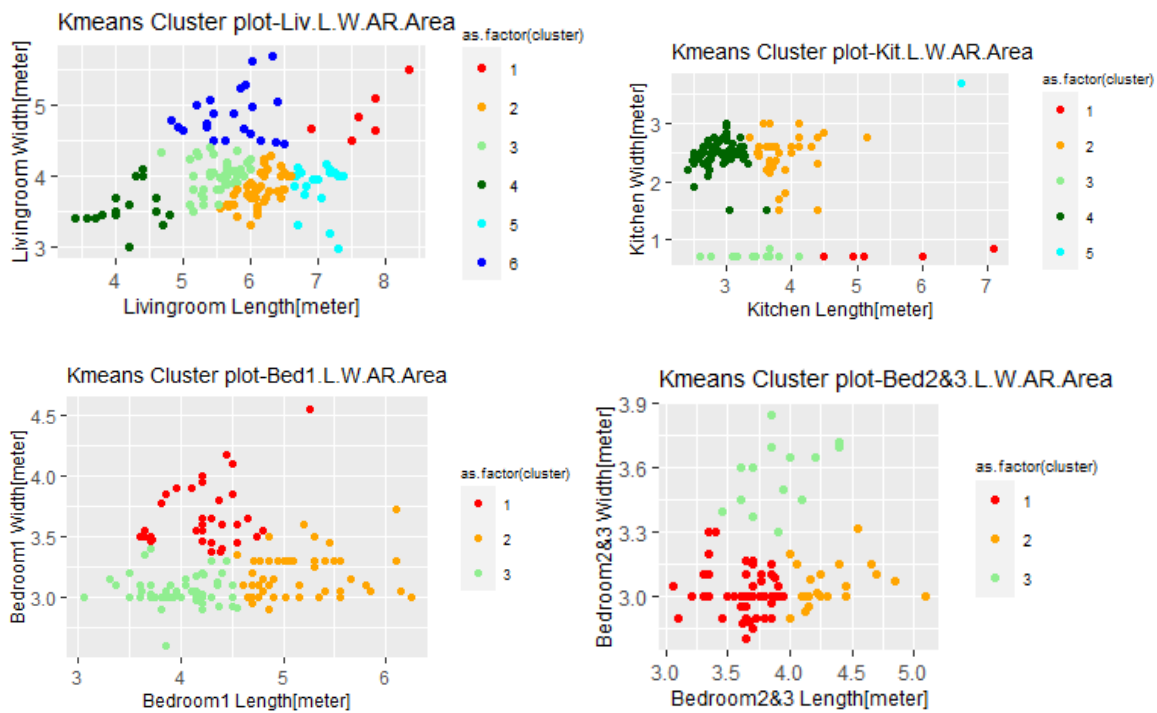


Figure 43- Number of clusters for balcony- left to right Elbow, Silhouette, Frequency among30 indices methods

The cluster analysis was performed based on the number of clusters listed in Table 14. In K-means clustering, after standardisation, the algorithms start randomly selecting K objects from the data set to serve as the initial centres for the clusters. The selected objects are also known as cluster means or centroids. Next, each of the remaining objects is assigned to its closest centroid, where the closest is defined using the Euclidean distance between the object and the cluster mean. After this step, the algorithm computes the new mean value of each cluster. Now that the centres have been recalculated, every object is checked again to see if it might be closer to a different cluster. All the objects are reassigned again using the updated cluster means. The cluster assignment and centroid update steps are iteratively repeated until the cluster assignment stops changing. The algorithm works iteratively to assign each data point to one K groups with the Euclidean measuring distance method. Data points are clustered based on object similarity (Kassambara 2017).

Clusters scatter plots are presented in the following figure. The clustering results, namely size, mean, SD, and cluster validation index (silhouette coefficient), based on the number of K for each spatial void, are listed by spaces in Table 15. The cluster size indicates the number of spatial voids that belong to the cluster. The mean and SD present the most repetitive dimensions and the amount of dataset variation in the corresponding cluster of each spatial void (Kassambara 2017).



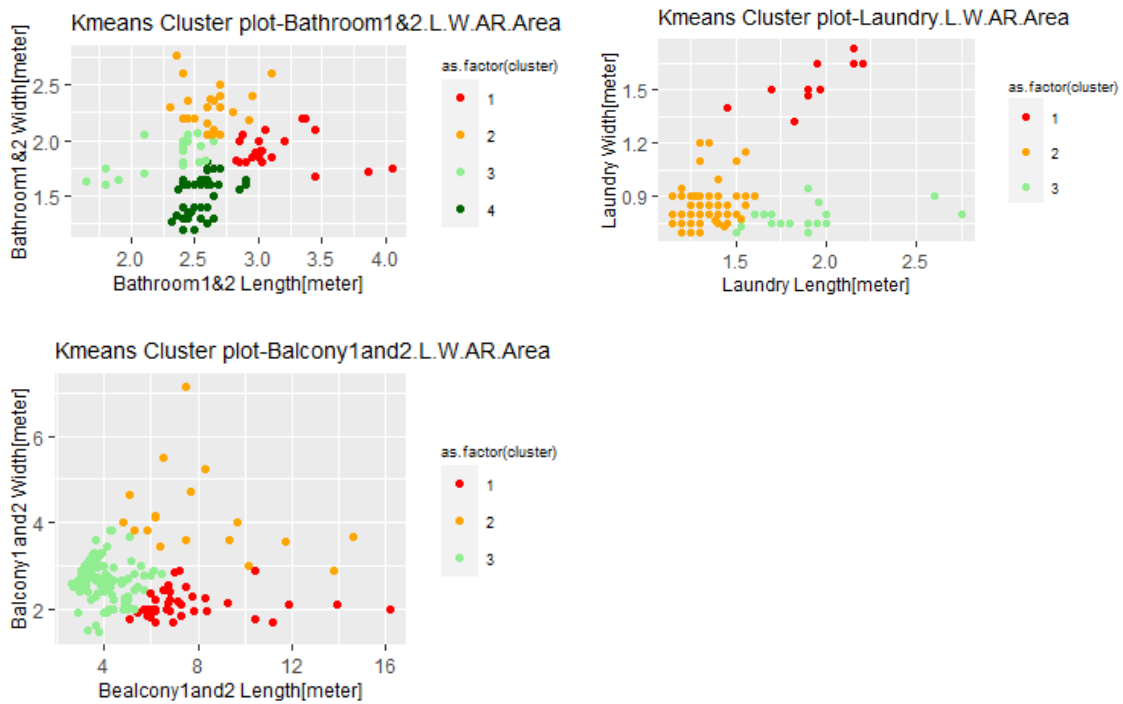
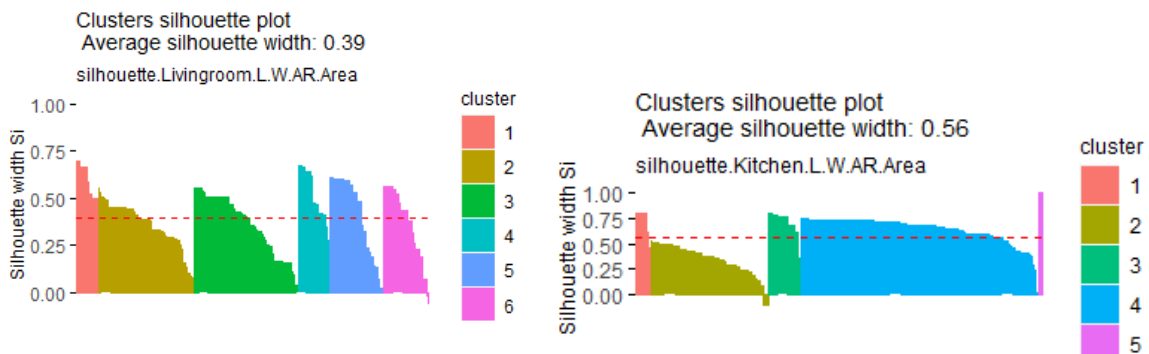


Figure 44- Clusters scatter plots, left to right, living& dining room, kitchen, main bedroom, additional bedroom, bathroom, laundry, balcony

The silhouette coefficient (S_i) is typically utilised to validate clustering. The value of S_i close to 1 indicates that the object is well clustered. On the other hand, a value of S_i close to -1 indicates the objects are poorly clustered (Kassambara 2017). Figure 45 presents the silhouette coefficient of each cluster in each spatial void. By considering the average silhouette width, it can be concluded that the data is well clustered.



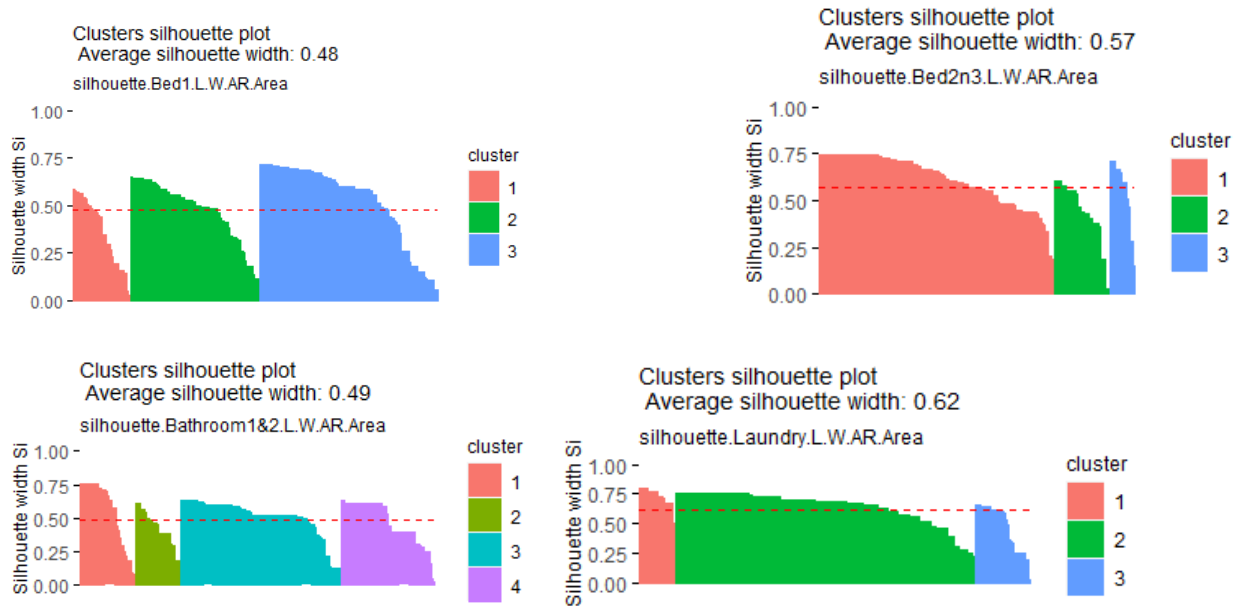


Figure 45- Cluster validation with silhouette index in each spatial void. Left to right living& dining room, kitchen, main bedroom, additional bedroom, bathroom, laundry

One of the main features of the K-means clustering algorithm that this research leverages is the clusters' centroid and SD, corresponding to the mean of points and the range of variation which are assigned to the cluster. Mean, and SD can be used to label data. These features can be applied to specify the probabilistic acceptability of the spatial voids dimensions and modular design patterns. Naturally, the mean of each cluster extracted from the building drawings showed decimal numbers, i.e., non-modular dimensions. However, modular design requires to comply with manufacturing components' dimensions and round up to grid size. Modular building design is a complex interrelationship between architectural design and structural design, i.e., client-driven design and manufacturing efficiency, respectively. One of the main issues of manufacturing efficiency is to determine the panel size since different sizes of components require different setups of the production line equipment. The building design and components should have a grid size to meet the modular design concept. Internationally, a modular dimension of 100 mm has been conceived as one module. However, to increase manufacturing productivity, manufacturers tend to conduct larger sizes for the modular dimension of the panels. In terms of manufacturing and cost efficiency, the larger the modules, the lower the relative transport and manufacturing costs. Parameters such as multiplicity for making spatial voids modules, component manufacturing efficiency, compatibility with the component size currently manufactured, etc., play significant roles in determining grid size. As the suitable grid system differs depending on the nature of the

building components, in this research, 100 mm was conceived as an appropriate grid size to match floor panel size with architectural layout designs. Hence, the clustering results were rounded to 100 mm in Table 15. The data analysis results indicate that two or three clusters in each spatial void include a higher population than the others, which could be considered as a base for spatial voids module dimensions. A schematic view of an apartment plan and the dominant dimension of spatial voids based on cluster analysis results is presented in the next figure.

Data analysis provides simple yet sufficiently generic spatial voids that are applicable to residential buildings. In terms of dimension, the number of alternatives for each space is reduced through clustering, referring to the cluster center, SD, and modular grid size. The cluster analysis is a way of indicating the expected probability of acceptable spatial voids design parameters. Therefore, the layout design is limited to the number of feasible and desirable options designed with spatial void modules. This would benefit production by constraining the variety of spatial voids, which leads to standardisation or modularisation of the apartment structure, i.e., floor panels. Hence, the tasks or work packages needed to build the modular parts of an apartment may turn into standardised.

Table 15- Cluster analysis results sorted separately by spaces

Space	Cluster No	Cluster size	Mean Length - meter	SD (Length)- meter	Mean Width - meter	SD (Width)- meter	Mean Aspect Ratio	SD (Aspect Ratio)	Mean Area - square meter	SD (Area)- square meter	Silhouette coefficient for each cluster	Validation index (Average silhouette)
Living & dining room	1	45	7.4	0.4	4.7	0.2	1.5	0.1	35.1	2.8	0.59	0.39
	2	192	6.2	0.2	3.8	0.2	1.6	0.1	23.8	1.9	0.35	
	3	207	5.5	0.2	4	0.2	1.4	0.1	22.2	1.7	0.36	
	4	62	4.2	0.3	3.6	0.3	1.2	0.1	15	1.8	0.52	
	5	110	7.0	0.2	3.9	0.2	1.8	0.1	27.6	2.0	0.41	
	6	88	5.7	0.4	4.9	0.3	1.2	0.1	28.2	3.2	0.37	
Kitchen	1	26	5.1	0.5	0.7	0.02	7.3	0.5	3.6	0.5	0.72	0.56
	2	203	3.9	0.3	2.4	0.3	1.6	0.3	9.5	1.8	0.34	
	3	56	3.4	0.4	0.7	0.0	4.9	0.6	2.4	0.3	0.69	
	4	412	2.9	0.2	2.5	0.2	1.2	0.1	7.2	0.9	0.64	
	5	7	6.6	0	3.7	0	1.8	0	24.4	0	1	
Main Bedroom	1	111	4.2	0.4	3.7	0.3	1.1	0.1	15.3	1.9	0.36	0.48
	2	249	5.1	0.4	3.2	0.2	1.6	0.1	16.2	1.6	0.47	
	3	344	4	0.3	3.1	0.1	1.3	0.1	12.1	1.1	0.52	
Additional bedroom	1	412	3.6	0.2	3	0.1	1.2	0.1	10.9	0.7	0.61	0.57
	2	98	4.3	0.3	3	0.1	1.4	0.1	13.2	1	0.43	
	3	43	3.9	0.2	3.6	0.1	1.1	0.1	13.85	1.1	0.55	

Bathr oom	1	110	2.6	0.1	2.3	0.1	1.2	0.1	6.2	0.5	0.54	0.49
	2	89	3.1	0.2	2	0.1	1.6	0.1	6.1	0.7	0.42	
	3	320	2.5	0.1	1.6	0.1	1.6	0.1	4	0.4	0.51	
	4	158	2.3	0.2	1.9	0.1	1.2	0.1	4.4	0.6	0.47	
Laund ry	1	59	1.9	0.2	1.6	0.1	1.2	0.1	3	0.4	0.71	.62
	2	478	1.3	0.1	0.8	0.1	1.2	0.2	1.6	0.2	0.64	
	3	86	1.8	.2	0.8	0.05	2.3	0.3	1.3	0.2	0.48	
Study room	1	11	4.1	0.3	2.1	0.3	2.00	0.1	8.4	2.0	0.58	0.51
	2	25	1.9	0.3	1.5	0.2	1.3	0.2	3.1	0.8	0.47	
	3	16	2.3	0.3	1.1	0.2	2	0.2	2.7	0.9	0.59	
	4	54	2.9	0.3	2.2	0.2	1.3	0.2	6.3	1	0.5	
Balco ny	1	152	7.6	2.1	2.1	0.3	3.7	1.0	15.9	4.9	0.41	0.50
	2	65	7.1	2.1	4.1	0.8	1.8	0.7	29.0	8.3	0.31	
	3	487	4.0	1.0	2.7	0.5	1.5	0.4	11	3.1	0.56	



Figure 46- A schematic view of an apartment plan and the dominant dimensions of spatial voids based on the cluster analysis results

This section aimed to specify the spaces that require a higher degree of variety or standardisation. Also, it intended to identify common spatial voids dimensions for each functional space of apartments. The following section aims to meet this research's first objective, i.e., to

identify prevalent design patterns in residential building layouts and systematically assess their manufacturability.

4.3 Analysing manufacturability of layout designs through investigating the capability of prefabricated systems manufacturers (manufacturing perspective)

Modular building design is a complex interrelationship between architectural design and structural design. One of the main concerns of the MC design is to consider the manufacturability of the architectural design. The construction cost can be minimised during the architectural design stage by choosing from different alternatives that suit off-site production. In the conventional approach, however, the structural system is not usually specified until the structural engineer is engaged, which often occurs when the major part of the architectural design is completed. This means that the architect usually does not consider structural component sizes, such as structural walls or floor spans in each building class, that can be optimally manufactured off-site (Roy and Roy 2016) (Benros and Duarte 2009). Moreover, the architect may not have a solid knowledge of the production processes nor the optimisation techniques (Benros and Duarte 2009). The latter is of importance as an architectural floor plan may produce numerous feasible solutions in terms of structural spans and component dimensions. While running an optimisation algorithm may be out of an architect's area of expertise, s/he needs to be provided with fact-based insight into the manufacturability of the architectural plans. This can simultaneously assist with implementing MC in practice and eventually lead to an alternative approach to the conventional design of multistory buildings. Such a fact-based insight is non-existent or requires significant improvement. To fill this gap, in this section, first, in Subsection 4.3.1, the frequency histograms of spans in residential buildings are illustrated to identify the most common patterns in terms of horizontal and vertical design, i.e., floor plan and the number of floors. Then, in Subsection 4.3.2, Australia's manufacturing design guides of some predominant residential building systems, including Precast Solid Slab (PSS), Autoclaved Aerated Concrete (AAC), Hollowcore, and Cross Laminated Timber (CLT), are compared to investigate the capability of the manufacturers and the manufacturability of existing designs. This subsection aims to meet the research's first objective, i.e., recognising the manufacturability of apartment layout designs. In Subsections 4.3.3 and 4.3.4, span patterns regarding architectural floor and vertical design are specified through cluster analysis. These subsections intend to identify modular design scenarios and finding patterns based on recognising the manufacturability of layout design and similarities of architectural design. Finally, in

Subsection 4.3.5, data analysis validation and contribution to MC in the residential building industry are discussed.

4.3.1 Apartments' spans analysis

This research endeavours to find some modular design scenarios that provide a degree of standardisation for structural spans by identifying similarities of apartments' architectural design derived from building drawings. In structural engineering and architecture, span is the term given to the length of a structural component –floor panels in this research, that extends between two supports, that is, structural wall and column. Hence, a structural floor panel may be supported at either end, in which case it is said to span between the two points. A general engineering principle is the longer the span, the deeper the structural floor panel will have to be to safely to support the dead and live load (CCAA 2003). Thus, span plays a key role in structural and architectural design. First, the cost of structure highly depends on the span, determinative of structural dimensions. Second, it may limit the architectural design if it is not determined in an appropriate size. In general, the longer the structural span, the more freedom will be provided to architectural design, like open-plan dwelling design (CIA 2009). Hence, the main characteristics of architectural design that may affect structural span have been considered in this thesis. The apartments' architectural characteristics, including apartments spanning direction dimensions (SDD), apartments spans, apartments lengths or widths, number of bedrooms, and the number of building floors, were coded and recorded in a spreadsheet to be prepared for analysing. Some of these characteristics and the related measuring approach are illustrated in the following figure.

Spanning direction dimension is the dimension of either apartment width or length that the structural span was designed. The spanning direction dimension may consist of one or more spans. Whether the span is aligned with the apartment width or length, spanning direction dimension corresponds to either apartment width or length. The structural floor panel width of a building is usually a fixed size in prefabricated systems, while floor panel length, which is represented as a span, is usually considered a variable due to a wide variety of design requirements. Statistical analysis and a clustering technique were utilised to perform data analysis.



Figure 47 -Illustration of building spans

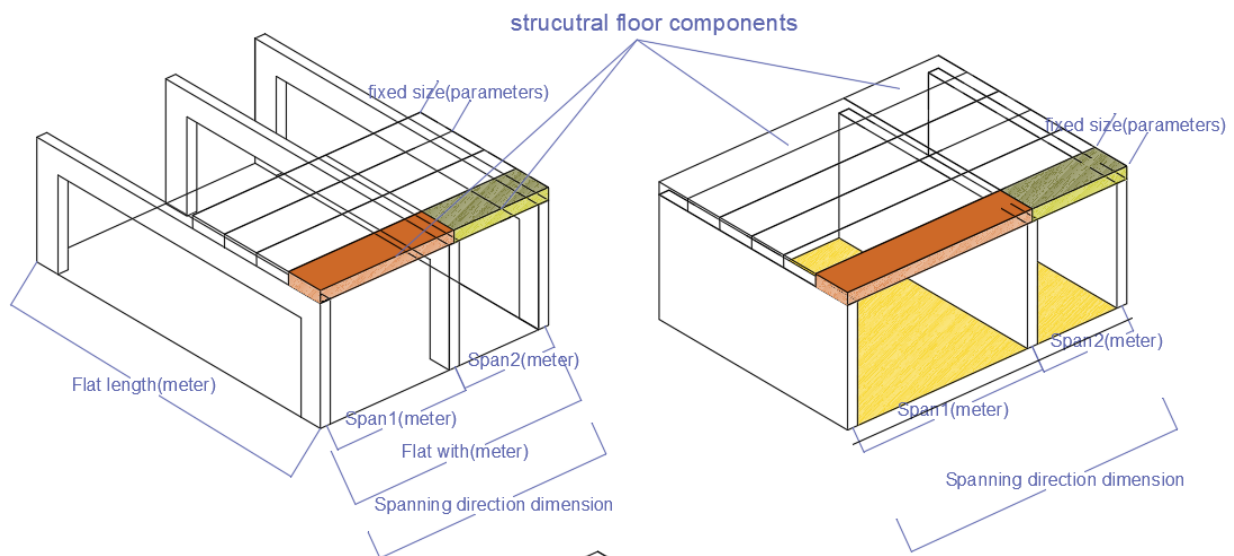


Figure 48- Illustration of apartment variables and indicating how they measured

Based on engineering rules of thumb, the span should be extended within the shorter side of buildings/ apartments to minimise the building structure cost (Caprani 2010; Sharafi et al. 2015). Nevertheless, this rule would not always be taken into account in all buildings or apartments due to the architectural and structural design complicated interrelationships. The following histogram illustrates spanning directions frequencies aligned with either the length or width of the apartment.

The histogram indicates that most of the designed spans extend in the transverse direction of apartments. By considering the average land size and spanning direction of apartments, attached in Appendix B, it can be inferred that apartments with spans aligned with their longitudinal direction possess larger land sizes and longer building frontage. It appears that apartments designed within a wide building frontage are usually extended along the building façade to maximise the natural lighting availability through openings (windows) and to create differentiation in terms of façade design. Hence, spreading load-bearing walls or wide columns along the frontage is generally prevented. Also, the size of the land is one of the criteria for the total number of building floors. Taller residential buildings are usually built in large lots, and the complexity of structural design is prevalent in this class of buildings.

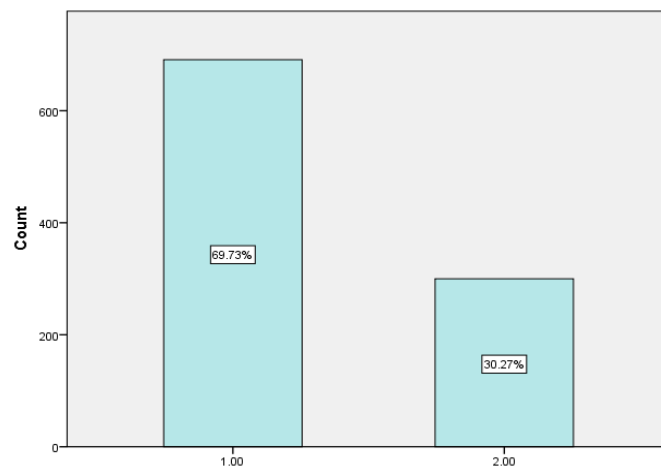


Figure 49- transverse (1) or longitudinal (2) arrangement of spans

Diverse architectural and structural design requisites contribute to a broad spectrum of spans, as depicted in the upper-left histogram in the subsequent figure. The succeeding normal distribution histograms reveal that the majority (68%) of spanning direction dimensions within apartment units are designed to fall between 6.3 and 10.5 meters. Concurrently, the planned spans exhibit dispersion across the range of 4.4 to 7.4 meters. This dimensional range can be regarded as the prevailing spans or floor panel sizes prevalent in the realm of residential building construction. Notably, 95% of the designed spans range from 2.9 to 8.8 meters. Apartments featuring spanning direction dimensions approximately less than 7.5 meters typically incorporate a single span, approximately equal to the dimension of the spanning direction. Conversely, apartments with spanning direction dimensions exceeding 7.5 meters encompass two or more spans.

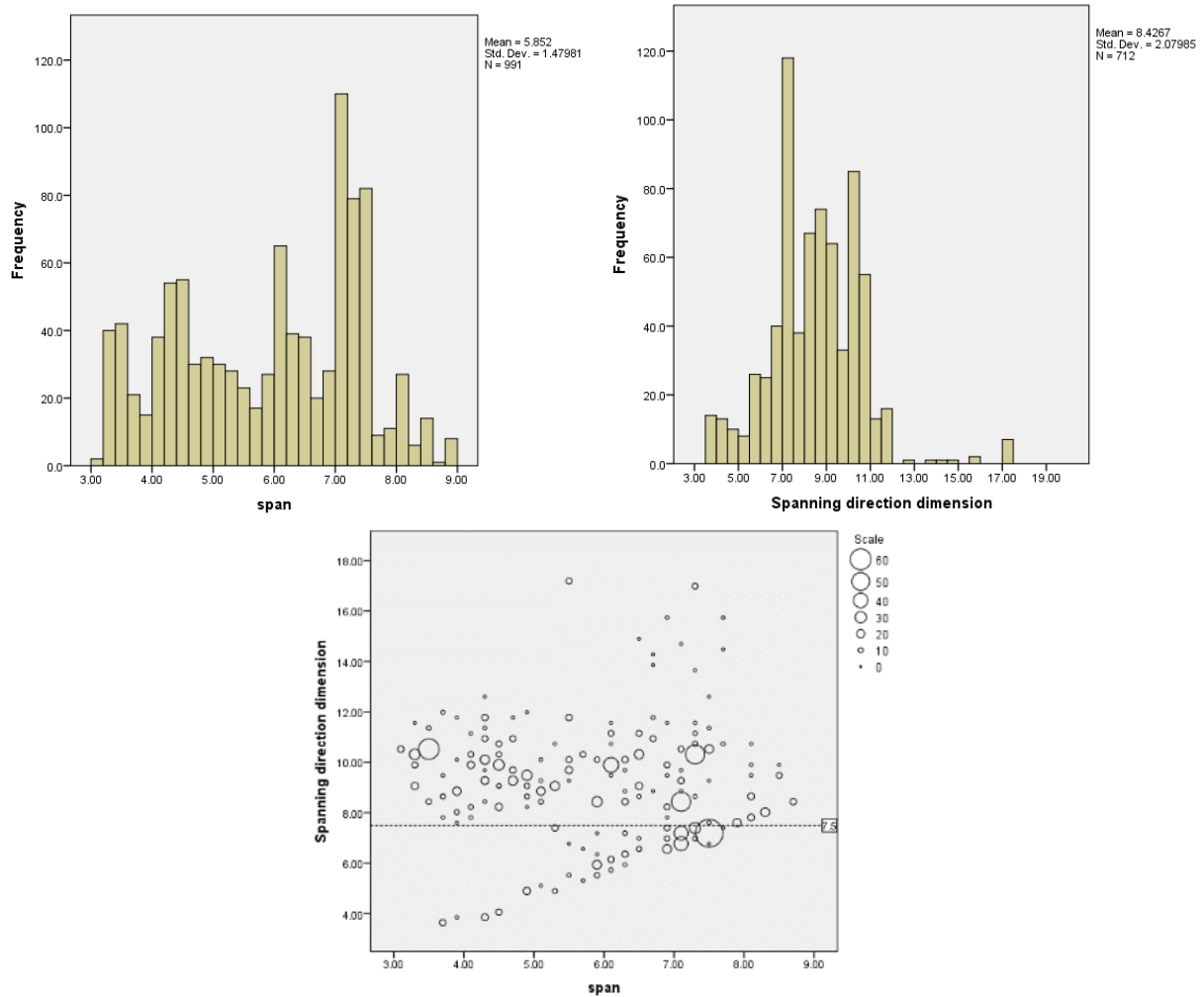


Figure 50- Apartments' spans and spanning direction dimension distributions

4.3.2 Component manufacturing practices in Australia

MC demands compromise. In other words, not all notational customisation options are being offered, but only those that are consistent with the capabilities of the production processes, the given product architecture, and the given degree of variety (Piroozfar and Piller 2013; Salvador et al. 2009). This part provides information about the capabilities of the production processes, i.e., the manufacturability of the designed spans based on the real practice of component manufacturing. Therefore, the range of spans that could be manufactured in different prefabricated systems has been examined. National construction code- volume one (NCC, 2019), which is the prevalent building code for multi-storey residential buildings in Australia, does not specify prefabricated construction approaches. It has dealt with masonry, concrete construction (reinforced and prestressed concrete), steel construction, and timber. Thus, this section refers to each factory's practical design and manufacturing guides to find a range of manufacturable panel sizes and,

accordingly, manufacturable layout designs. As spans are representative of floor panel longitudinal sizes, the constructability of design (spans) could be checked based on the manufacturers' capability. As panelised systems have been considered suitable modular elements for multi-storey residential buildings in the literature section, the typical prefabricated panel sizes of some well-known manufacturers in Australia are presented in Table 15. These systems include precast concrete slabs, autoclaved aerated concrete floors, hollowcore slabs, CLT panels. These structural systems are the predominant residential building systems in Australia (CIA 2009) (CCAA 2003). This information has been extracted from the Australian manufacturers' manuals and initial design guides. Although most companies declare that they can fabricate panels at any size (length, width, and thickness), the size of panels must be compatible with transport, optimal structural performance, local access, and installation constraints.

In practice, the panel width is typically limited between 0.6 and 4.2 meters since the standard dimensions of the truck used to transport the element to the construction site are 12.3 meters long, 2.5 meters wide, and 4.3 meters high. Payload either wider or/and higher than 2.4 and 4.2, respectively, requires one pilot vehicle with some special arrangement. Therefore, the maximum floor panel width in Table 16 is limited to the abovementioned dimensions. The optimal structural performance also limits the panel length to the maximum panel span. The maximum span is the maximum structural capacity of the panels regarding the serviceability requirements (deflection and vibration) without utilising any auxiliary components, which leads to a manufacturable design and a relatively economical structure (Sharafi et al. 2017). The maximum structural capacity of the panels was considered based on the common loads in mid-rise residential buildings, i.e., 2 Kpa live-load and 0.0 Kpa superimposed dead load. The maximum span is presented in maximum floor panel length and minimum panel thickness. Hence, the maximum panel length and minimum panel thickness are the optimal practice in terms of structural performance and material usage. For example, based on Xlam design guide, the maximum structural capacity of panels with common load in mid-rise residential buildings is provided with a floor panel of 7.300 meters in length and 0.315 meters in thickness. Although the given panel thickness is applicable for spans smaller than 7.300 meters, it is not optimal or economical regarding the amount of material used to bear the imposed loads (live- and dead-load).

Table 16- Maximum span of panelised system regarding the maximum panel length, the common panel width, and the minimum panel thickness in meters for mid-rise residential buildings

Company	Components	Maximum Panel Length (meters)	Panel Width (meters)	Minimum Panel Thickness (meters)
---------	------------	-------------------------------	----------------------	----------------------------------

Austral precast (Australprecast 2021)	Precast solid floor (slab)	4.000	1.200	0.100
	Austral floor deck (Single)	3.500,4.00,4.500,5.000,5.500,6.000,6.700,7.750	2.400	0.150,0.175,0.200,0.225,0.250,0.275,0.300,0.350
Hebel (Hebel 2010)	Autoclaved aerated concrete floor	4.200, 4.500, 5.100, 5.500, 6.000	0.600	0.150,0.175,0.200,0.225,0.250
Hollow-core concrete (HollowcoreConcrete 2018) (CCAA 2003)	Hollow core floor	10.000, 11.000,14.000	1.200	0.205,0.220,0.300
	Mini slab(floor)	2.500,3500,4.500,5.500	1.200	0.095,0.115,0.135, 0.150
Xlam (XLam 2017)	CLT floor	2.800,3.400, 3.800,4.200,4.400,4.600,4.900,5.300,5.600,5.800,6.100,6.200,6.700,6.800,7.100, 7.300,	0.900,1.000,1.200,2.400,2.700, 3.000,3.500,4.000,4.200	0.085, 0.105,0.115,0.125,0.135,0.145,0.160,0.175,0.195,0.205,0.225,0.245,0.265,0.275,0.295,0.315
	CLT cantilever floor	1.600, 1.900, 2.000, 2.200, 2.300, 2.300,2.400, 2.600, 2.700, 2.800, 2.900, 3.000, 3.200, 3.400, 3.400	0.900,1.000,1.200	0.085,0.105,0.115,0.125,0.135,0.145,0.160,0.175,0.195,0.205,0.225,0.245,0.265,0.275,0.295,0.315
Cross Lam (Downing 2016)	CLT floor	3.250,3.700,4.480,5.150,5.600,6.440,6.630, 7.600	2.400, 3.000	0.087,0.105,0.139,0.175,0.191,0.245,0.243,0.315
Note: The maximum structural capacity of the panels was considered based on the common loads in mid-rise residential buildings, i.e., 2 Kpa live-load and 0.0 Kpa superimposed dead load. Superimposed deal load may include weights imposed by mechanical equipment (such as heating, ventilation, and air conditioning systems), services piping, ductworks, building greeneries, and solar panels.				

To assess the manufacturability of the architectural designs, the apartment span distribution in the previous figure has been transformed into a normal distribution histogram in the subsequent figure. As previously mentioned, aligned with the normal distribution histograms in the following figure, the majority of the designed spans are dispersed within the range of 4.4 to 7.4 meters. This range of dimensions is indicative of the most prevalent spans or floor panel sizes within the realm of residential building construction. Additionally, approximately 95% of the designed spans fall between 2.9 to 8.8 meters. Furthermore, within the histogram, the minimum and maximum span for each prefabricated system are highlighted. As an illustrative instance of assessing the manufacturability of architectural design practices, the subsequent histogram suggests that CLT manufacturers (Xlam and Crosslam) could viably accommodate 68% of the total typical spans

prevalent in residential building design, as per the normal distribution histogram. However, it should be noted that these manufacturers lack the capacity to produce the entirety of the designed spans (95%) without supplementary components. This limitation stems from the system's economic feasibility being constrained for spans exceeding 7.6 meters. Similar interpretations can be extrapolated for other prefabricated systems as well.

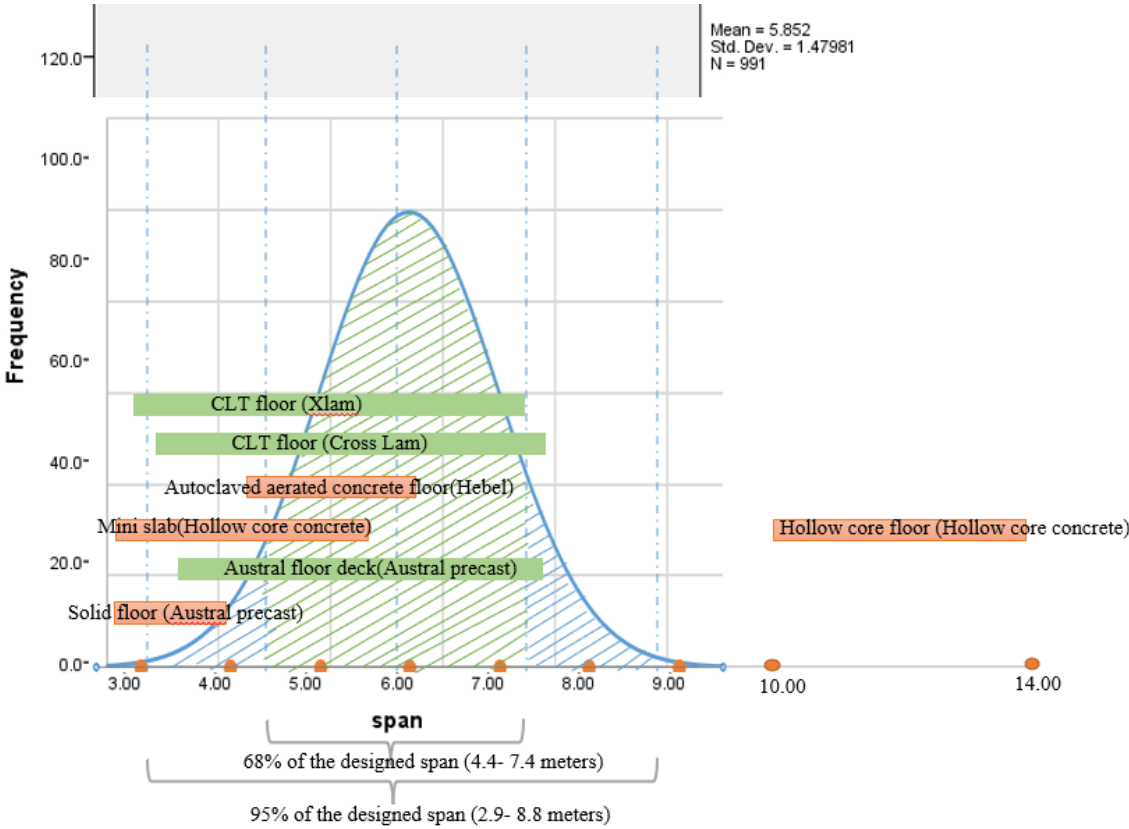


Figure 51- Manufacturability of spans in different prefabricated systems

The following table provides good information to architects who are looking to improve the manufacturability of their designs. Also, it is beneficial for manufacturers who intend to either extend their production line to cover all customised designs or focus on producing the most demanded panel sizes with respect to the existing designed span to implement a degree of standardisation. This thesis aims to provide insight to architects to improve the manufacturability of design and equip the manufacturer with the design pattern in order to take one step towards modular /MC design.

Table 17- The details of the manufacturability of spans in different prefabricated systems

Company	Components	68% of the designed span, according to Figure 50, 51: (4.4 to 7.4 meters)	95% of the designed span, according to Figure 50, 51: (2.9-8.8 meters)
---------	------------	---	--

Austral precast	Precast solid floor (slab)	No	No
	Austral floor deck	Yes	No
Hebel	Autoclaved aerated concrete floor	No	No
Hollow-core concrete	Hollow core floor	No (spans shorter than 5 meters are not economical)	No (spans shorter than 5 meters are not economical)
	Mini slab (floor)	No	No
Xlam	CLT floor	Yes	No
Cross Lam	CLT floor	Yes	No

This subsection intended to recognise the manufacturability of apartment layout designs. The following subsections, i.e., 4.3.3 and 4.3.4, aim to identify modular design scenarios and find patterns based on recognising the manufacturability of layout design and similarities of architectural design.

4.3.3 Recognising modular design patterns in architectural floor plans through cluster analysis

Identifying similarities in the architectural design of different apartments can be considered as a means to find a pattern for apartments' modular designs offered to different clients. Achieving this objective is based on the fact that the MC approach does not mean that an infinite number of options have to be offered. Rather, in a tailor-made dwelling, an appropriate number of options can be sufficient. An infinite number of options is the other extreme of demand-side satisfaction. This approach includes a lot of waste, that imposes a high price will be presented to the demand-side. In other words, MC demands compromise, i.e., not all notational customisation options are being offered, but only those that are consistent with the capabilities of the production processes, and the given degree of variety.

Different architectural and structural designs lead to a wide variety of spans and panel sizes, which is indicated in Figure 50. A wide range of component sizes causes inefficient production and implementation on the factory floor and construction site. Hence, by recognising patterns of structural spans in architectural designs, the number of options is limited to the manufacturable spans in this section. Considering the span patterns in architectural design building, either horizontally or vertically, could be beneficial for both architects and manufacturers to investigate the most repetitive spans and frequent spanning direction dimensions to enhance the repeatability of design and manufacturing. The main objective of this and the following subsections is to specify

common structural spans based on buildings' horizontal (i.e., apartment floor) and vertical design. In other words, these subsections identify modular design scenarios and finding patterns based on recognising the manufacturability of layout design and similarities of architectural design. Similar to what was carried out in section 4.3.2, K-means clustering groups architectural and structural characteristics to limit options in a wide spectrum of designs and increase repeatability. The optimal number of clusters (K) was determined by the frequency of the (K) proposed by Elbow, Average silhouette, and Frequency among 30 indices methods. The median was selected when each of those methods proposed a different number of clusters. The number of clusters proposed by each method is indicated in Appendix C.

Clustering has been performed with three approaches: (i) without considering the apartment architectural layout, (ii) considering the apartment architectural layout, and (iii) considering the vertical design of buildings. The first two approaches are discussed in this section, whereas the third approach is explained in the next section.

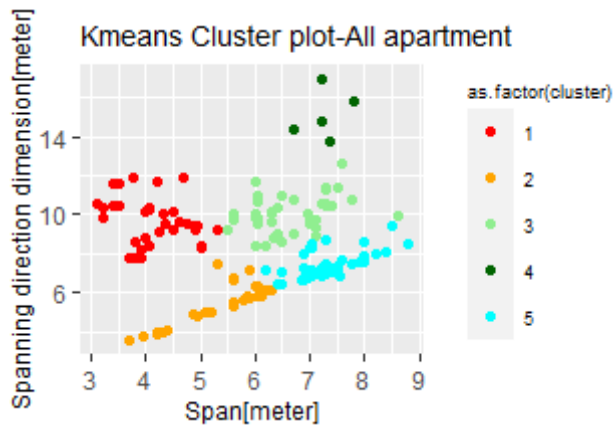


Figure 52- Cluster scatter plots regarding span and spanning direction dimensions

Initially, cluster analysis was conducted without factoring in the architectural layout of apartments. The analysis was based on two primary variables—span length and spanning direction dimensions—for all apartments. The core objective of this clustering was to identify the prevalent spans across all apartment designs, irrespective of their specific types. As a result, five distinct clusters were identified and visualised in Figure 52. The subsequent table presents the cluster centers, revealing dominant spans of 7.3, 6.6, 5.2, and 4.1 meters. By scrutinising the spanning direction dimension (SDD), which signifies the side along which spans are situated, it becomes apparent that two spans, namely 4.1 and 6.6 meters, constitute this spanning direction. In contrast, sides with spanning directions shorter than 7.5 meters encompass a single span. Independent of any

architectural design considerations, architects could deem dimensions such as 7.3, 6.6, 5.2, and 4.1 meters as the most prevalent spans within any apartment architectural layout. Simultaneously, manufacturers could concentrate their efforts on optimising the production process for generating fully modularised or partially standardised components.

Table 18- The dominant spans and spanning direction dimensions in apartments design

Cluster Size	Span	SD	SDD	SD	Cluster validation (silhouette)
163	4.1	0.6	9.7	0.9	0.52
99	5.2	0.8	5.3	1.1	0.45
162	6.6	0.6	9.9	0.9	0.41
12	7.2	0.3	16.1	1.2	0.75
271	7.3	0.5	7.5	0.7	0.56

Finding patterns based on apartment architectural layouts could also be advantageous for architects and manufacturers to consider those patterns as modular designs. In other words, on the one hand, architects could perform modular design by understanding the span of each architectural layout. The modular design scenario helps to increase off-site and on-site production efficiency. On the other hand, manufacturers tend to produce the most market-demanded panel sizes in order to implement a degree of standardisation by considering the architectural layout of apartments.

The configuration of the whole apartment layout is out of the scope of this research. In other words, in terms of architectural design, the spanning direction dimension is the main factor that affects the floor panel sizes and span. Therefore, the focus of this section is placed on spatial voids arrangement aligned with the spanning direction. The following figure presents the schematic view of the existing arrangement of spatial voids in apartments spanning directions. Therefore, ten identified arrangements of spaces were coded (Table 19) to analyse the frequency of each design pattern and specify the most demanded panel sizes.

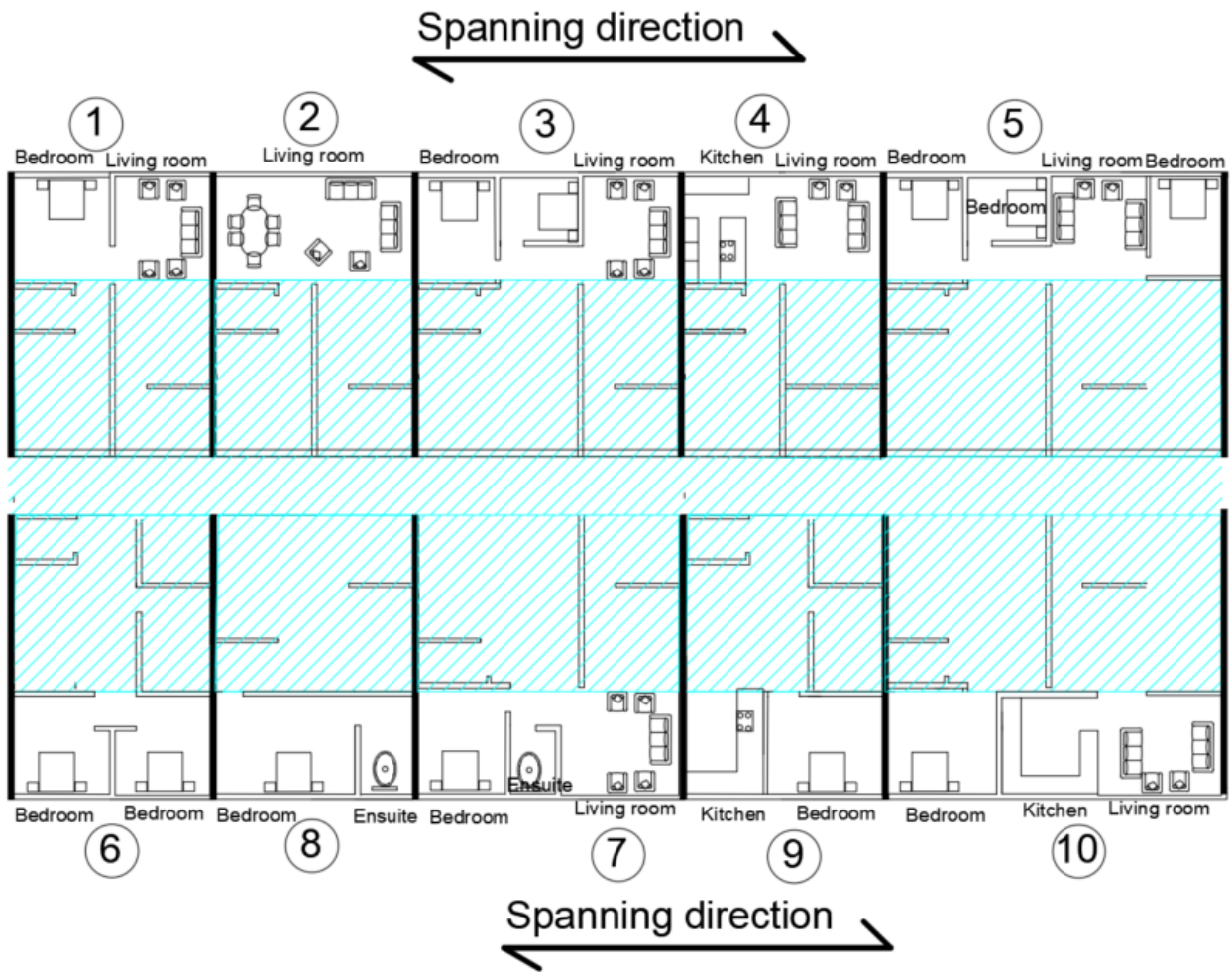


Figure 53- Schematic view of the existing arrangements of spaces in the span direction side of apartments

Table 19- Spatial voids layout or arrangement aligned with spanning direction

No	Abbreviation	Descriptions
1	BL	A bedroom and living room are placed in the spanning direction.
2	L	A living room is placed in the spanning direction.
3	LBB	A living room with two bedrooms are placed in the spanning direction.
4	LK	A living room and a kitchen are placed in the spanning direction.
5	BBBL	Three bedrooms with one livingroom are placed in the spanning direction
6	BB	Two bedrooms are placed in the spanning direction.
7	BEL	A bedroom, an ensuite/bathroom, and a living room are placed in the spanning direction.
8	BE	A bedroom and and ensuite/bathroom are placed in the spanning direction.
9	BKL	A bedroom, kitchen, and living room are placed in the spanning direction.
10	BK	A bedroom and kitchen are placed in the spanning direction.
L: Living room B: Bedroom K: Kitchen		E: Ensuite/Bathroom

Among the layout patterns in the spanning direction side as outlined in Table 19, BL (a bedroom and living room), L (a living room), and LBB (a living room with two bedrooms) emerge as the most repetitive arrangements of spatial voids on the spanning direction side. To illustrate, these prevalent spatial void arrangements are investigated to establish a relationship between apartment layout and span through clustering analysis. The optimal number of clusters and the resulting clustering outcomes are presented in Tables 20 and 21 respectively. The clustering outcomes in Table 21 encompass the cluster center, SD, and cluster validation. The clustering outcomes in Table 21 demonstrate that each spatial void arrangement is associated with two or three typical structural spans. Notably, the predominant span clusters differ from one apartment layout (i.e., spatial void arrangement) to another. In the first apartment layout group, the most common span cluster is 7.2 meters, whereas the second and third groups encompass spans of dimensions 6.1 and 4.3 meters respectively.

As indicated in Table 21, the results can be categorised into three scenarios:

(i) In the first scenario, which encompasses the largest clusters in the BL and L spatial void arrangements, the spans closely align with the spanning direction dimensions, deviating only by 10 to 20 centimeters. This discrepancy can be attributed to measurement errors. For instance, in layouts like BL, the span measures 7.2 meters, while the spanning direction dimension is 7.1 meters.

(ii) The second scenario entails spans significantly longer than the spanning direction dimensions. In this case, a combination of two spans forms the spanning direction. For instance, in layouts labeled as BL, the 4.2 and 6.2 spans collectively form a spanning direction with dimensions ranging from 9.3 to 10.1 meters.

(iii) The third scenario, observed in a few clusters, comprises spans that do not fit within the first two scenarios. A closer examination of apartment architectural designs for these spans reveals that some apartment floors are cantilevered. This design choice is influenced by two factors: (a) the presence of apartment balconies and (b) the positioning of apartments on the top levels of buildings. These factors exert less stress on the building and apartment structures, allowing certain apartment slabs to be cantilevered. Consequently, in cases such as LBB, the spanning direction dimensions exceed the spans by 2.7 meters.

Drawing from the clustering outcomes in Table 21, Figure 55 offers a schematic representation of the modular design scenarios based on architectural design similarities.

Table 20- Optimal number of clusters in analysing data based on the apartments architectural layouts design

Method	Elbow method	Average silhouette	Frequency among 30 indices	Number of final clusters
L	4	4	5	4
BL	5	8	4	5
LBB	5	5	3	5

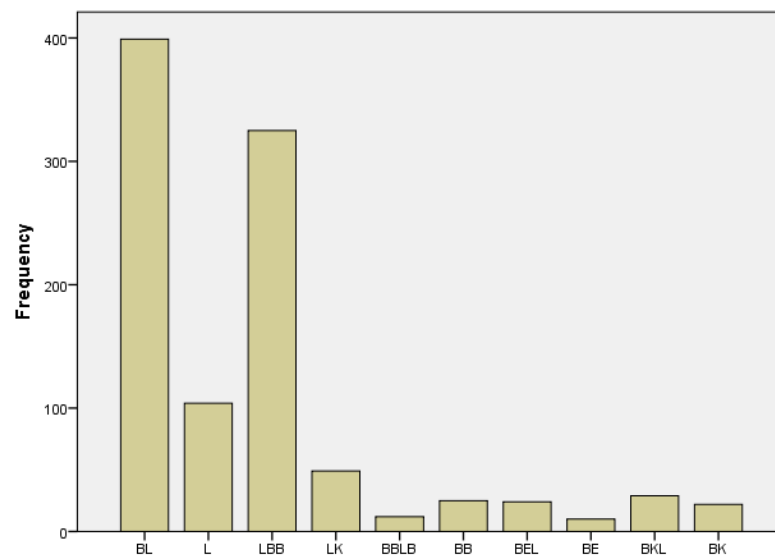


Figure 54- Frequency of spatial voids arrangement aligned with apartments spanning direction

Table 21- The dominant spans and spanning direction dimensions patterns in apartments regarding the architectural layout

Apartment spatial voids arrangement Cluster No	BL						L						LBB								
	Size	Span (meters)	SD	Spanning direction dimension (meters)	SD	Cluster validation (silhouette)	Average silhouette	Size	Span (meters)	SD	Spanning direction dimension (meters)	SD	Cluster validation (silhouette)	Average silhouette	Size	Span (meters)	SD	Spanning direction dimension (meters)	SD	Cluster validation (silhouette)	Average silhouette
1	64	4.2	0.6	9.3	1.1	0.43	0.61	1	8.9	0	9.9	0	0	0.68	15	5.4	0.1	9.6	0.4	0.7	0.61
2	120	7.2	0.2	7.1	0.2	0.7		41	6.1	0.3	6	0.3	0.63		41	4.3	0.2	10.5	0.8	0.44	
3	52	6.2	0.5	10.1	0.4	0.5		18	5.1	0.2	4.9	0.2	0.72		17	7.0	0.4	7.1	0.2	0.62	
4	88	7.6	0.3	7.8	0.3	0.59		27	4.1	0.3	3.9	0.2	0.69		34	5.9	0.3	8.6	0.4	0.64	
5	7	7.2	0	17	0	1									21	6.6	0.3	10.8	0.2	0.78	



Figure 55- A schematic view modular design scenario based on recognising the manufacturability of layout design and finding a pattern according to the similarities of architectural design

4.3.4 Recognising modular design patterns considering the building vertical design (floor levels)

The preceding section identifies the modular design patterns within architectural floor plans. This section aims to recognize modular designs based on pattern recognition between different floor levels. Since span dimensions are greatly influenced by the building load and the number of floors, the buildings were classified into three distinct categories to ensure reliable clustering. This classification process was carried out through multiple trial and error iterations, taking into account the quality of clusters measured by the silhouette measure of cohesion and separation analysis. Ultimately, buildings with fewer than six floors, those with six to ten floors, and those with more than ten floors were respectively assigned to Class 1, Class 2, and Class 3. The apartment span dimension histogram for each building class is depicted in the subsequent figure. The mean span length within Class 1 is the shortest, measuring at 5.4 meters. While the mean span length of Class 3 is shorter than that of Class 2, it isn't conclusive that Class 3 inherently possesses shorter spans. Nevertheless, due to its larger standard deviation, it can be inferred that Class 3 exhibits a broader range of spans. To put it differently, the histogram reveals that apartments within this class are characterised by a combination of short spans (approximately 3.2-3.8 meters) and long spans (almost 7.2-7.6 meters). This observation is also supported by the scatter plot in Figure 56. Notably, the prominent points in the scatter plot highlight that the spanning direction dimensions of buildings in Class 3 exceed 10 meters. As a result, a majority of apartments in this class encompass two spans.

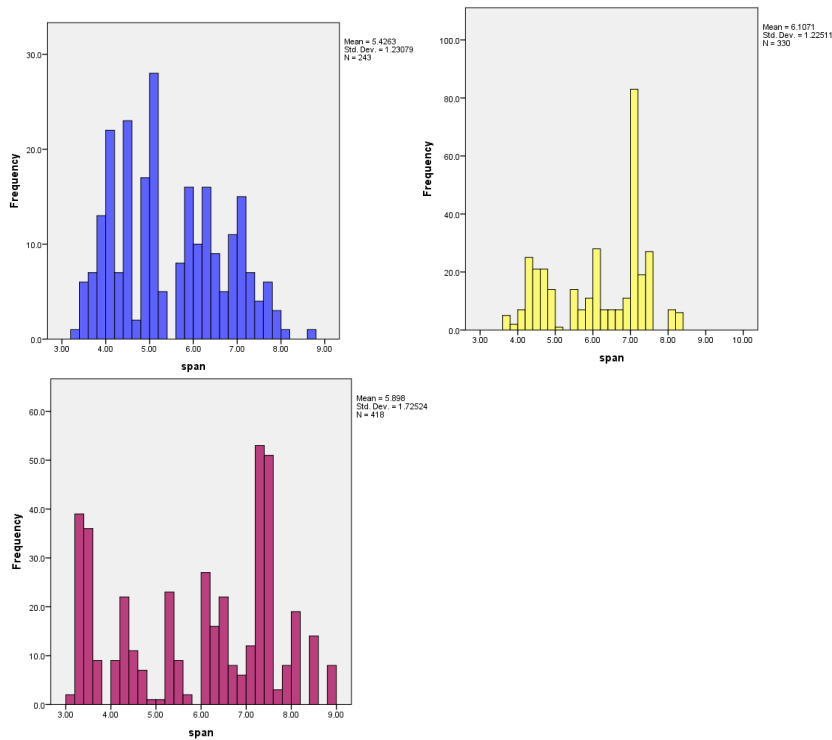


Figure 56- Span distribution in building Class1,2 and3 from left to right

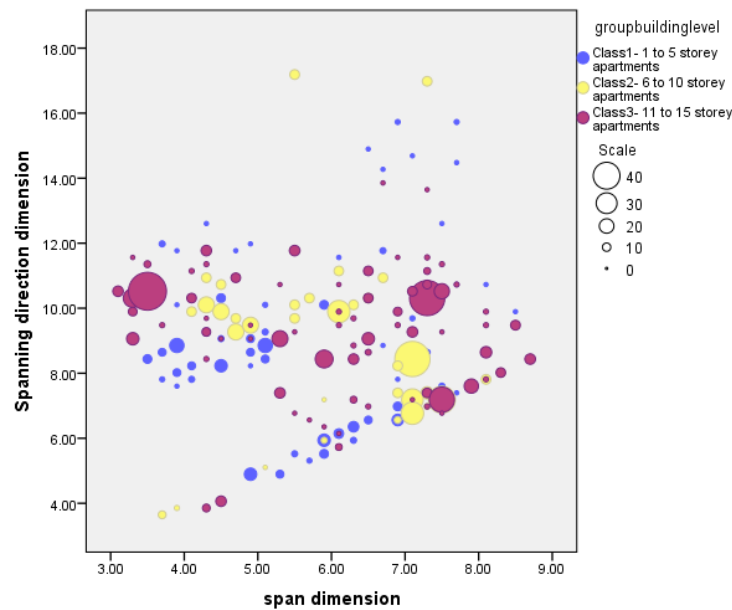


Figure 57- Apartments spans and spanning direction dimensions scatter plots based on different building categories

Figure 58 illustrates that the incongruity between the spanning direction and the width of the apartment is more evident in Building Class 3 compared to the other two building classes. This highlights the increased complexity in the structural design within this specific building category. Building Class 3 demands significant design efforts for both vertical and horizontal components to effectively manage factors such as earthquake and wind loads, along with live and dead loads. The architectural composition of this class integrates multiple elements,

including panels, frames, cantilevered terraces and balcony floors, along with a supporting structure for extensive glass facades. Furthermore, apartments within Class 3 are commonly situated on land with a broader frontage when compared to the other two groups. In simpler terms, these apartments showcase larger spanning direction dimensions and incorporate cantilevered floors to a greater extent than the other building categories. As mentioned earlier, apartments within a building featuring a wide frontage are often elongated along the building facade to amplify the size of openings and enhance facade diversity. These factors contribute to the notable distribution of spans observed within Class 3. For a more comprehensive overview of the average building frontage within each building class, please refer to Appendix B.

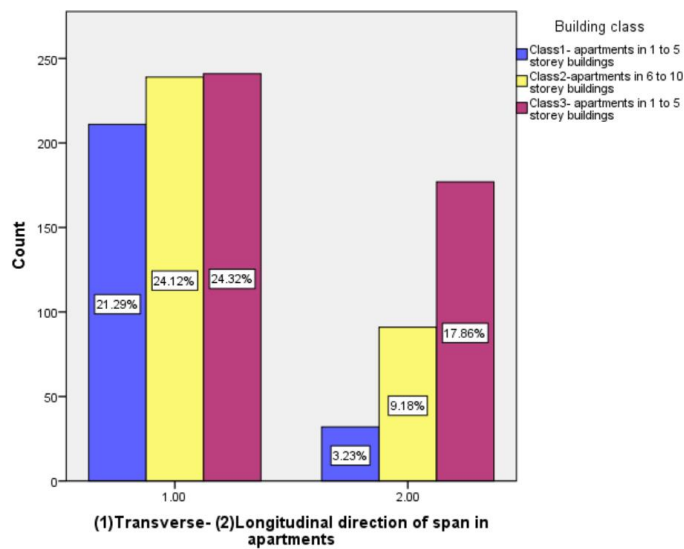


Figure 58- The percentage of span direction in each group

Likewise the previous clustering analysis, the optimal number of clusters was extracted based on the methods previously mentioned (Appendix C). The clustering outcomes of each building class listed in Table 22 and presented in Figure 59 indicate that each building class has two or three typical structural spans. The most common clusters of spans vary from one building class to another. The most common clusters of spans in Class 1 of buildings are 4.3 and 6.8 meters, while in Class 2 are 5.5 and 7.2 meters. In Class 3 the combination of short (3.5 meters) and long spans (7.2 meters) constitute the spanning direction (10.5 meters). The optimal number of clusters, average cluster validation, and cluster scatter plots of each building class are attached in Appendix C.

Table 22- The dominant spans and spanning direction dimensions in apartments regarding the number of floors

				Span	SDD		
--	--	--	--	------	-----	--	--

Building class	Cluster No	Cluster size	Percentage in a cluster (%)	Mean	SD	Mean	SD	Cluster validation (silhouette)	Average silhouette
1	Cluster1	59	34%	4.3	0.5	9.1	1.0	0.64	0.55
	Cluster 2	58	33%	6.8	0.5	6.9	0.8	0.52	
	Cluster3	15	8%	7.0	0.8	11.7	2.4	0.24	
	Cluster4	39	22%	5.3	0.6	5.2	0.6	0.57	
2	Cluster1	77	31%	5.5	0.8	10.0	0.4	0.52	0.68
	Cluster 2	146	60%	7.2	0.4	7.6	0.7	0.74	
	Cluster3	12	4%	4.0	0.4	3.8	0.4	0.86	
	Cluster4	7	2%	7.2	0	17	0	1	
3	Cluster 1	52	17%	7.5	0.3	7.3	0.2	0.74	0.64
	Cluster2	22	7%	5.8	0.4	6.9	0.6	0.43	
	Cluster3	57	19%	6.0	0.4	8.9	0.4	0.57	
	Cluster4	13	4%	4.3	0.05	4.1	0	0.98	
	Cluster5	61	20%	3.5	0.4	10.5	0.6	0.73	
	Cluster6	30	9%	8.4	0.3	8.6	0.4	0.57	
	Cluster7	59	20%	7.2	0.3	10.5	0.7	0.6	

Spans:6 meters and (3.5& 7.2 meters)

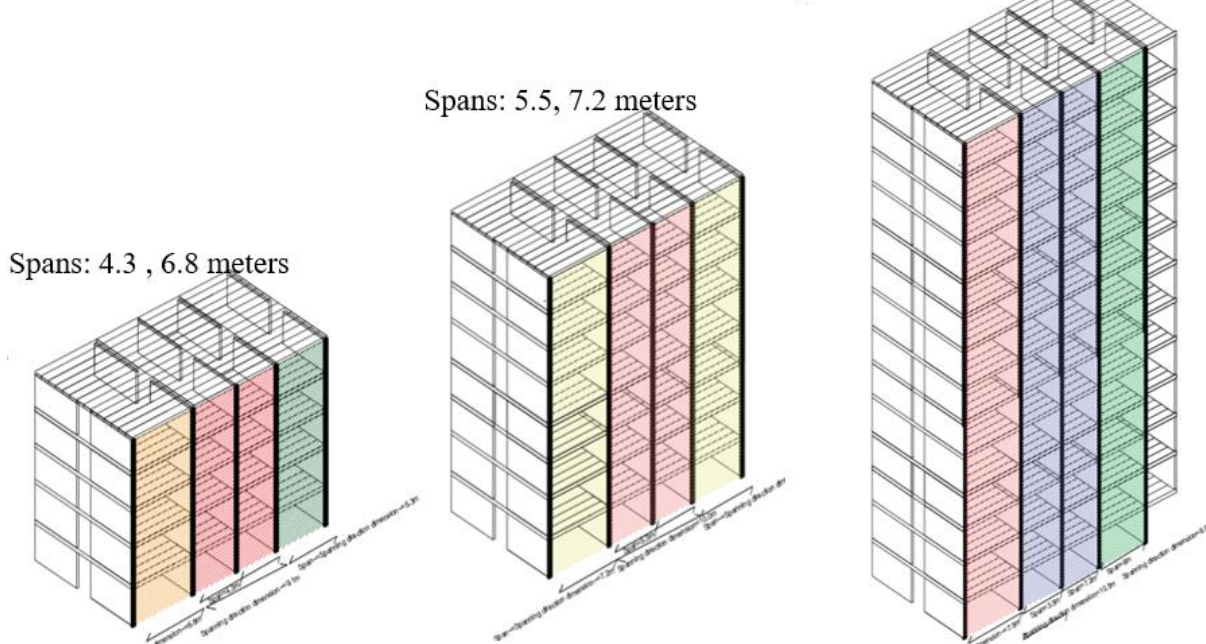


Figure 59- A schematic view of modular design patterns concerning the vertical building design

4.4 Data analysis validation and contribution to MC in the residential building industry

Clustering results are validated through triangulation. As mentioned in Section 3.2, there are four types of triangulation for the validation of any construct (here clustering results), i.e., data source triangulation, theory triangulation, investigator triangulation, and methodological triangulation. Among four types of triangulation, theory triangulation is employed in this chapter to validate the clustering results. This validation method includes using theories, laws, or hypotheses when examining a situation or phenomenon so that investigators with different points of view interpret the same results (Denzin 2010).

In this context, Silhouette method, a form of law, is applied as a cluster validation measure in this chapter. The cluster validation measure is a theoretical triangulation because investigators with different points of view can interpret the same results based on the rules. The

rules are related to the goal of clustering. As the goal of K-means clustering is to split the data set into clusters of objects such that (i) the objects in the same cluster are similar as much as possible, (ii) and the objects in different clusters are highly distinct, the average distance within a cluster should be as small as possible, while the average distance between clusters to be as large as possible. Hence, cluster validation measures reflect the compactness and separation of the cluster partitions. Compactness or cluster cohesion measures how close the objects are within the same cluster. A lower within-cluster variation is an indicator of good cluster compactness, i.e., good clustering. Separation measures how well-separated a cluster is from other clusters. Silhouette coefficient or silhouette analysis measures how well an object is clustered, and it estimates the average distance between clusters. The silhouette value is a measure of how similar an object is to its own cluster (cohesion) compared to other clusters (separation). The silhouette plot displays a measure of how close each point in one cluster is to points in the neighbouring clusters (Kassambara 2017). The silhouette ranges from -1 to $+1$, where a high value indicates that the object is well-matched to its own cluster and poorly-matched to neighboring clusters. The clustering configuration is appropriate if most objects have a high value. A small silhouette (i.e., around 0) means that the object lies between two clusters. If many points have a negative silhouette, then objects are probably placed in the wrong cluster (Kassambara 2017). By considering the average silhouette coefficient in cluster analysis (Table 15, 18, 21), it can be concluded that the data is well clustered, and the results are reliable.

The proposed method for recognising the manufacturability of apartment layout designs and identifying modular design scenarios based on recognising the similarities of architectural design was also evaluated by three architects with an average industry experience of 10 years in building design. Prior to elaborating on the data analysis methods and concepts, the architects were briefed on the mass customisation concept and its key objectives. Subsequently, the data collection and clustering methodology, along with the variables contributing to achieving modular design scenarios, were expounded upon for evaluation using the following criteria within prefabricated systems: (i). significance and usefulness of the method for the residential building sector needs, (ii) relevance to mass customisation objectives, (iii) reflectiveness of results and insight for architectural design. Architects were asked to evaluate the system using a Likert scale based on the criteria. Although architects usually would like to design fully customised buildings in conventional design, the evaluation results indicated that the

participants agree or somewhat agree that the method is useful for architects to implement a mass customised design in the building industry. They strongly agree that, in conventional design, architects usually do not consider structural component sizes, i.e., floor spans, that can be optimally manufactured off-site. Also, they emphasised that architects do not have a solid knowledge of the production processes nor the optimisation techniques. While running an optimisation algorithm may be out of an architect's area of expertise to specify spans, they need to be provided with fact-based insight into the manufacturability of the architectural plans. This can simultaneously assist with implementing MC in practice and eventually lead to an alternative approach (i.e., modular design approach) to the conventional design of multistory buildings. They pointed out that the results give them insight into designing layouts that are manufacturable while at the same time desirable for different clients. They agree that this approach provides a number of desirable architectural design options and reduces the need to develop unique parts for each new apartment, and potentially reduces part count for a variety of apartments.

4.5 Summary

This chapter operates on the premise that architects are seeking modular design patterns that align with Mass Customisation (MC) principles via product platform concepts. In simpler terms, the aim is to identify manufacturable design patterns that are both applicable and appealing to specific clients. Therefore, the chapter focused on uncovering modular design scenarios that introduce a level of standardisation for structural spans by identifying commonalities in the architectural designs of apartments through an analysis of building drawings data. This approach reduces the need to develop unique parts for each new apartment and potentially reduces part count for a variety of apartments. The chapter is structured into two primary sections. The initial section (Section 4.2) conducts an analysis of architectural design parameters—particularly from the perspective of architectural or spatial voids. This analysis is undertaken to address spaces that necessitate greater variety in terms of dimensions, while simultaneously identifying spaces that share similar architectural traits. This distinction facilitates the recognition of typical architectural design parameters. The subsequent section (Section 4.3) delves into the realm of manufacturing practices, particularly in relation to the sizes of prefabricated components—essentially adopting a manufacturing perspective. The primary focus of Section 4.3 is the assessment of manufacturability within architectural designs and the identification of recurring span patterns present in various architectural layouts. This process allows for the specification of modular design scenarios.

The outcomes of this chapter offer valuable insights, especially for scenarios where a company or architect lacks access to such an extensive volume of information. These findings can serve as essential inputs for seamlessly integrating architectural design with efficient manufacturing. Furthermore, the results are particularly beneficial during the conceptual design stage.

Chapter 5: Analysing and Validating MC-based Modelling of Building Layout

5.1 Overview

This chapter focuses on the validation of the mathematical model's computational efficiency. In Subsection 5.1.1, the main characteristics considered in the proposed model are discussed. In other words, before examining model's computational efficiency, some of the model's key features are summarised. Then, in Subsection 5.1.2, and 5.1.3 the model computational efficiency with three different scenarios, i.e., mass customised, mass produced, and fully customised design scenarios, with a preliminary architectural floor plan as a case example, are examined. Genetic Algorithm (GA) is considered an appropriate method to solve the developed model. Therefore, GA parameters are discussed in this chapter. In Sections 5.2 , theory triangulation, law of variability and theory of swift even flow are applied for model validation model.

The following figure shows Stage C research roadmap regarding the generic phases of the constructive research approach.

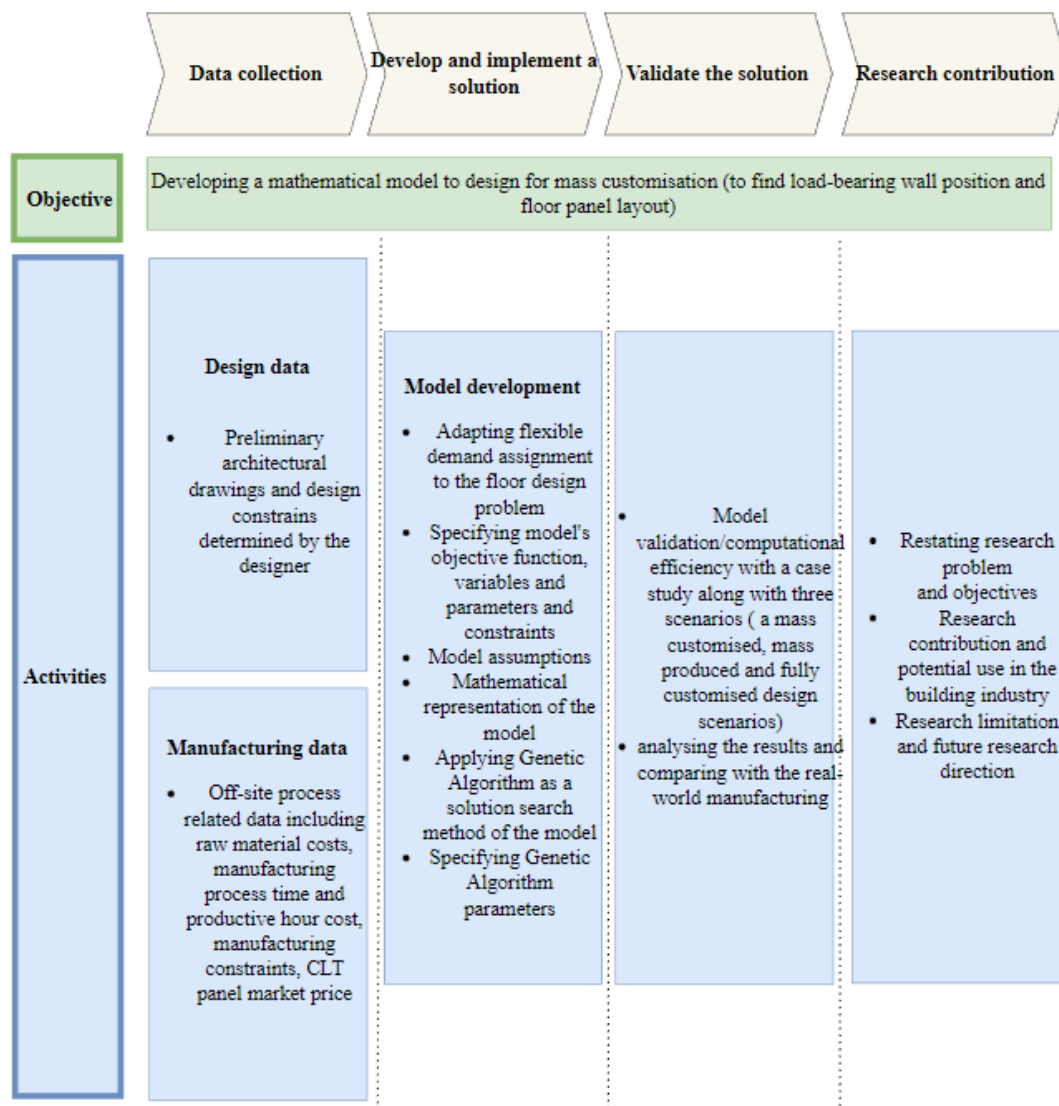


Figure 60- Stage C research roadmap

5.1 Model's computational efficiency with a case study

The exercise of this chapter is based on the concept that to apply product platform strategies for mass customisation of buildings the focus must be on design specifications that lie between ETO and SV (Bonev et al. 2015). Because, as discussed in Chapter 2, between these two levels of mass customisation the supply-side and demand-side could agree on building design adjustments at a part or component level module. Hence, this provides a degree of standardisation.

This chapter assumes that the architect has been tasked to design a fully customised building layout. This task takes place during the preliminary design stage. Under this scenario, the architect has little room to offer modular design layouts; instead, s/he must endeavour to accommodate MC through integrating production processes in the building design without compromising the flexibility in the customised architectural design. In other words, while this

approach does not lend itself to identifying similarities in the clients' architectural design, the architect is still responsible to optimise the design for manufacturability.

The model development procedure is discussed in detail in Chapter 3, Section 3.5. In Subsection 5.1.1, before examining model's computational efficiency, some of the model's key features are summarised.

5.1.1 The main characteristics considered in the proposed model

MC definitions tend to look at MC as a strategy to meet clients' requirements or value (i.e., generating customisation in products) and manufactureres' needs (i.e., producing products with production efficiency). Production efficiency brings economy efficiency. Hence, maximum production efficiency requires that products be produced at the lowest possible cost. Production efficiency is achieved when the product is produced at a minimum cost (Commission 2013), and the profit is high. Then the client would subsequently buy the customised building structure at a reasonable price. Aesthetic and other subjective aspects of the design were ignored in the optimisation model because they are difficult to model with mathematics. Hence, the subjective aspects were not modeled in this thesis.

Measuring the client requirements or value, which is supported by utility theory, is complicated and requires considering several variables in building design and is out of this research scope. However, this research has attempted to simplify it by considering the following elements: (i) considering the architect's suggestion regarding architectural design constraints and client's desires, and (ii) limiting the price of the product (i.e., building structure) by reducing client costs or considering the client's willingness to pay. Since architectural design and building structure price, which involve the customisation part of MC strategy, are considered as a design constraint and clients requirements in mathematical modelling, the emphasis of the objective function is on the optimal production processes or on maximising profit. In order to focus on the main objective of this thesis and simplify the model, a single objective to maximise profit is set.

Off note, as the focus of this research is placed on apartment floor plans, layout design problem approach to compare the floor design alternatives is considered in this research. Layout design problem is concerned with finding feasible and desirable dimensions and locations for a set of interrelated spaces or components that meet all design requirements (architect's or client' requirements) within the layout. Design requirements including spaces length, width, aspect ratio, shape, connectivity, maximise design quality in terms of design preferences (Michalek et

al. 2002). Based on the client and manufacturer requirements, the apartment spaces from the spatial voids perspective and apartment structure and floor panel from the solid mass perspective are the levels of interest in this research.

Component production costs comprise 80% of prefabricated structure costs (Forsythe and Sepasgozar 2019; Goh and Goh 2019; Hasan et al. 2018). Therefore, off-site manufacturing processes play a significant role in building production efficiency and building structure price. As mentioned in Chapter 3, pressing and CNC router cutting stage and raw materials are the high-cost factors in fabricating billets and panels. Therefore, the off-site process-related data and design data targeting production efficiency and profit include but are not limited to: (i) average lumber and adhesive costs (raw materials) and their ratio in each billet, (ii) manufacturing process time, and productive hour cost (PHC), (iii) manufacturing constraints and typical CLT billets dimensions, (iv) architectural and structural design constraints, (v) CLT panel market price per unit.

Some of the information was extracted from a reputable CLT factory in Australia. The factory's logistics director provided the material costs and related information. The estimated time of two main manufacturing stages, i.e., press and CNC process stages, for different billet and panel types was adapted from the research conducted by Araujo Carneiro (de Araujo Carneiro 2019) which is elucidated in Section 2.5.4. In this study, to simplify the conversion of production time into cost, only the production direct cost, which is referred to here as the productive hour cost (PHC), is considered. The unit productive hour cost, which is the sum of standard direct labor cost, was estimated based on the average number and wages of the workers involved in the factory manufacturing process. Manufacturing constraints were identified by interviewing the director of technical service, investigating literature and manufacturers' websites, and attending webinars. CLT billets and structural design constraints presented in Table 25, were extracted from the manufacturer's preliminary design guide. Also, architectural design constraints were recognised according to an initial customised architectural design. The factory's sales and marketing supervisor presented the market price.

Off-site transportation and installation of materials have been estimated to account for 10–20% of the total project expenditure in construction projects. Transportation cost depends on the size and weight of panels, transportation method, and distance of travel. Among different modes of transportation, namely trucks, trains, and ships, truck transportation is the most feasible and common type of shipment method regionally. However, it adds some limitations to the project. Truck transportation requires transportation permits for oversized loads, dimensional limitations, and road regulation restrictions. City and government permissions or

truck escort add costs to the project and is not always feasible. Furthermore, the size of the hauling is limited by the regulation as well. The maximum truck size authorised by Australia's government is 2.5 meters wide, 4.3 meters tall or high, and 12.3 meters long (National Heavy Vehicle Regulator 2016). In practice, the panel width is typically limited between 0.6 and 4.2 meters, and panel length is considered up to 12.00 meters due to the standard dimensions of the truck used to transport the element to the construction site. Payload either wider or/and higher than 2.4 and 4.2 meters or/and longer than 12.00 meters requires one pilot vehicle with some special arrangement (Sharafi et al. 2017). Therefore, the maximum floor panel width, height, and length in this research are limited to these dimensions. Once the CLT panels arrive at the construction site, the installation and erection process initiates. As mentioned before, component production costs comprise 80% of prefabricated structure costs (Forsythe and Sepasgozar 2019; Goh and Goh 2019; Hasan et al. 2018), and this percentage is significant compared to transport and installation costs. Hence, in model development the focus was on optimising the manufacturing process of CLT elements, but it considers the transport and installation constraints.

The following section examines the model computational efficiency with three scenarios, i.e., mass customised, mass produced, and fully customised design scenarios.

5.1.2 Running the model for a mass customised design scenario

The integration of design and manufacturing is seen as a solution to the problem of achieving the balance between customisation and mass production efficiency in residential buildings. The mathematical model presented in Chapter 3, which meets the second, third and fourth objectives of this research, balances the supply-side and demand-side requirements by focusing on building design adjustments at a part level. The proposed model optimises the interactions between the structural wall placement and CLT floor panel dimensions on an architectural plan by determining building spans, floor panel lengths, and thicknesses. The model presented in Chapter 3 could be classified in MTO approach, where the lowest level of system standardisation targets the component level. From a CLT manufacturing perspective, such components are represented by different sizes (length, width, and thickness) of CLT panels.

To compare the floor design alternatives, the mathematical model is developed in Chapter 3, where maximising the manufacturer's profit is introduced as an objective function in Eq (7) while reducing the client's cost appears in the form of constraint in Eq (8). In addition to

transportation constraints, the model considers the design parameters and off-site manufacturing information to meet demand- and supply-side requirements, respectively. The variables are the size of spans which include specifying floor panel length and thickness. In any project, there is likely to be an assortment of panel shapes and sizes to be cut from billets. Manufacturers cannot simply just ‘remove or reduce’ these parts to make efficient use of the production time. However, what can be done is the arrangement of panels across multiple billets with a few changes in length to ensure efficient cutting. This scenario is usually allowed where manufacturer’s actions do not sacrifice architectural design and keep the client satisfied.

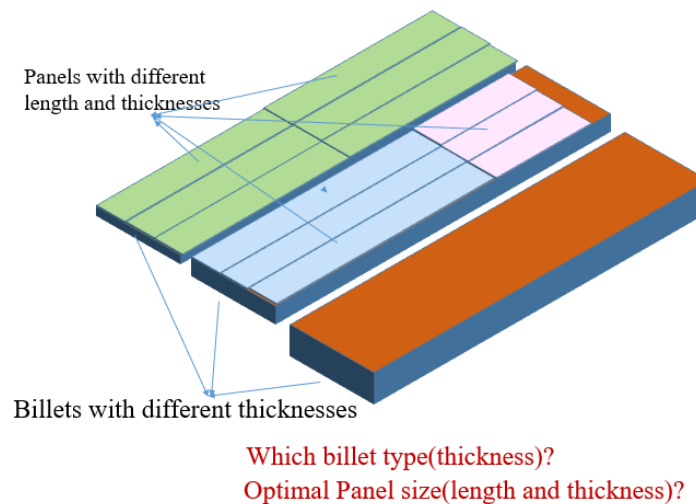


Figure 61- A schematic view of panel length and thickness as a variable of the model

The case example, illustrated with a 3D view in the following figure, with three different scenarios, is utilised to demonstrate the practicality and accuracy of the optimisation model. Section 5.1.1 and 5.1.2 discuss a mass customised design scenario, while Section 5.1.3. considers mass-produced and fully customised design scenarios. Accordingly, Tables 23, 28, and 29 indicate the design parameters and off-site manufacturing information as inputs of mass customised, mass-produced, and fully customised design scenarios, respectively.

It is noted that floor components (panels) may have defined shapes (square, rectangular, etc.) or loose shapes. However, loose shapes are undesirable in the layout design. Common spatial voids and floor plans usually include rectangular shapes in the layout design problem research. Rectangular spatial voids may have variable areas with fixed aspect ratios, fixed areas with continuously variable aspect ratios (upper and lower bounded), fixed areas with discrete allowed aspect ratios, and variable areas with upper and lower bounded and continuously variable aspect ratios (Baušys and Pankrašovaite 2005). In the layout problem addressed here, the rooms have rectangular shapes with variable areas and continuously variable aspect ratios which are suggested by the architect. However, the architectural design constraints, i.e.,

minimum and maximum areas and aspect ratios, could be determined by the analysis of architectural design data addressed in Chapter 4 as well. As indicated in Chapter 4, spatial voids dimensions that are in line with apartment spans determine the minimum and maximum range of span. This chapter assumes that the architect determines these architectural design constraints.

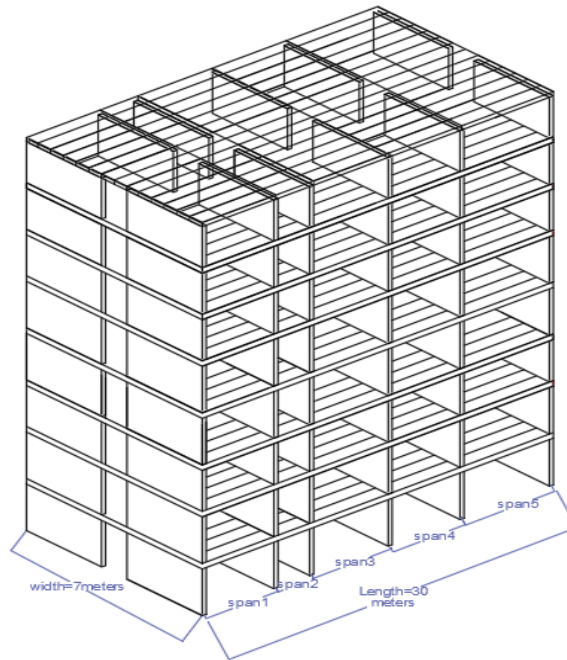


Figure 62- A case example

The model aims at simulating spans of one building's floor, and it is assumed that the other floors' spans, or load-bearing wall placement, are similar. The model's objective function mainly considers the key factors making up manufacturing process associated costs, including raw materials, pressing stage, and CNC router cutting stage. Eq 14 indicates the objective function with some parameters and input derived from Table 23. Table 23 shows the extract of the data sourced by the preliminary architectural design, demand- and supply-side, which are fed into the developed model as inputs for the first scenario.

Objective function:

$$Eq(14). \max \sum_{i=1}^{i=5} \sum_{t=1}^{t=16} R_{it} S_{it} - \sum_{t=1}^{t=16} C_t Z_t - r \sum_{t=1}^{t=16} (B_t Z_t - \sum_{i=1}^{i=5} S_{it}) - PHC \sum_{t=1}^{t=16} Press_t Z_t - PHC \sum_{i=1}^{i=5} \sum_{t=1}^{t=16} CNC_{it}$$

$$I = \{1,2, \dots 5\}, T = \{1,2, \dots 16\}$$

I presents the number of different spans or floor panel lengths. It is assumed that the panels are similar in each span, whereas in different spans, the panels could be different in terms of length and thickness. Hence, based on the case example, i.e., the preliminary architectural design reflected in Figure 62, it can be concluded that the case example includes five different spans with the potential of having five different panels, i.e., $I = \{1,2, \dots 5\}$. The second to fourth parameters of Table 23 were extracted from preliminary architectural design and the architect's advice. As mentioned before, the mass customised design scenario is allowed where manufacturer's actions do not sacrifice architectural design and keep the client satisfied. Therefore, these parameters are determined according to the architect's advice in the preliminary architectural design. l_i and u_i show the panel size range (minimum and maximum span) determined based on the architect's opinions. L represents the floor area or bound size that panels should cover. The bound size constraint specifies the buildable area length and width in the model. l_i, u_i, L are notations related to the model constraints, which are related to Eq 20 and 23 and discussed in the following paragraphs.

Table 23- Model inputs for the mass-customised design scenario

	Symbol	Unit	Input	Source of the data	Description
1	$I = \{1, 2, \dots, i\}$	-	$i=5$ $I = \{1, 2, 3, 4, 5\}$	Demand-side (architectural floor design)	The number of different panels/spans
2	l_i	Square meter	6.8; 5.7; 4.2; 5.7; 6.8	Demand-side (architectural floor design)	
3	u_i	Square meter	7.6; 6.3; 5.8; 6.3; 7.6	Demand-side (architectural floor design, architect)	
4	L	Square meter	210	Demand-side (architectural floor design)	30- and 7-meters length and width, respectively
5	T	-	$\{1, 2, \dots, 16\}$	Supply-side (manufacturing constraints)	With the option of choosing thicknesses from the following 16 billet types: 3-layer billets thicknesses(meters): 0.085, 0.105, 0.115, 0.125, 0.135, 5-layer billets thicknesses(meters): 0.145, 0.160, 0.175, 0.195, 0.205, 0.225, 7-layer billet thicknesses(meters): 0.245, 0.265, 0.275, 0.295, 0.315
6	B_t	Square meter	36	Supply-side (manufacturing constraints)	12 and 3 meters in length and width, respectively
7	R_t	\$ per square meter	122,136,149,164,177,192,209,230,256,272,301,323,357,367,398,422	Supply-side	For each thickness listed in raw 5
8	C_t	\$ per billet	2164,2448,1320,2682,2952,3186,3762,4140,48965418,6426,6606,7164,7596	Supply-side	For each 12 by 3 meters billet with the thicknesses listed in raw 5
9	r	Per cubic meter	100	Supply-side	
10	PHC	\$ per minute	10	Supply-side	
11	$Press_t$	Minute	91, 102, 110	Supply-side (manufacturing constraints)	For three-, five- and seven-layer billets, respectively
12	PW	Minute	10	Supply-side (manufacturing constraints)	
13	CNC_{it}	Minute	Eq (1),(2),(3)	Supply-side (manufacturing constraints)	
14	K	\$	70.000	Demand-side	It is calculated based on the average market price (333 \$ per square meter)

The manufacturing parameters and constraints in Table 23, i.e., items 5 to 9, were extracted from a reputable CLT factory in Australia. T indicates the number of different billet thicknesses in a factory. Based on Table 23, sixteen different thicknesses are the billets

produced by the factory in this case. B_t presents the typical billet size produced by the manufacturer, which in this case, billets with 12.00 meters long and 3.00 meters wide are considered standard billet.

For estimating raw material costs (C_t), the adhesive spread rate specifying the amount of utilised adhesive and lumber in a billet is considered 250 kilograms per square meter based on the common practice in the industry. The factory's logistics director provided average lumber and adhesive costs (raw materials) and their ratio in each billet, and the factory's sales and marketing supervisor presented the market price per square meter for each type of billet, i.e., R_t . It is notable to mention that in the case of applying different billet thicknesses during the manufacturing process, a fixed cost equivalent to $8000(x - 1)$ is added to the total client cost (total panels price), i.e., $\sum_1^i \sum_1^t R_{it} S_{it} + 8000(x - 1)$. x indicates the number of different billets. According to the supply-side statement, this parameter is the base cost of changing the production line (setting up the press and CNC machine) and, consequently, waiting time due to producing different billet and panel thicknesses that they consider in clients' costs. For instance, suppose three different types of panels in terms of thicknesses are produced. Therefore, based on the number of different panels, the total client cost is $\sum_1^i \sum_1^t R_{it} S_{it} + 8000(3-1)$.

The estimated time of the two main manufacturing stages (press and CNC process, items 10 to 13) for different billet and panel types was adapted from the research conducted by Araujo Carneiro (de Araujo Carneiro 2019), elucidated in Section 2.5. The estimated press time was checked with a technical service engineer in order to identify their applicability to the model. As calculating CNC process time is complicated and depends on two different variables, i.e., the number of panels and waste of billets during the cutting stage, cutting time for six panels from a billet has been tested, which was approximately aligned with the outputs of the formula. Therefore, the researcher was assured of the model's inputs and parameters for the manufacturing processes section.

Table 24- Pressing stage time estimated for billet 3*12 meters adapted from (de Araujo Carneiro 2019)

Number of layers in a CLT billet	Pressing stage time - minutes	
3-layer	91	$Press_{three-layer\ billets}$
5-layer	102	$Press_{five-layer\ billets}$
7layer	110	$Press_{seven-layer\ billets}$
	10	PW

$$(16). CNC_{three-layer\ panels} = 1.13 + \frac{9.77NP + 0.525W + 2.567set}{NP}$$

$$(17). CNC_{five-layer panels} = 14.3 + \frac{9.77NP + 0.525 W + 2.567set}{NP}$$

$$(18). CNC_{seven-layer panels} = 25.09 + \frac{9.77NP + 0.525 W + 2.567set}{NP}$$

In this study, to simplify the conversion of production time into cost, only the production direct cost, referred to as the productive hour cost (PHC), is considered. Pressing stage ($Press_t$) and CNC router cutting stage time (CNC_{it}) are multiplied by productive hour cost (PHC) to convert time into the cost. The unit productive hour cost, which is the sum of standard direct labour cost, was estimated based on the average number and wages of the workers involved in the manufacturing process. On average, two labour are involved in the factory during the pressing and cutting process.

The objective function is subject to the following constraints:

Eq (18) which limits the client cost, indicates the maximum building floor structure price accepted by the client. With the aid of the architect, the maximum structure price is determined based on the extant market price and the client's willingness to pay for standardisation. To simplify the model, it is supposed that the floor structure price per meter must be equal to or less than the average price proposed by different manufacturers. K is calculated based on the average market price of \$333 per square meter.

$$(19). \sum_{i=1}^{i=5} \sum_{t=1}^{t=16} S_{it} R_{it} \leq K$$

The assignment constraint, Eq (20), requires assigning each panel to exactly one billet. This constraint also limits the assigning of panels to billets based on the structural design guide of the manufacturer. Structural design constraints were extracted from the Xlam preliminary design guide listed in Table 25. Structural design constraints in Table 25 are limited to medium-rise residential buildings with 2 kPa live-load and 0.0 kPa superimposed dead-load. It is notable that the simply supported floor and its corresponding structural constraints are considered. As mentioned before, a simply supported floor is a floor with its ends simply supported on two walls, free to bend at the ends without any restraint; it has only one span between two supports.

$$(20). \sum_{t=1}^{t=16} X_{it} = 1, \text{ for all } i \in \{1,2,..5\}$$

Table 25- Preliminary structural design table utilised as input for the model

Panel designation (number of layer/thickness meters)	Maximum span (meters)
CLT3/0.085	2.800
CLT3/0.105	3.400
CLT3/0.115	4.100
CLT3/0.125	4.200
CLT3/0.135	4.900
CLT5/0.145	5.100
CLT5/0.160	5.400
CLT5/0.175	5.900
CLT5/0.195	6.200
CLT5/0.205	6.400
CLT5/0.225	6.600
CLT7/0.245	6.800
CLT7/0.265	7.200
CLT7/0.275	7.400
CLT7/0.295	7.600
CLT7/0.315	7.800
Note: - The panel size and span are considered based on the following load specification: Live load= 2Kpa, Superimposed dead load = 0 Kpa - Panel designation shows the number of layers and thickness in a CLT panel. As an example, CLT7/0.315 indicates a seven-layer billet with 0.315 meters of thickness.	

Eq (21) shows the panel size range (minimum and maximum span) determined based on the architect's opinion. Floor panels are placed on the load-bearing walls and specified apartment spans. Span plays a critical role in apartment layout design. Therefore, the maximum (u_i) and minimum size (l_i) of panel or span i is determined based on the architect's opinion. This equation represents architectural design constraints based on the preliminary apartment layout design. In other words, this equation ensures that if panel i assigned to billet t , the panel size lies between its allowable minimum and maximum size (Items 2 and 3 of Table 23); otherwise, the size of panel i assigned to billet t must be zero. As typical implementation in prefabricated buildings, the width of all floor panels is the same and is considered a parameter; therefore, in this case, the panel width is 1 meter. Still, the panel length and thickness, which represent span, are variables.

The billet size constraint, Eq (22), specifies that the total size (length) of panels assigned to a given billet must not exceed that billet size. This constraint also prevents assigning panels to billets that are not chosen. As mentioned before, in this case, the most common billet size of the manufacturer, which is 12 by 3 meters, is considered for testing the model's computational efficiency.

$$(21). l_i X_{it} \leq S_{it} \leq u_i X_{it}, \quad \text{for all } i \in \{1,2,..5\} \text{ and for all } t \in \{1,2, \dots, 16\}$$

$$(22). \sum_{i=1}^{i=5} S_{it} \leq B_t Z_t, \quad \text{for all } t \in \{1,2, \dots, 16\}$$

(23). $X_{it} = 1$ or 0 , for all $i \in \{1,2, \dots 5\}$ and for all $t \in \{1,2, \dots 16\}$

$$(24). L = \sum_{i=1}^{i=5} S_{it}, \text{ for all } t \in \{1,2, \dots 16\}$$

Structure design constraints, i.e., Eq (23), avoid assigning panels to billets that cannot be utilised due to structural design considerations. Although each CLT manufacturer has its own distinct design guide, the structure design constraints are formulated based on Table 25, indicating whether panel i with the corresponding length can be cut from billet t or not. This table can also be replaced with any other manufacturer's design tables.

Eq (24), the bound size constraint, represents the floor area that panels should cover. Bound size constraint specifies the buildable area length and width in the model. These constraints are extracted from the preliminary architectural layout design (item 4 in Table 23).

Genetic algorithm parameters

In Chapter 3, Genetic Algorithm (GA) is considered an appropriate method to solve the developed model. GA is a stochastic search method based on a natural selection where a population is formed by individuals (Augusto et al. 2012; Hassanat et al. 2019). Each individual is a solution to the problem. If the solutions can be divided into a series of small blocks, then the steps, which are represented by genes and a series of genes (a chromosome), will encode the complete solutions (Hassanat et al. 2019). The length of the chromosomes depends on the problems, i.e., model variables. As specified in the next figure, the chromosome length for the current research problem (MC design scenario) should have 45 building blocks, with three sets of genes as model variables. The first set, including five genes in a chromosome, determines the panel sizing for each span. Panel sizing range is specified as per the architect's opinion about the minimum and maximum load-bearing wall distances. This set comprises five random numbers. The second set with five genes is attributed to allowable billet thickness selection. Panels are limited to cut from one billet type in each span due to maintaining aesthetical features of ceiling and spaces. Still, panels of each span could be cut from different types of billets. Hence, in the mass customised design scenario, the maximum number of different billets that may be utilised for the floor plan should equal the number of spans which is 5, according to the case example, i.e., Figure 62. Finally, the total number of panels assigned to billets is related to the last set of genes. Based on the case example, the number of spans is 5, the building and panel widths equal 7 meters and 1 meter, respectively. By multiplying these numbers, the total

number of assigned panels is 35. As a result of adding the number of three sets of genes, the chromosome should have 45 genes.



Figure 63- Chromosome structure

Fitness classifies chromosomes in accordance with an objective function. Then, the best group of individuals is allowed to continue the process, whereas the others are rejected. Roulette Wheel Selection is adopted for selection operation. A mutation point is randomly selected, and reaching a fixed number of generations is utilised as a termination strategy.

In this thesis, the designed genetic algorithm is implemented in Matlab environment, where optimisation can be conducted. The coding of the model is attached in Appendix D. Generally, four major parameters playing an important role in gaining appropriate solutions used by GA include cross-over and mutation rate, population size, and the number of generations (Hassanat et al. 2019). The determination of these parameters is dependent on specific optimisation problem and testing of optimisation performance (Xu et al. 2017). After several trials and errors and computational tests in Matlab platform the running parameters for the optimisation problem are set as follows:

Table 26- GA parameters in this research

Parameters name	Amount
Cross-over rate	40%
Mutation rate	60%
Population size	1000
Number of generations	5000

Model's outputs

The model was run 100 times in Matlab environment with the above parameters, and the first five-run results are reported in the next table. This table indicates that the convergence of the algorithm for such a complicated problem is satisfactory. The average computation time is 158 seconds (computer configuration: Intel Core i 5; Processors 4.5 GHz; Ram 8 GB).

Table 27 shows that the results in different runs are nearly identical. With reference to the model inputs presented in Table 23, while multiple options exist concerning billet or panel thicknesses, the findings suggest that employing a uniform billet thickness within the floor layout enhances the production process. Consequently, this practice contributes to a boost in the manufacturer's profits. Moreover, imposing restrictions on structural pricing and architectural design results in the selection of billets that align with the client's cost and

architectural requirements. The outcomes reveal that constructing buildings using a single panel thickness category, but adapting them to various lengths to match the building layout, emerges as the most profitable scenario for CLT manufacturers. This approach also proves to be a financially prudent choice for clients. This alignment with practical industry norms is underscored by insights from the supply side. In actual manufacturing, even though adopting a single billet thickness might increase the weight of the building structure and potentially escalate the structural price in certain instances, it invariably leads to higher profits for manufacturers compared to the use of varying thicknesses. Therefore, if architects permit a certain level of design flexibility, and manufacturers (supply side) and clients (demand side) concur on adjustments to the building design at the module, part, or component level, manufacturers can capitalize on producing panels with a consistent thickness across the entire floor. This provides a degree of standardisation and is aligned with the product platform concept discussed in Chapter 2. Consequently, both the client and manufacturer will benefit from a mass customised design and increase their corresponding profit.

Table 27- Model outputs for the mass-customised design scenario (optimal solution)

No of Run	Manufacturer's profit (\$)	Client cost/Structure price (\$)	Material cost (\$)	Recycling cost (\$)	Pres cost (\$)	CNC cost (\$)	Panel length/[thickness] (meters)	Number of different billet thicknesses	Run time
1	18286	67830	37926	1029	7700	2888	(6.800,5.700,5.000,5.700,6.200/[0.245])	1	262
2	18286	67830	37926	1029	7700	2888	(6.800,5.700,5.000,5.700,6.800/[0.245])	1	91
3	18286	67830	37926	1029	7700	2888	(6.800,5.800,4.800,5.800,6.800/[0.245])	1	130
4	18286	67830	37926	1029	7700	2888	(6.800,6.000,4.400,6.000,6.800/[0.245])	1	117
5	18286	67830	37926	1029	77000	2888	(6.800,5.700,5.000,5.700,6.800/[0.245])	1	144

5.1.3 Running the model for mass-produced and fully-customised design scenarios

A mass-produced and fully customised design scenario with the case example illustrated in Figure 62 are considered in this section to compare the results with the mass customised design scenario. The mass customised design scenario is discussed in 5.1.2. Comparing the results of these scenarios helps us to demonstrate the practicality and accuracy of the optimisation model. Tables 28 and 29 indicate the design parameters and off-site manufacturing information as inputs of mass-produced and fully-customised design scenarios, respectively. Although the building floor dimensions (length and width) and the number of spans were

considered the same in the three scenarios to examine the objective function, there are a few differences among inputs in each scenario as follows:

- (i) In the first scenario, i.e., mass customised design scenario, since spans and, consequently, panel size and thickness were considered as variables, a range of panel sizes between l_i and u_i with different thicknesses were regarded as inputs. As mentioned before, by considering these variables, the supply-side and demand-side could agree on building design adjustments at a part or component level without compromising the flexibility in architectural design. While in the second and third scenarios, spans are predesignated and fixed, and there is no potential for design adjustment at the components level. Therefore, panel size and thickness are considered parameters. Accordingly, in Tables 28 and 29 l_i equals u_i .
- (ii) The CLT manufacturer stated that the maximum production efficiency (equivalent to MP) is implemented in the factory environment, provided that panels' length would be 6.000 meters with 0.195 meters thickness due to the lowest wastage of material and production time generated. Therefore, these dimensions are considered as input for span size in the mass-produced design scenario. In the fully-customised design scenario, different panel thicknesses and lengths in the case example are also tested to examine the objective function and the structure price.
- (iii) In the mass-produced and fully customised design scenarios, spans or panel sizes are predesignated. Hence, with the predetermined panel sizes, the optimisation model aid in minimising CNC cost and wastage of material by determining how panels need to be placed on billets.
- (iv) Also, there is no constraint for the structure price in fully customised, and mass-produced design. Hence, no limited structure price is specified in the second and third scenarios.

The manufacturer's profit is the representation of the production efficiency, and the structure price indicates the client cost. The manufacturer profit and the client cost, in the mass customised design scenario (Table 27) are compared with mass-produced (Table 30) and fully customised design outputs (Table 31) as follows:

On the one hand, in real word practice, in a mass-produced design, a manufacturer usually takes advantage of manufacturing panels with repetitive size to increase production process efficiency, which leads to maximising their profit and reducing the structure price. Comparing the results of the model acknowledges that maximising profit and reducing the client cost are

observed in the mass-produced design scenario of this research. On the other hand, the fully customised design outputs indicate that applying different billet thicknesses (raw 1 to 4 of Table 31) results in lower production efficiency, i.e., manufacturer's profit, and consequently leads to a higher client cost. However, utilising only one type of billet (raw 5 of Table 32) results in a relatively higher manufacturer's profit, but in this scenario, it significantly leads to a higher client costs than the mass customised and mass-produced design scenarios since there is no flexibility to design adjustments at components level. In other words, the spans are predesignated, so based on the largest span, which is 7.2 meters, the panel thickness is chosen. However, in the mass customised design scenario, instead of a 7.2 meters span, we had some degree of flexibility to select spans between 6.8 to 7.6, where 6.8 was selected as an optimal size.

Table 28- Inputs for the mass-produced design scenario

Symbol	Unit	Input
i		1, 2, 3, 4, 5
$l_i = u_i$	Square meter	6, 6, 6, 6, 6
L	Square meter	210
T	-	{1,2,..t} With the option of choosing 5-layer billets with 0.195 meters of thickness
B_t	Square meter	36
R_t	\$ per square meter	256
C_t	\$ per billet	4896
r	\$ per cubic meter	100
PHC	\$ per minute	10
$Press_t$	Minute	102 (five-layer billet)
PW	Minute	10
CNC_{it}	Minute	Eq (1),(2),(3)
K	\$	-

Table 29- Inputs for the fully customised design scenario

Symbol	Unit	Input	Descriptions
i		1, 2, 3, 4, 5	
$l_i = u_i$	Square meter	5.7, 5.8, 7.2, 4.1, 7.2	
L	Square meter	210	30 and 7 meters in length and width, respectively
T	-	{1,2,..t}	With the option of choosing thicknesses from the following billet types: 3-layer billets thicknesses(meters): 0.085, 0.105, 0.115, 0.125, 0.135, 5-layer billets thicknesses(meters): 0.145, 0.160, 0.175, 0.195, 0.205, 0.225, 7-layer billet thicknesses(meters): 0.245, 0.265, 0.275, 0.295, 0.315
B_t	Square meter	36	12 and 3 meters length and width, respectively

R_t	\$ per square meter	122,136,149,164,177,192,209,230,256,272,301,323,357,367,398,422	For each thickness listed in raw5
C_t	\$ per billet	2164,2448,1320,2682,2952,3186,3762,4140,4896,5418,6426,6606,7164,7596	For each 12 by 3 meters billet with the thicknesses listed in raw 5
r	\$ per cubic meter	100	
PHC	\$ per minute	10	
$Press_t$	Minute	91, 102, 110	For three-, five- and seven-layer billets, respectively
PW	Minute	10	
CNC_{it}	Minute	Eq (1),(2),(3)	
K	\$	-	

The aforementioned outcomes can be attributed to the fact that, in the context of a fully customised design approach, the supply side is compelled to fabricate panels strictly in accordance with predetermined and fixed drawings, leaving minimal room for component adjustments. Essentially, architects delineate spans devoid of any flexibility, thereby limiting the manufacturer's latitude in specifying panel dimensions and thickness. The model's findings underscore that the production of panels with varying thicknesses culminates in reduced manufacturer profits and elevated costs for clients. In contrast, the mass customised design scenario strikes a balance between the manufacturer's profitability and client expenses through a mutual agreement to introduce a certain degree of flexibility in span lengths and panel sizes. As depicted in Table 27, the optimal panel length or span gravitates toward approximately 6 meters, and the preferred thickness is selected from a single billet type. These model outputs encapsulate the optimal solution for increasing manufacturer profits while simultaneously decreasing client expenses.

Table 30- Results of mass-produced design scenario

Manufacturer profit	Client cost/ Structure price (\$)	Material cost (\$)	Recycling cost (\$)	Press cost (\$)	CNC cost (\$)	Parameters	
						Panel length/[thickness](meters)	Number of different billet thicknesses
20891	53760	24840	117	6120	1791	6.000,6.000,6.000,6.000,6.000/[0.195]	1

Table 31- Results of fully customised design scenario

Case example	Manufacturer profit (\$)	Client cost/ Structure price (\$)	Material cost (\$)	Recycling cost (\$)	Press cost (\$)	CNC cost (\$)	Parameters	
							Panel length/[thickness] (meters)	Number of different billet thicknesses

1	13597	8904 5	44928	4608	18750	7161	4.200/[0.125],5.700/[0.160], 5.900/[0.175], 6.800/[0.245], 7.400/[0.275]	5
2	13991	8313 9	41634	3800	17100	6615	4.200/[0.125], 5.700/[0.160], 5.900/[0.175], 7.400/[0.275], 6.800/[0.275]	4
3	12518	7597 7	39042	3218	15570	5330	4.200/[0.125], 5.700/[0.175], 5.900/[0.175], 7.400/[0.275], 6.800/[0.275]	3
4	9817	6991 8	37782	2801	14370	4997	4.200/[0.175],5.700/[0.175], 5.900/[0.175], 7.400/[0.275], 6.800/[0.275]	2
5	18132	7497 0	39998	1113	11550	4183	7.200, 4.400, 5.700,5.900, 6.800/[0.265]	1

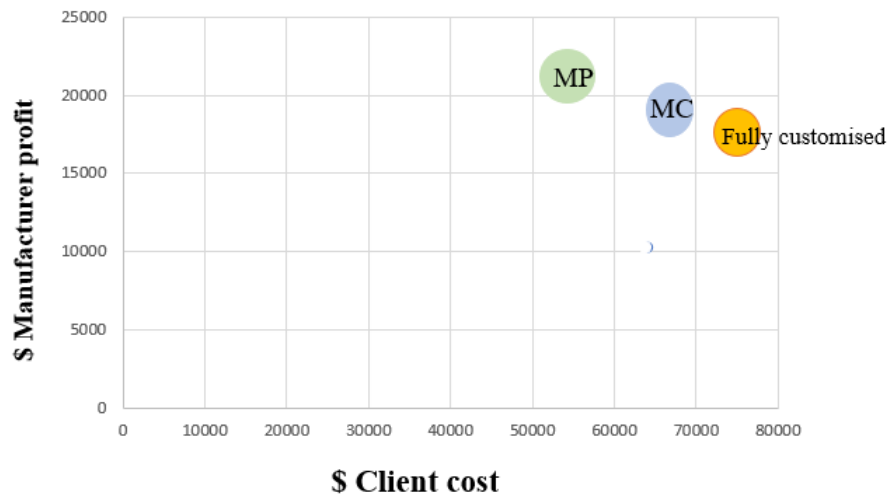


Figure 64- Comparing the results of three scenarios

5.2 Model validation and contribution to MC in the building industry

The results indicate that constructing buildings with single category of thickness of panels but customised in various lengths to accommodate the building layout are the most profitable scenario for CLT manufacturers. Additionally, it presents cost-effective option for clients. In terms of theory triangulation, law of variability and theory of swift even flow are applied in model validation. The model results are aligned with the law and theory. Based on this law, the greater the random variability, either demanded of the process or inherent in the process itself or in the items processed, the less productive the process is. The more variable the timing or the nature of the jobs to be done by the process, and the more variable the processing steps themselves or the items processed, the less output there will be formed the process, as captured

by machine productivity measures, material productivity measures, or total factor productivity measures (Schmenner and Swink 1998). Given that the fully-customised scenario entails greater panel thickness variability compared to the mass customised and mass produced design scenario, manufacturing process productivity diminishes due to extended setup times for changing machine set up time. Consequently, these setup delays lead to reduced manufacturer profits and elevated client costs. The results showed that multistorey apartments can be adapted for mass customisation, resulting in 10% cost saving for the client and additional 1% profit for the manufacturer. The table below provides a comparative analysis between the optimal outcomes of the fully customised and mass customised design approaches, revealing the extent of cost savings at each stage and the corresponding increase in manufacturer profit.

Table 32- Comparing the results of the mass customised and fully customised design scenarios

	Manufacturer profit (\$)	Client Structure cost/ price (\$)	Manufacturing process costs			
			Material cost (\$)	Recycling cost (\$)	Press cost (\$)	CNC cost (\$)
Fully customised design	18132	74970	39998	1113	11550	4183
Mass customised design	18286	67230	37926	1029	7700	2888
Cost saving or profitability % in the mass customised design scenario	1%	10%	5%	7%	33%	30%

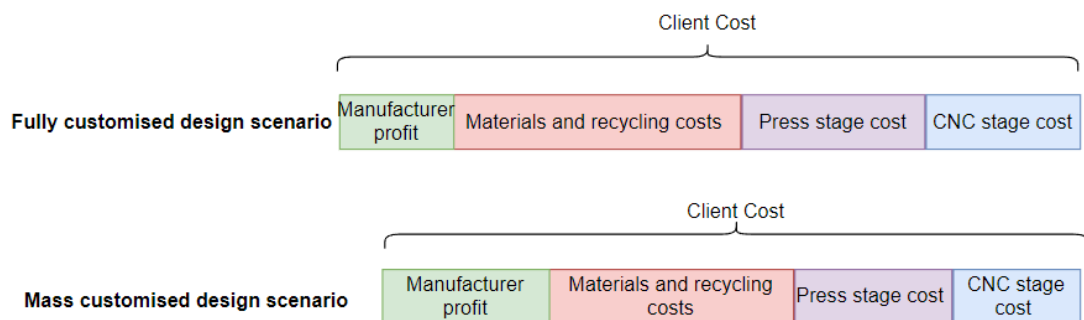


Figure 65- A schematic view of comparing the results of mass customised and fully customised design scenarios

The evaluation of production processes quality also adheres to principles outlined by Koskela (2000) for improving flow. By comparing the results of the fully customised design scenario with the mass customised design scenario, it can be inferred that reducing the waste of material and waiting time improves production process flow.

The proposed model was also evaluated by a panel of three experts with an average industry experience of 10 years and advanced to expert experience in timber building design and manufacturing. A demo of the system was presented to the participants for evaluation based on the following criteria in CLT system: (i) usefulness for the building industry needs and novelty, (ii) relevance to mass customisation practice and insight for design optimisation, (iii)

reflectiveness of results. Experts were asked to evaluate the system using a Likert scale based on the criteria. The evaluation results indicated that all participants agree or strongly agree that the tool is useful for architects to implement mass customised design in the building industry. They also pointed out that the balance between client's cost and manufacturing efficiency through manipulating panel size and thickness is unknown, which implies the novelty of this research. Experts agree that the tool provides insight into optimisation designs and that the model results reflect the degree of optimisation.

The proposed model meets the principle of MC, i.e., balancing the demand-side and supply-side requirements through agreeing on a certain level of design adjustments on spans. In addition, the model provides high level of detail at components and manufacturing levels; by doing so, integrating the building design and manufacturing are met.

5.3 Summary

This chapter provided the mathematical model's computational efficiency with a case study of three different scenarios, i.e., mass customised, mass-produced, and fully customised design scenarios. The GA algorithm as a solution search method and its parameters were elucidated. The results showed that multistorey apartments can be easily adapted for mass customisation and doing so, can result in 10% cost saving for the client and 1% more profit for the manufacturer. The law of variability and theory of swift even flow were applied as a means of model validation based on theory triangulation. Model outputs are aligned with the law and theory. The proposed model was also evaluated by a panel of three experts. The evaluation results indicated that all participants agree or strongly agree that the tool is useful for architects to implement mass customised design in the building industry.

Chapter 6: Conclusions

6.1 Overview

This chapter concludes the thesis by presenting a summary of the research findings, main contributions, and implications of the work presented. It refers back to the approaches and methods taken to meet the four main research objectives of the thesis, as outlined in Chapter 1. This is then followed by discussing the main conclusions, associated with each objective, drawn based on the findings presented in previous chapters in this thesis. It then states implications of this thesis's findings for both research and practice. Finally, a number of suggestions for future work are made based on the existing gaps in the literature and limitations of the present study.

6.2 Research objectives and key findings

The central objective of this research is to develop a data-driven design framework for mass customisation of multistorey buildings. To achieve this goal, the thesis targeted four sub-objectives:

6.2.1 Sub-objective 1: Manufacturable layout design

- To identify prevalent design patterns in residential building layouts and systematically assess their manufacturability.

To meet this objective, the focus was placed on investigating mass-customisability of building layouts at the conceptual design stage. This was done to see if there are adequate repetitions in building designs that would justify economy of scale to mass manufacture various layout options.

The similarities in architectural design of apartments and manufacturability of apartment layouts were considered as the main indicators of patterns for dwellings' modular design. A major finding is that building spans play a critical role in evaluating manufacturability of design. Based on the statical analysis of design data from more than 710 apartment units, it is inferred that the most common clusters of spans vary from one building class to another. Nonetheless, a prevailing span range continues to be relevant for the majority of residential buildings. The most frequently designed spans for residential structures typically fall within the range of 4.4 to 7.4 meters. This dimension range represents 68% of the spans or floor panel sizes used in the residential buildings.

From architectural design perspective, the prevalent layout pattern often pertains to apartments that encompass both a living room and a bedroom along a single spanning dimension. This particular apartment type features a span of 7.2 meters. The manufacturability of layout design was examined through reviewing the manuals and contemporary design practices within the existing prefabricated structural systems. These systems encompass CLT, Austral floor deck, precast solid floor, hollow core, and mini slab floor. The study determined that manufacturers of CLT and Austral floor deck can provide the typical 68% spans used in residential building designs at an economical cost. However, manufacturers of precast solid floor, hollow core, and mini slab floor face challenges in economically producing such common spans unless they can adapt their production processes to accommodate the specialised structural components required for the buildings. It should be noted that none of these manufacturers can efficiently produce the remaining 32% of the spans falling outside the 4.4-7.4 meters range in a cost-effective manner.

6.2.2 Sub-objective 2: Architectural-Structural Interrelationships

To mathematically model the interrelationships between architectural and structural layout designs

To achieve this objective, the emphasis was placed on comprehending the mutual influence of architectural and structural design on the spatial arrangements within a building.

The primary finding of the thesis is the intricate interconnection between the architectural layout and the positioning of load-bearing walls, both of which significantly impact the spatial arrangements within a building. The analysis has led to the conclusion that structural engineers can optimize the structural walls by ensuring their placement within a defined coordinate range of +/- 50 cm, as specified by the architect. Simultaneously, this positioning results in the optimisation of dimensions of floor panels. Hence, the configuration of spaces can be upheld according to the intended architectural design, while facilitating cost savings through the optimised placement of walls and dimensions of floor panels. Any process involving building layout modelling should incorporate the identification of optimal load-bearing wall placement, thereby influencing the dimensions of floor panels.

6.2.3 Sub-objective 3: Key stages in offsite prefabrication processes

To determine the most critical manufacturing processes influencing building layout

With this aim in mind, the research focus was oriented toward comprehending the processes of offsite building prefabrication, exploring beyond academic aspects to analyse practical implementations of mass-produced structural building components.

Aligned with the scope of this research, the study exclusively examined factories specialising in panelised prefabrication. Data and constraints related to the manufacturing processes were gathered by conducting a literature review, interviewing staff from Xlam company (an Australian CLT manufacturer), exploring their websites and factory operation manuals, and participating in webinars about panelised timber systems.

Among the various manufacturing factors, raw materials, pressing time, and CNC machining time emerge as the most pivotal elements that influence the efficiency and economy of CLT panel production for building layouts. The cutting plan from a mother panel (or billet) determines the quantity of raw material needed and the extent of wastage during the production process. Pressing time assumes significance due to its time-intensive nature, closely tied to the required number of timber layers within a CLT panel, as well as the billet's length and thickness. Equally critical is the CNC machining time, a decisive manufacturing factor influenced by the dimensions of prefabricated panels of varying types to accommodate specific building layouts. The CNC machining time also depends on factors such as the the number of panels cut from each billet, the percentage of waste material produced after cutting from the billet, and the estimated process time from coding software. Ultimately, these parameters were used to validate the literature formula against real manufacturing practices.

6.2.4 Sub-objective 4: Optimal design for manufacture

To integrate manufacturing processes in building layout design for attaining optimal factory efficiency and preserving architectural flexibility

To achieve the fourth objective, the thesis centered on integrating MC during the preliminary design stage. This was achieved by formulating a mathematical model for designing building layouts. The model accommodates a certain level of standardization while upholding a heightened degree of flexibility in the design of building layouts.

The development of the model incorporated findings from the preceding sub-objectives. This involved parameterising data linked to manufacturing processes, as well as data associated with design spans. Additionally, the model integrated manufacturing efficiency constraints, including the limits on the panel dimensions, pressing and CNC machining times. It also adhered to the limits imposed by layout design considerations, including the location of the load-bearing walls, upper and lower limits for the building spans, and dimensions of floor

panels. The study used Cross-Laminated Timber as a mass customisable prefabricated system increasingly gaining momentum in Australia's building sector to test and validate the model.

The objective function is to find the optimal production process which leads to maximising the manufacturer's profit. This objective was subject to reducing the client's costs without compromising the architectural design. The results showed that multistorey apartments can be adapted for mass customisation and in doing so, can result in a 10% cost saving for the client and a 1% increase in profit for the manufacturer. The 10% cost saving for the client is achieved through lowering the production cost by ordering a larger number of standard panel sizes. The results indicate that buildings made of a single category of thickness of panels but customised in various lengths to suit different building layouts are the most profitable scenario for CLT manufacturers and are a cost-effective option for clients.

6.3 Research contribution and potential use in the building industry

In this section the research contributions and potential uses of the research findings in the building industry are discussed.

6.3.1 Implication for research

The implications of this thesis for research are as follows:

Comprehensive Approach to Mass Customisation (MC) Literature: The existing MC literature has primarily examined one aspect of MC, often overlooking the simultaneous consideration of both demand-side factors (designers and building developers) and supply-side factors (manufacturers) requirements. This research sheds light on the need to bridge this gap by integrating these perspectives.

Lack of Quantitative Integration of Design and Production: Quantitative research that effectively integrates design and production processes is notably lacking. While a few studies have touched on the production processes of prefabricated systems, they fall short of parameterising production processes and variables, preventing accurate measurement of cost and time savings post MC implementation:

Optimised Layout Design and Manufacturability: The prevalent optimised layout design methods in the literature tend to neglect manufacturability concerns and architectural

flexibility. In this context, the research introduces a framework that not only parameterises manufacturing processes but also integrates these processes into building layout design. This integration aims to achieve optimal factory efficiency while preserving architectural flexibility.

Clustering Architectural Designs for Manufacturing: An important aspect of efficient offsite fabrication involves identifying and clustering similarities in various building layouts to create building families. However, studies analysing and clustering architectural designs for manufacturing purposes are currently scarce. This research endeavors to address this gap by exploring and assessing architectural designs from a manufacturing perspective. A systematic assessment of prevalent design patterns in residential building layouts from a manufacturability standpoint is undertaken. This analysis serves to provide insights into the feasibility of these patterns for efficient offsite fabrication.

Client-Centered Design and Efficient Manufacturing Integration: The research contributes to addressing the aforementioned gaps by focusing on the integration of client-driven design and efficient manufacturing. It proposes and develops a comprehensive framework aimed at parameterising manufacturing processes and seamlessly integrating these processes into building layout design. The objective is to enhance factory efficiency while ensuring architectural adaptability.

Overall, this research endeavors to provide a more comprehensive and integrated approach to Mass Customisation literature, quantitative research in design and production integration, manufacturability considerations in layout design, and clustering architectural designs for efficient offsite fabrication.

6.3.2 Implication for practice

Identifying similarities with the clustering technique in architectural design and structural spans of different apartments can help to provide dwellings' modular design offered to different clients. Classifying apartments and buildings enable building architects to effectively and efficiently adapt the design of residential buildings to modular dimensions. The proposed modular design patterns contribute to the mass customisation of the building in the conceptual design stage. Also the mathematical model contributes to the mass customisation of the building in the preliminary design stage by balancing the manufacturer's profit and the client's cost. The model helps architects systematically determine the structural wall placement with the optimal production process.

This research will benefit primarily (i) the architects to respond to the mid-income housing clients' demand in a modular apartment discussed here, (ii) the prospective manufacturers of components who will get essential standards for manufacturing components, and also (iii) policymakers to frame policy concerning the supply of mid-income housing units using prefabricated building system.

6.4 Research limitation and future research direction

This thesis represents an initial effort to address the gaps identified earlier in the literature concerning the implementation of MC in the building sector. The study encountered a number of challenges and limitations, which are outlined below, to create a path for further exploration and future research:

6.4.1 Research limitations

- The panelised prefabrication, building spans and modular design scenarios discussed in this thesis are within the context of Australian housing sector. While this is expected to be applicable to multi-story panelised timber buildings any where, not all cities may find these equally applicable. Contextualisation is, therefore, necessary.
- Transport and installation requirements have been considered as constraints in the model development. However, this research has not investigated the extent of the impact that design may have on transport and installation requirements. In other words, design improvements have only been made for meeting the requirements of transport and installation stages but not for optimisation of these two stages.
- The model formulations have been developed for rectilinear floor plans, commonly found in multi-storey buildings. However, since architectural floor plans can be more intricate and non-rectilinear, further research is needed to expand and validate the proposed model for complex building layouts.

6.4.2 Future research

This study is expected to pave way for further research in the following directions:

- The modular design scenarios have been proposed for apartment layouts, specifically focusing on certain building types categorized by the number of floors. The thesis has discovered that the common span sizes are primarily influenced by the number of floor levels in multistorey buildings and secondarily by the arrangement of living

spaces. Further research is required to investigate those statistical outliers that do not meet such commonalities in span.

- Exploring the potential linkage between the mathematical model of MC and Building Information Modelling (BIM) for the purpose of implementing automated design offers an avenue for future investigation. Such automated design could enable diverse spatial arrangements based on different panel dimensions.
- The design optimisation model for mass customization introduced in this thesis operates under the premise that a panelised system is suitable for a country like Australia as a modular building approach. Therefore, further research is needed to study alternative forms of component modularity for mass customisation of housing. While the developed model is tailored to a CLT structural system, there is potential to adapt it to other structural systems, including precast concrete structures.

Bibliography

- ABS (2017). "Census of Population and Housing: Reflecting Australia." *Australian Bureau of Statistics*, <https://www.abs.gov.au>.
- ACIF (2019). "Australia Construction market report." *Australian Construction Industry Forum (ACIF)*, <https://www.acif.com.au/>.
- 3DHUBS (2021). "Guide CNC machining: The complete engineering guide." *Exhibition catalogue*, 3DHUBS, ed., Walla Walla University, Washington-USA.
- Abdel-Basset, M., Abdel-Fatah, L., and Sangaiah, A. (2018). "Chapter 10-metaheuristic algorithms: a comprehensive review. Computational intelligence for multimedia big data on the cloud with engineering applications." *Elsevier Inc Amsterdam*.
- Abdul-Kadir, M. R., and Price, A. D. F. (1995). "Conceptual phase of construction projects." *International Journal of Project Management*, 13(6), 387-393.
- Abiri, B. (2020). "Decision-Making for Cross-Laminated Timber Modular Construction Logistics Using Discrete-Event Simulation." *Master of Science in Civil Engineering, Oregon State University*.
- Abulfahem, M. F. (2012). "Mass customization limitation and guidelines in prefabricated construction." *Advanced Construction Building Technology for Society*, International Council for Research and Innovation in Building and Construction, Germany, 1-6.
- Ahmadian, F. A., Akbarnezhad, A., Rashidi, T. H., and Waller, S. T. (2016). "Accounting for transport times in planning off-site shipment of construction materials." *Journal of Construction Engineering and Management*, 142(1), 04015050.
- Alidaee, B., Wang, H., and Landram, F. (2011). "On the flexible demand assignment problems: case of unmanned aerial vehicles." *IEEE transactions on automation science and engineering*, 8(4), 865-868.
- Altman, D. G., and Bland, J. M. (1995). "Statistics notes: the normal distribution." *Bmj*, 310(6975), 298.
- Alwi, S., Hampson, K., and Mohamed, S. "Non value-adding activities: a comparative study of Indonesian and Australian construction projects." Proc., *Proceedings of the 10th Conference of the International Group for Lean Construction*, Federal University of Rio Grande do Sul, 627-638.
- Arashpour, M., Wakefield, R., Blismas, N., Lee, E. (2014). "Analysis of disruptions caused by construction field rework on productivity in residential projects.", *Journal of construction economic and management* 140(2), 04013053.
- Arvin, S. A., and House, D. H. (2002). "Modeling architectural design objectives in physically based space planning." *Automation in Construction*, 11(2), 213-225.
- Augusto, T., Mounir, K., and Melo, A. M. (2012). "A cost optimization-based design of precast concrete floors using genetic algorithms." *Automation in construction*, 22, 348-356.
- Australprecast (2021). "Precast Concrete Solutions." *Australprecast*, ed., Australprecast, Australia.
- Baghdadi, A., Heristchian, M., and Kloft, H. (2020). "Design of prefabricated wall-floor building systems using meta-heuristic optimization algorithms." *Automation in Construction*, 114(103156), 1-10.
- Balakrishnan, A., and Geunes, J. (2003). "Production planning with flexible product specifications: An application to specialty steel manufacturing." *Operations Research*, 51(1), 94-112.

- Baldwin, C. Y., Clark, K. B., and Clark, K. B. (2000). "Design rules: The power of modularity", *MIT press*.
- Barlow, J. (1999). "From craft production to mass customisation. Innovation requirements for the UK housebuilding industry." *Journal of Housing studies*, 14(1), 23-42.
- Barlow, J., and Ozaki, R. (2003). "Achieving 'customer focus' in private housebuilding: Current practice and lessons from other industries." *Journal of Housing Studies*, 18(1), 87-101.
- Baušys, R., and Pankrašovaite (2005). "Optimization of architectural layout by the improved genetic algorithm." *Journal of Civil Engineering and Management* 11(1), 13-21.
- Benros, D., and Duarte, J. P. (2009). "An integrated system for providing mass customized housing." *Automation in Construction*, 18(3), 310-320.
- Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., and Woetzel, J. (2019). "Modular construction: From projects to products." *McKinsey & Company: Capital Projects & Infrastructure*, 1-34.
- Bianconi, F., Filippucci, M., and Buffi, A. (2019). "Automated design and modeling for mass-customized housing. A web-based design space catalog for timber structures." *Automation in Construction*, 103, 13-25.
- Bock, T., and Linner, T. (2010). "Mass Customization in a knowledge-based Construction Industry for sustainable high-performance Building Production." *CIB World Congress*.
- Boër, C. R., Pedrazzoli, P., Bettoni, A., and Sorlini, M. (2013). *Mass customization and sustainability*, Springer.
- Böhme, T., Escribano, A., Heffernan, E. E., and Beazley, S. (2018). "Causes and mitigation for declining productivity in the Australian mid-rise residential construction sector." *Built Environment Project and Asset Management*, 8(3), 253-266.
- Bonev, M., Wörösch, M., and Hvam, L. (2015). "Utilizing platforms in industrialized construction." *Construction Innovation*, 15(1), 85-102.
- Brandner, R. (2013). "Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report." *Proc., Focus Solid Timber Solutions-European Conference on Cross Laminated Timber (CLT)*, University of Bath, 3-36.
- Brandt, K., Wilson, A., Bender, D., Dolan, J. D., and Wolcott, M. P. (2019). "Techno-Economic Analysis for Manufacturing Cross-Laminated Timber." *BioResources*, 14(4), 7790-7804.
- Broekhuizen, T. L. J., and Alsem, K. J. (2002). "Success factors for mass customization: a conceptual model." *Journal of Market-Focused Management*, 5(4), 309-330.
- Buck, D., Hagman, O., Wang, A., and Gustafsson, A. "Further development of Cross-laminated timber (CLT): Mechanical tests on 45 alternating layers." *Proc., World Conference on Timber Engineering (WCTE 2016)*, Vienna University of Technology, Austria.
- Can, K. C. (2008). "Postponement, mass customization, modularization and customer order decoupling point: building the model of relationships." *Degree of Master, Linköping University*, Linköping University.
- Caprani, C. (2010). "Preliminary Design of Building Structures 3rd Year Structural Engineering." Monash University.
- CCAA (2003). "Guide to Residential Floors-concrete." CCAA T49-2003, Cement Concrete & Aggregates Australia 2003, Australia, NSW, 1-46.
- CIA (2009). Precast concrete handbook, *Construction Institute of Australia*.
- Commission, P. (2013). "On efficiency and effectiveness: some definition." P. Commission, ed., Commonwealth of Australia, Australia, Canberra.
- Cuperus, Y. "Mass customization in housing, an open building/lean construction study." *Proc., Proceedings of Dense Living Urban Structures International Conference on Open Building*, Hong Kong, China, Citeseer, 113.

- da Rocha, C. G., and El Ghaz, H. B. (2019). "A model for implementing product modularity in buildings design." *Engineering, Construction and Architectural Management*, 27(3), 680-695.
- Da Rocha, C. G., and Formoso, C. T. (2013). "Configuring product variants in customisation strategies for house-building." *Open House International*, 38(3), 48.
- Da Rocha, C. G., and Kemmer, S. (2018). "Integrating product and process design in construction." *Construction Management and Economics*, 36(9), 535-543.
- Da Silveira, G., Borenstein, D., and Fogliatto, F. S. (2001). "Mass customization: Literature review and research directions." *International journal of production economics*, 72(1), 1-13.
- Dai, Z., and Scott, M. J. (2007). "Product platform design through sensitivity analysis and cluster analysis." *Journal of Intelligent Manufacturing*, 18(1), 97-113.
- de Araujo Carneiro, B. (2019). "A scheduling model for industrial process management: an innovative application of cross-laminated timber (CLT) manufacturing." *Master of Applied Science University of British Columbia*, University of British Columbia.
- de Weck, O. L., Suh, E. S., and Chang, D. "Product Family and Platform Portfolio Optimization." *Proc., ASME 2003 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 175-185.
- Denzin, N. (2010). "The fundamentals." *An Introduction to Triangulation*, D. Rugg, editor. *UNAIDS Monitoring and Evaluation Fundamentals*, Geneva, Switzerland, 12.
- Diday, E., and Simon, J. (1976). "Clustering analysis." *Digital pattern recognition*, Springer, 47-94.
- Dowling, R. (2005). "Residential building in Australia, 1993–2003." *Journal of Urban Policy Research*, 23(4), 447-464.
- Downing, B. (2016). "CrossLam Design Guide." *CrossLam*, ed., CrossLam, Australia.
- Duarte, J. P. (2005). "A discursive grammar for customizing mass housing: the case of Siza's houses at Malagueira." *Automation in Construction*, 14(2), 265-275.
- Duray, R., Ward, P. T., Milligan, G. W., and Berry, W. L. (2000). "Approaches to mass customization: configurations and empirical validation." *Journal of Operations Management*, 18(6), 605-625.
- Duray, R. (2002). "Mass customization origins: mass or custom manufacturing?" *International Journal of Operations & Production Management*, 22(3), 314-328.
- Elliott, A. C., and Woodward, W. A. (2007). "Statistical analysis quick reference guidebook: With SPSS examples", *Sage*.
- Farr, E. R., Piroozfar, P. A., and Robinson, D. (2014). "BIM as a generic configurator for facilitation of customisation in the AEC industry." *Automation in Construction*, 45, 119-125.
- Fettermann, D., Tortorella, G., and Taboada, C. M. (2019). "Mass customization process in companies from the housing sector in Brazil." *Managing Innovation in Highly Restrictive Environments*, Springer, 99-118.
- Fogliatto, F. S., da Silveira, G. J. C., and Borenstein, D. (2012). "The mass customization decade: An updated review of the literature." *International Journal of Production Economics*, 138(1), 14-25.
- Forsythe, P. J., and Sepasgozar, S. (2019). "Measuring installation productivity in prefabricated timber construction." *Engineering, Construction and Architectural Management*, 26(4), 578-595.
- Frost, N. (2018). "One bedroom vs two bedroom apartments – which is better for the first home buyer?", <https://www.domain.com.au/advice/one-bedroom-v-two-bedroom-apartments-which-is-better-for-the-first-home-buyer-20180102-h02xg7/>. (15February, 2021).

- Frutos, J. D., Santos, E. R., and Borenstein, D. (2016). "Decision Support System for Product Configuration in Mass Customization Environments." *Concurrent Engineering*, 12(2), 131-144.
- Fukao, S. "Function of grids in adaptable buildings." *Proc., IASS International Conference on Adaptability in Design and Construction*, 123-127.
- FWPA (2014). "Massive Timber Construction Systems Cross-laminated Timber (CLT)." *Forest and Wood Products NSW-Australia*, 1-24.
- Gbadamosi, A.-Q., Mahamadu, A.-M., Oyedele, L. O., Akinade, O. O., Manu, P., Mahdjoubi, L., and Aigbavboa, C. (2019). "Offsite construction: Developing a BIM-Based optimizer for assembly." *Journal of cleaner production*, 215, 1180-1190.
- Ghasemi, A., and Zahediasl, S. (2012). "Normality tests for statistical analysis: a guide for non-statisticians." *International journal of endocrinology and metabolism*, 10(2), 486.
- Gibb, A., and Isack, F. (2010). "Re-engineering through pre-assembly: client expectations and drivers." *Building Research & Information*, 31(2), 146-160.
- Gibb, A. G. (2001). "Standardization and pre-assembly-distinguishing myth from reality using case study research." *Construction Management & Economics*, 19(3), 307-315.
- Gilbert III, L. R., Omar, M., and Farid, A. M. "An integrated QFD and axiomatic design methodology for the satisfaction of temporary housing stakeholders." *Proc., the 8th International Conference on Axiomatic Design*, Citeseer.
- Gilmore, J. H., and Pine, B. J. (1997). "The four faces of mass customization." *Harvard Business Review*, 75(1), 91-102.
- Goh, M., and Goh, Y. M. (2019). "Lean production theory-based simulation of modular construction processes." *Automation in Construction*, 101, 227-244.
- Gosling, J., and Naim, M. M. (2009). "Engineer-to-order supply chain management: A literature review and research agenda." *International journal of production economics*, 122(2), 741-754.
- Gosling, J., Pero, M., Schoenwitz, M., Towill, D., and Cigolini, R. (2016). "Defining and categorizing modules in building projects: An international perspective." *Journal of Construction Engineering and Management*, 142(11), 401-420.
- Hasan, A., Baroudi, B., Elmualim, A., and Rameezdeen, R. (2018). "Factors affecting construction productivity: a 30 year systematic review." *Engineering, Construction Architectural Management*, 25(7), 916-937.
- Hassanat, A., Almohammadi, K., Alkafaween, E., Abunawas, E., Hammouri, A., and Prasath, V. (2019). "Choosing mutation and crossover ratios for genetic algorithms—a review with a new dynamic approach." *Information*, 10(12), 1-36.
- Haug, A., Ladeby, K., and Edwards, K. (2009). "From engineer-to-order to mass customization." *Journal of Management Research News*, 32(7), 633-644.
- Haverila, M. J., and Fehr, K. (2016). "The impact of product superiority on customer satisfaction in project management." *International Journal of Project Management*, 34(4), 570-583.
- Hebel (2010). "Technical Manual Part 4: Wall & Floor Panel Design & Construction." *Hebel, ed.*, Hebel, Australia.
- Hofman, E., Halman, J. I. M., and Ion, R. A. (2006). "Variation in Housing Design: Identifying Customer Preferences." *Housing Studies*, 21(6), 929-943.
- Hofmeyer, H., Rutten, H. S., and Fijneman, H. J. (2006). "Interaction of spatial and structural design, an automated approach." *Design Studies*, 27(4), 423-438.
- HollowcoreConcrete (2018). "Load span chart flyer for hollow core slabs." *Hollow Concrete, ed.*, Hollowcore Concrete Pty Ltd
- Homayouni, H. (2007). "A genetic algorithm approach to space layout planning optimization." *Doctoral dissertation, University of Washington*, University of Washington.

- Hughes, R., and Thorpe, D. (2014). "A review of enabling factors in construction industry productivity in an Australian environment." *Construction Innovation*, 14(2), 210-228.
- Hvam, L., Mortensen, N. H., and Riis, J. (2008). Product customization, *Springer Science & Business Media*, Springer-Verlag.
- IndustryEdge (2015). "Market trends in multi-residential construction." *Industry Edge*, Australia.
- IndustryEdge (2020). "Australia's growing CLT market." *Industry Edge*, Australia.
- Isaac, S., Bock, T., and Stoliar, Y. (2016). "A methodology for the optimal modularization of building design." *Automation in Construction*, 65(1), 116-124.
- Jansson, G. (2013). "Platforms in industrialised house-building." PhD, Luleå University of Technology, Luleå University of Technology
- Jansson, G., Johnsson, H., and Jensen, P. "Modularization in a housing platform for mass customization." *Proc., Annual ARCOM Conference*.
- Jensen, K. N. (2020). "Mass Customization in Building & Construction: mass customization as a strategy improving the productivity within the building and construction industry." PhD, Aalborg Universitetsforlag, Aalborg University Press.
- Jensen, P. (2014). "Configuration of platform architectures in construction." Ph.D, Luleå University of Technology, Luleå University of Technology
- Jiao, J., Ma, Q., and Tseng, M. M. (2003). "Towards high value-added products and services: mass customization and beyond." *Technovation*, 23(10), 809-821.
- Jiao, J., Tseng, M. M., Ma, Q., and Zou, Y. (2000). "Generic bill-of-materials-and-operations for high-variety production management." *Concurrent Engineering*, 8(4), 297-321.
- Jiao, J. R., Simpson, T. W., and Siddique, Z. (2007). "Product family design and platform-based product development: a state-of-the-art review." *Journal of Intelligent Manufacturing*, 18(1), 5-29.
- Joanes, D. N., and Gill, C. A. (1998). "Comparing measures of sample skewness and kurtosis." *Journal of the Royal Statistical Society*, 47(1), 183-189.
- Jonsson, H., and Rudberg, M. (2015). "A production system classification matrix: Matching product standardization and production system design." *Journal of construction engineering and management*, 141(6), 205-216.
- Juan, Y.-K., Shih, S.-G., and Perng, Y.-H. (2006). "Decision support for housing customization: A hybrid approach using case-based reasoning and genetic algorithm." *Expert Systems with Applications*, 31(1), 83-93.
- Toth, J., Pip Freebairn, and Hu, Y. M. (2015). "Australia's Construction Industry: Profile and Outlook ", AiGroup, Economics Research, 1-14.
- Kadam, P., and Bhalerao, S. (2010). "Sample size calculation." *International journal of Ayurveda research*, 1(1), 55.
- Kaiser, A., Larsson, M., and Girhammar, U. A. (2019). "From file to factory: Innovative design solutions for multi-storey timber buildings applied to project Zembla in Kalmar, Sweden." *Journal of Frontiers of Architectural Research*, 8(1), 1-16.
- Kassambara, A. (2017). "Practical guide to cluster analysis in R: Unsupervised machine learning", Sthda.
- Khalili, A., and Chua, D. (2014). "Integrated prefabrication configuration and component grouping for resource optimization of precast production." *Journal of Construction Engineering and Management*, 140(2), 401- 418.
- Khemlani, L., Timerman, A., Bennen, B., and Kalay, Y. E. (1998). "Intelligent representation for computer-aided building design." *Automation in Construction*, 8(1), 49-71.
- Kim, H., Querin, O., and Steven, G. (2002). "On the development of structural optimisation and its relevance in engineering design." *Design studies*, 23(1), 85-102.
- Knaack, U., Chung-Klatte, S., and Hasselbach, R. (2012). "Prefabricated systems, Principles of Construction", Birkhäuser, Delft University of Technology.

- Koskela, L. (2000). An exploration towards a production theory and its application to construction, VTT Technical Research Centre of Finland, Finland.
- Kremer, P. D. (2018). "Design for Mass Customised Manufacturing and Assembly (DfMCMA): A New Framework for Mass Timber Construction." *Mass Timber Construction Journal*, 1(1), 9-13.
- Kuhlang, P., Edtmayr, T., and Sihm, W. (2011). "Methodical approach to increase productivity and reduce lead time in assembly and production-logistic processes." *CIRP Journal of Manufacturing Science and Technology*, 4(1), 24-32.
- ABS (2017). "Census of Population and Housing: Reflecting Australia." *Australian Bureau of Statistics*, <https://www.abs.gov.au>.
- Ledinek (2018). "Turnkey CLT production line for Down under", <https://www.ledinek.com/clt-production-line-australia>.
- Ledinek (2018). "In Constructional Engineered Timber." L. Company, ed., Ledinek Company, Slovenia, 1-15.
- Lee, R. C. (1981). "Clustering analysis and its applications." *Advances in Information Systems Science*, Springer, 169-292.
- Lee, X. S., Khamidi, M. F., Kuppusamy, S., and Heng, C. T. "Client-oriented building mass customization (CoBMC)." *Proc., IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 112-121.
- Lehtiranta, L., Junnonen, J.-M., Kärnä, S., and Pekuri, L. (2015). "The constructive research approach: Problem solving for complex projects." *Designs, methods and practices for research of project management*, 95-106.
- Li, Y., Liu, C. (2010). "Malmquist indices of total factor productivity changes in the Australian construction industry.", *Construction management and economics*, 28(9), 933-945.
- Lin, X., and Lu, Y. (2020). "Research on Mathematical Model of Cost Budget in the Early Stage of Assembly Construction Project Based on Improved Neural Network Algorithm." *Mathematical Problems in Engineering*, 20 (1), 1-7.
- Livingstone, A., Menendez, J., Leitch, K., and Hairstans, R. "The case for mass customisation of structural timber design." *Proc., Structures Congress 2015*, ASCE, 2804-2814.
- Ma, C. Y., and van Ameijde, J. (2022). "Adaptable modular construction systems and multi-objective optimisation strategies for mass-customised housing: A new user-driven paradigm for high-rise living in Hong Kong." *International Journal of Architectural Computing*, 20(1), 96-113.
- Marchesi, M., and Ferrarato, I. A. (2015). "Addressing the adaptive customization of timber prefabricated housing through axiomatic design." *Procedia CIRP*, 34, 199-205.
- Marchesi, M., and Matt, D. T. (2017). "Design for Mass Customization: Rethinking Prefabricated Housing Using Axiomatic Design." *Journal of Architectural Engineering*, 23(3), 1-20.
- Maxwell, D. "Platforms for industrialised construction—lessons from Sweden." *Proc., International Conference of the Architectural Science Association*, The University of Adelaide, 785-795.
- Michalek, J., Choudhary, R., and Papalambros, P. (2002). "Architectural layout design optimization." *Engineering Optimization*, 34(5), 461-484.
- Mishra, P., Pandey, C. M., Singh, U., Gupta, A., Sahu, C., and Keshri, A. (2019). "Descriptive statistics and normality tests for statistical data." *Annals of cardiac anaesthesia*, 22(1), 67.
- Mitchell, A., Frame, I., Coday, A., and Hoxley, M. (2011). "A conceptual framework of the interface between the design and construction processes." *Engineering, Construction and Architectural Management*, 18(3), 297-309.

- Monizza, G. P., Rauch, E., and Matt, D. T. (2017). "Parametric and generative design techniques for mass-customization in building industry: a case study for glued-laminated timber." *Procedia CIRP*, 60, 392-397.
- Mourtzis, D., and Doukas, M. (2014). "The evolution of manufacturing systems: From craftsmanship to the era of customisation." *Handbook of research on design and management of lean production systems*, IGI Global, 1-29.
- National Heavy Vehicle Regulator. (2016). "National heavy vehicle mass and dimension limits." National Heavy Vehicle Regulator, Australia, 1-10.
- Neelamkavil, J. (2009). "Automation in the prefab and modular construction industry." *Proc., 26th symposium on construction robotics ISARC*, 299-304.
- Niazi, A., Dai, J. S., Balabani, S., and Seneviratne, L. (2006). "Product cost estimation: Technique classification and methodology review." *Journal of Manufacturing Science and Engineering*, 128, 563-575.
- Noguchi, M., and Hernández-Velasco, C. R. (2005). "A 'mass custom design' approach to upgrading conventional housing development in Mexico." *Habitat International*, 29(2), 325-336.
- NSW Department of Planning Environment (2015). "Apartment design guide." *NSW Department of Planning Environment*, NSW, Australia, 1-180.
- Olewnik, A., and Lewis, K. (2006). "A decision support framework for flexible system design." *Journal of Engineering Design*, 17(1), 75-97.
- Oyegoke, A. (2011). "The constructive research approach in project management research." *International Journal of Managing Projects in Business*, 4(4), 573-595.
- Pallant, J. (2020). "SPSS survival manual: A step by step guide to data analysis using IBM SPSS", Routledge.
- Petprakob, W. (2014). "Beam-slab Floor Optimization Using Genetic and Particle Swarm Optimization Algorithms." Master of Science (Engineering and Technology), Thammasat University, Thammasat University.
- Piller, F. T. (2004). "Mass customization: reflections on the state of the concept." *The International Journal of Flexible Manufacturing Systems*, 16(4), 313-334.
- Pine, B. J. (1991). "Paradigm Shift: from Mass Production to Mass Customization." Ph.D., Massachusetts Institute of Technology.
- Pine, B. J. (1993). "Mass customizing products and services." *Planning Review*, 21(4), 6-55.
- Pine, B. J., Victor, B., and Boynton, A. C. (1993). "Making mass customization work." *Harvard business review*, 71(5), 108-111.
- Piroozfar, P., Farr, E. R., Hvam, L., Robinson, D., and Shafiee, S. (2019). "Configuration platform for customisation of design, manufacturing and assembly processes of building façade systems: A building information modelling perspective." *Automation in Construction*, 106, 1-14.
- Piroozfar, P. A., and Piller, F. T. (2013). *Mass customisation and personalisation in architecture and construction*, Routledge, New York.
- Pollack, J. (2007). "The changing paradigms of project management." *International journal of project management*, 25(3), 266-274.
- Popovic, D. (2018). "Off-site manufacturing systems development in timber house building: Towards mass customization-oriented manufacturing.", Ph.D., Jönköping University, School of Engineering, Jönköping, Sweden.
- Ramaji, I. J., and Memari, A. M. (2015). "Information Exchange Standardization for BIM Application to Multi-Story Modular Residential Buildings." *AEI 2015*, 13-24.
- Ramaji, I. J., and Memari, A. M. (2016). "Product Architecture Model for Multistory Modular Buildings." *Journal of Construction Engineering and Management*, 142(10), 40-47.
- Riala, M., and Ilola, L. (2014). "Multi-storey timber construction and bioeconomy—barriers and opportunities." *Scandinavian Journal of Forest Research*, 29(4), 367-377.

- Rocha, C. G. d. (2011). "A conceptual framework for defining customisation strategies in the house-building sector." PhD, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil.
- Rocha, C. G. d., Anzanello, M. J., and Gerchman, M. (2018). "Method to Assess the Match between Clients' Input and Decoupling Points in Customized Building Projects." *Journal of Construction Engineering and Management*, 144(5),1-9.
- Rocha, C. G. d., Formoso, C. T., and Tzortzopoulos, P. (2015). "Adopting product modularity in house building to support mass customisation." *Sustainability*, 7(5), 4919-4937.
- Rosewall, T., and Shoory, M. (2017). "Houses and Apartments in Australia." *Australian Economy*, 1-10.
- Roy, R., Brown, J., Gaze, C., (2003). "Re-engineering the construction process in the speculative house-building sector." *Journal of Construction Management & Economics*, 21(2), 137-146.
- Roy, U. K., and Roy, M. (2016). "Space standardisation of low-income housing units in India." *International Journal of Housing Markets and Analysis*, 9(1), 89-109.
- Sacks, R. (2016). "What constitutes good production flow in construction?" *Journal of Construction Management & Economics*, 34(9), 641-656.
- Sahab, M., Ashour, A., and Toropov, V. (2005). "Cost optimisation of reinforced concrete flat slab buildings." *Engineering structures*, 27(3), 313-322.
- Said, H. M., Chalasani, T., and Logan, S. (2017). "Exterior prefabricated panelized walls platform optimization." *Automation in Construction*, 76, 1-13.
- Salkin, C., Oner, M., Ustundag, A., and Cevikcan, E. (2018). "A conceptual framework for Industry 4.0." *Industry 4.0: managing the digital transformation*, Springer, 3-23.
- Salvador, F., De Holan, P. M., and Piller, F. (2009). "Cracking the code of mass customization." *MIT Sloan management review*, 50(3), 71-78.
- Salvador, F., Forza, C., and Rungtusanatham, M. (2002). "How to mass customize: Product architectures, sourcing configurations." *Business Horizons*, 45(4), 61-69.
- Schmenner, R. W., and Swink, M. L. (1998). "On theory in operations management." *Journal of operations management*, 17(1), 97-113.
- Schoenwitz, M., Naim, M., and Potter, A. (2012). "The nature of choice in mass customized house building." *Construction Management and Economics*, 30(3), 203-219.
- Schoenwitz, M., Potter, A., Gosling, J., and Naim, M. (2017). "Product, process and customer preference alignment in prefabricated house building." *International Journal of Production Economics*, 183, 79-90.
- Shafiee, S., Piroozfar, P., Hvam, L., Farr, E. R., Huang, G. Q., Pan, W., Kudsk, A., Rasmussen, J. B., and Korell, M. (2020). "Modularisation strategies in the AEC industry: a comparative analysis." *Architectural Engineering and Design Management*, 16(4), 270-292.
- Sharafi, P. (2013). "Cost optimization of the preliminary design layout of reinforced concrete framed buildings." PhD, University of Wollongong, Wollongong, Australia.
- Sharafi, P., Hadi, M. N., and Teh, L. H. (2012). "Heuristic approach for optimum cost and layout design of 3D reinforced concrete frames." *Journal of Structural Engineering*, 138(7), 853-863.
- Sharafi, P., Samali, B., Ronagh, H., and Ghodrati, M. (2017). "Automated spatial design of multi-story modular buildings using a unified matrix method." *Automation in Construction*, 82, 31-42.
- Sharafi, P., Teh, L. H., and Hadi, M. N. (2015). "Conceptual design optimization of rectilinear building frames: A knapsack problem approach." *Engineering Optimization*, 47(10), 1303-1323.

- Shin, Y., An, S.-H., Cho, H.-H., Kim, G.-H., and Kang, K.-I. (2008). "Application of information technology for mass customization in the housing construction industry in Korea." *Automation in Construction*, 17(7), 831-838.
- Solnosky, R. L., Memari, A. M., and Ramaji, I. J. "Structural BIM processes for modular multi-story buildings in design and construction." *Proc., 2nd residential building design & construction conference*, 201-215.
- Stehn, L., and Bergström, M. (2002). "Integrated design and production of multi-storey timber frame houses—production effects caused by customer-oriented design." *International Journal of Production Economics*, 77(3), 259-269.
- Su, J. C. P., Chang, Y.-L., and Ferguson, M. (2005). "Evaluation of postponement structures to accommodate mass customization." *Journal of Operations Management*, 23(3-4), 305-318.
- Tan, X., Hammad, A., and Fazio, P. (2010). "Automated code compliance checking for building envelope design." *Journal of Computing in Civil Engineering*, 24(2), 203-211.
- Tapao, A., and Cheerarot, R. (2017). "Optimal parameters and performance of artificial bee colony algorithm for minimum cost design of reinforced concrete frames." *Engineering Structures*, 151, 802-820.
- Tseng, M. M., Jiao, J., and Merchant, M. E. (1996). "Design for mass customization." *CIRP annals*, 45(1), 153-156.
- Ulrich, K. (1995). "The role of product architecture in the manufacturing firm." *Research policy*, 24(3), 419-440.
- Veenstra, V. S., Halman, J. I. M., and Voordijk, J. T. (2006). "A methodology for developing product platforms in the specific setting of the housebuilding industry." *Research in Engineering Design*, 17(3), 157-173.
- Wang, F., Lim, A., and Chen, H. "Flexible Demand Assignment Problem." *Proc., 16th European Conference on Artificial Intelligence*, 698-702.
- Wang, H., and Kimble, C. (2010). "Low-cost strategy through product architecture: lessons from China." *Journal of Business Strategy*, 31(3), 12-20.
- Wang, Y., and Duarte, J. P. (2002). "Automatic generation and fabrication of designs." *Automation in construction*, 11(3), 291-302.
- Warren-Myers, G., and Heywood, C. (2016). "Investigating demand-side stakeholders' ability to mainstream sustainability in residential property." *Pacific Rim Property Research Journal*, 22(1), 59-75.
- Wee, T. P., and Aurisicchio, M. "A Product Planning Framework For Mass-Customisation In Construction." *Proc., DS 92: Proceedings of the DESIGN 2018 15th International Design Conference*, 917-928.
- Wei, J., Noguchi, M., and Li, H. "Exploration of Human-Centered Mass Customisation and Personalization Potentials for Flood Shelter Evolution in Australia." *Proc., 8th Zero Energy Mass Custom Home International Conference*, 201-214.
- Wikner, J., and Rudberg, M. (2005). "Integrating production and engineering perspectives on the customer order decoupling point." *International Journal of Operations and Production Management*, 25(7), 623-641.
- XLam (2017). "XLam Australian Cross Laminated Timber Panel Structural Guide." *XLam Australia Design Guide VI*, XLam, Australia 26.
- Xu, Y., Landon, Y., Segonds, S., and Zhang, Y. (2017). "A decision support model in mass customization." *Computers & industrial engineering*, 114, 11-21.
- Yusof, N. M., Tahir, P. M., Lee, S. H., Khan, M. A., and James, R. M. S. (2019). "Mechanical and physical properties of Cross-Laminated Timber made from Acacia mangium wood as function of adhesive types." *Journal of Wood Science*, 65(1), 1-11.
- Yusoh, A. S., Tahir, P. M., Uyup, M. K. A., Lee, S. H., Husain, H., and Khaidzir, M. O. (2020). "Effect of wood species, clamping pressure and glue spread rate on the bonding

properties of cross-laminated timber (CLT) manufactured from tropical hardwoods." *Construction and Building Materials*, 1-8.

Zawidzki, M., Tateyama, K., and Nishikawa, I. (2011). "The constraints satisfaction problem approach in the design of an architectural functional layout." *Engineering Optimization*, 43(9), 943-966.

Appendices

Appendix A -Normality tests of data

- Normality tests architectural drawings data:

Quantitative methods to evaluate the normality of data include Shapiro-Wilk test, Kolmogrov-Smirnov test, skewness, kurtosis, z test, and mean with SD. SPSS software enables users to conduct all these tests. Each numerical method is appropriate for a specific sample size. As the current study population is considered as a large sample size ($n > 300$) skewness, kurtosis, and mean with SD are appropriate methods for testing normality (Mishra et al. 2019). Skewness measures symmetry, while kurtosis measures whether the data is heavy-tailed or light-tailed relative to normal distribution (Joanes and Gill 1998). For a large sample, the normality of data depends on the skewness and kurtosis absolute values. Either an absolute skewness value ≤ 2 or an absolute kurtosis ≤ 4 can be used to assess the normality. If the relative value of the SD with respect to the mean is less than 0.5, data is considered normal in large samples (Ghasemi and Zahediasl 2012; Mishra et al. 2019).

Table 33- Normality tests of all 710 apartment units dataset

Data type	Mean	Standard deviation	Skewness	Kurtosis
Span	6.1	1.4	-0.5	-0.8
Spanning direction dimension	8.4	2.1	0.5	2.3
Livingroom length	6.0	0.9	-0.2	0.3
Livingroom width	4.1	0.5	0.9	1.3
Kitchen length	3.3	0.7	1.8	4.6
Kitchen width	2.3	0.6	-1.5	1.6
Main bedroom length	4.4	0.6	0.5	-0.4
Main bedroom width	3.2	0.3	1.4	2.6
Additional bedroom length	3.7	0.3	0.7	0.8
Additional bedroom width	3.1	0.2	1.1	2.1
Bathroom length	2.5	0.3	0.6	2.0
Bathroom width	1.8	0.3	0.4	-0.3
Laundry length	1.4	0.2	1.3	3.8
Laundry width	0.9	0.2	1.9	3.8
Balcony length	5.3	2.5	1.7	3.9
Balcony width	2.5	0.8	1.4	4

- Analysing the dimensions of two different types of kitchens in a separate histogram:

Note that, Figure 30 and Table 34 show that the kitchen length is not normally distributed, and there is a large gap between the minimum width and the other width. Hence, this reflects the two recognisably different types of kitchens, i.e., one wall kitchen and rectangular kitchen. By separating these two types of kitchens, the average length, width, and the SD are not changed significantly, and it does not affect the Table13 results.

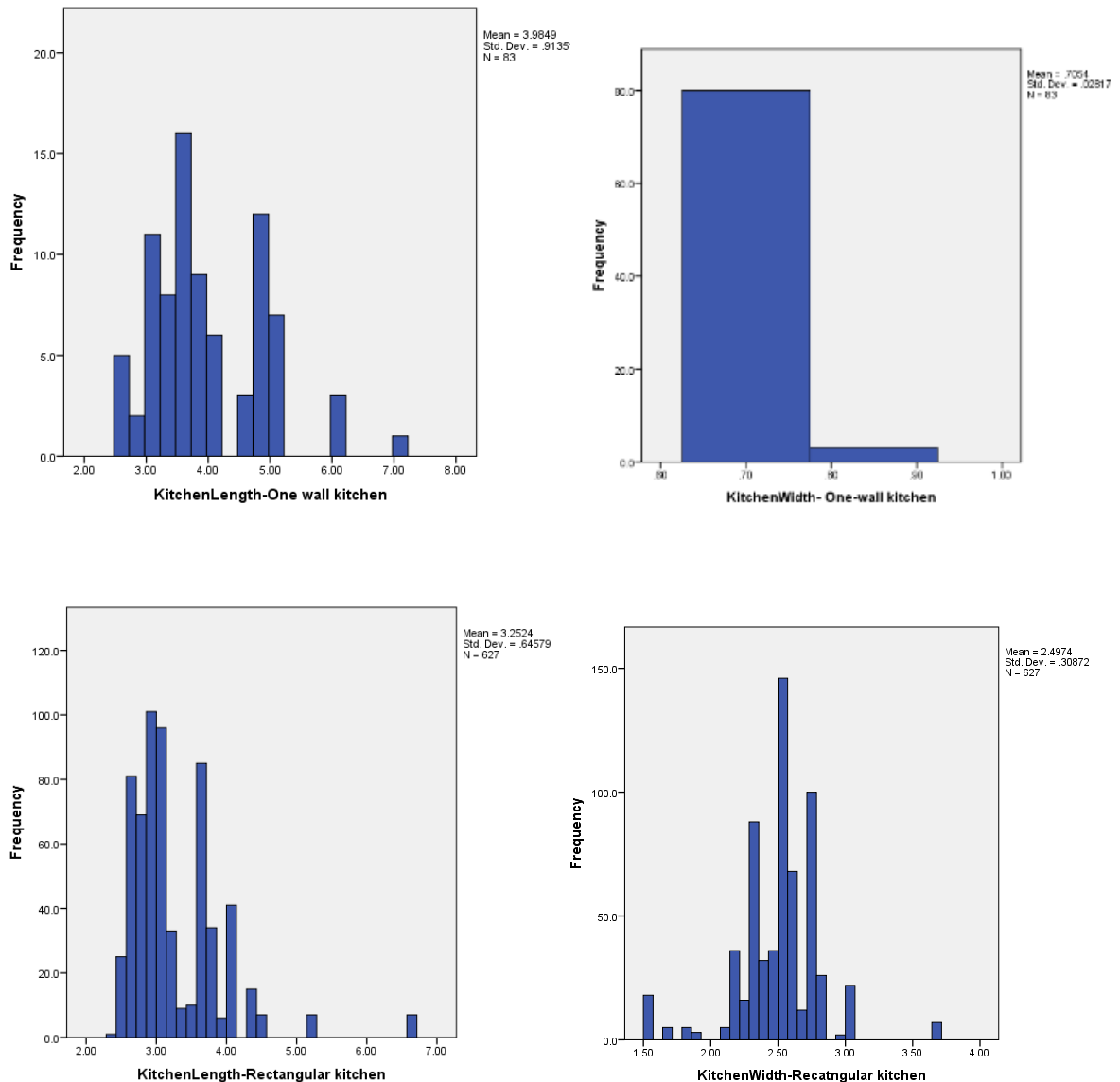


Figure 66- Frequency histograms of kitchen dimension based on kitchen type (left to right one wall kitchen and rectangular kitchen)

Appendix B- Spanning direction analysis

Table 34- Spanning direction and average land size

Average land size	Average land widths (meters)	Average land lengths (meters)
Architectural design characteristics		
Spanning direction aligned with apartment widths	40.5	66
Spanning direction aligned with apartment lengths	44	71.5

Table 35- Comparing building frontage in each building class

Building class	Low-rise buildings (Up to 5 storey- buildings Class1)	Mid-rise buildings (between 5 to 10 storey- buildings Class2)	High-rise buildings (more than 10 storey- buildings Class3)
Building characteristics			
Average building length (meters)	59	73	77
Average building width (meters)	40	44	50

Appendix C- Optimal number of clusters and clustering validation in data analysis

- Optimal number of clusters for analysing apartments architectural layouts design

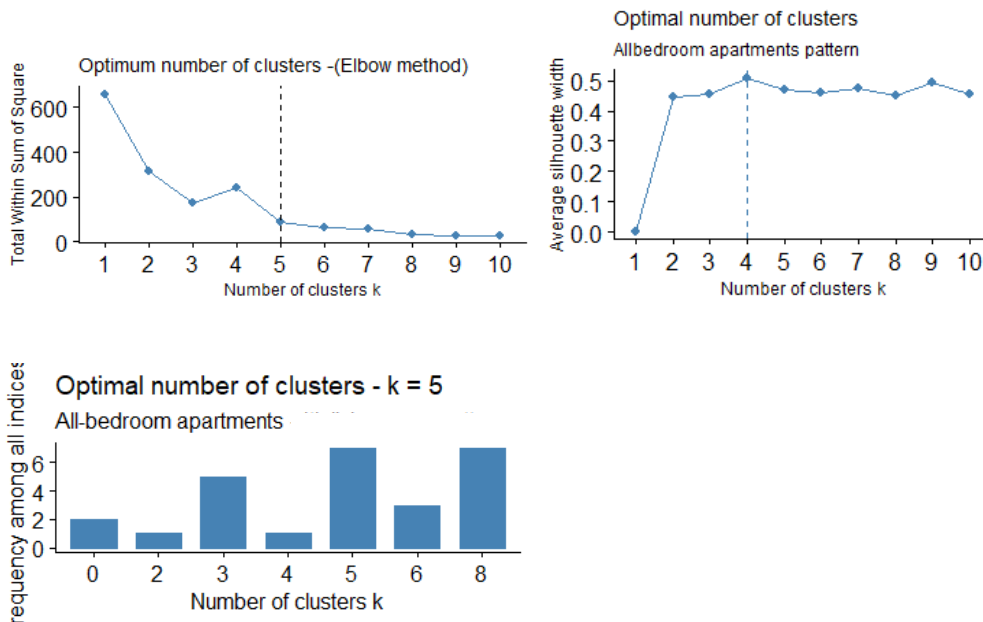


Figure 67- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data regardless of architectural design

Table 36- Number of clusters in clustering all apartments regardless of architectural design

Method	Elbow method	Average silhouette	Frequency among 30 indices	Number of final clusters
No of cluster in	5	4	5	5

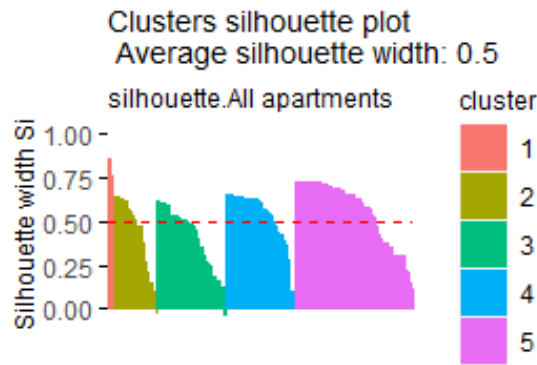


Figure 68- Cluster validation in analysing apartments regardless of architectural design

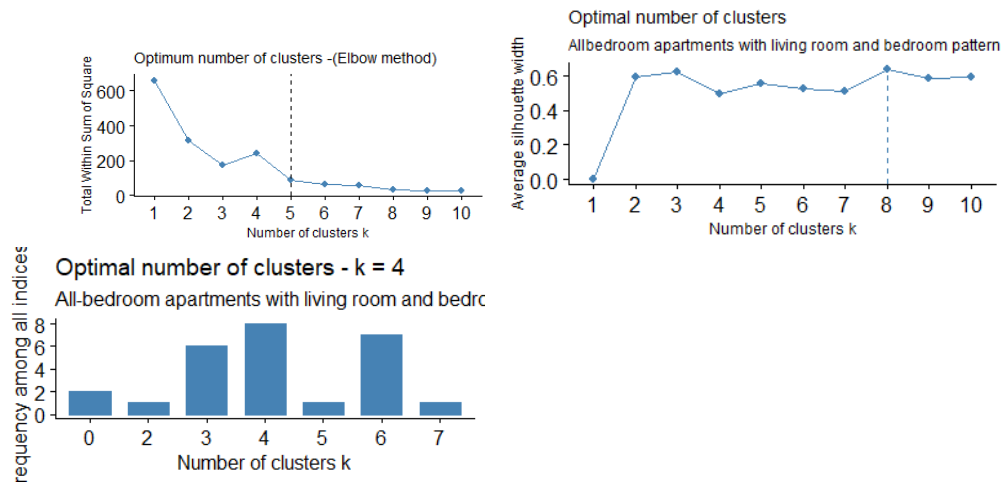


Figure 69- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on apartments architectural layouts design (Living room + bedroom)

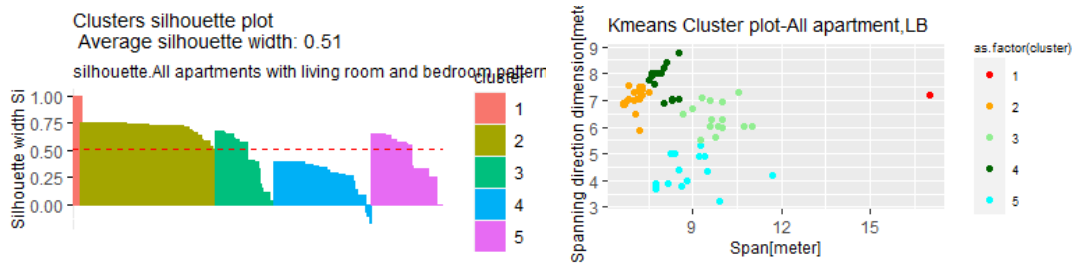


Figure 70- Cluster validation and scatter plots in analysing data based on apartments architectural layouts design (Living room +bedroom)

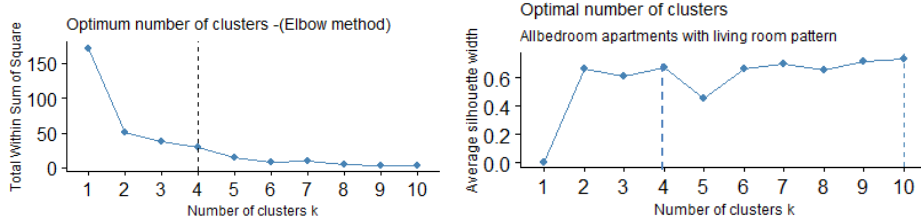


Figure 71- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on apartments architectural layouts design (Living room)

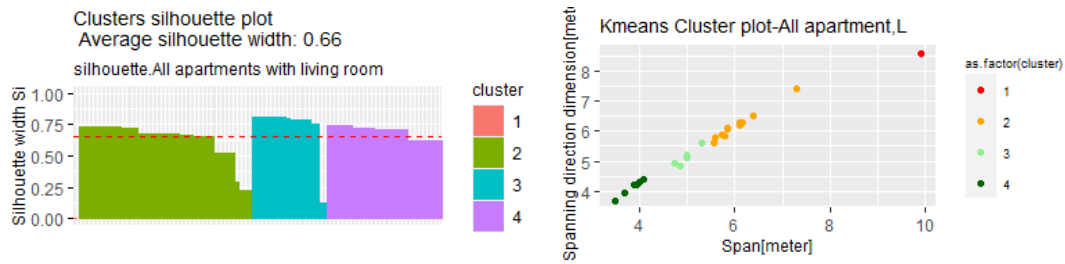


Figure 72- Cluster validation and scatter plots in analysing data based on apartments architectural layouts design (Living room)

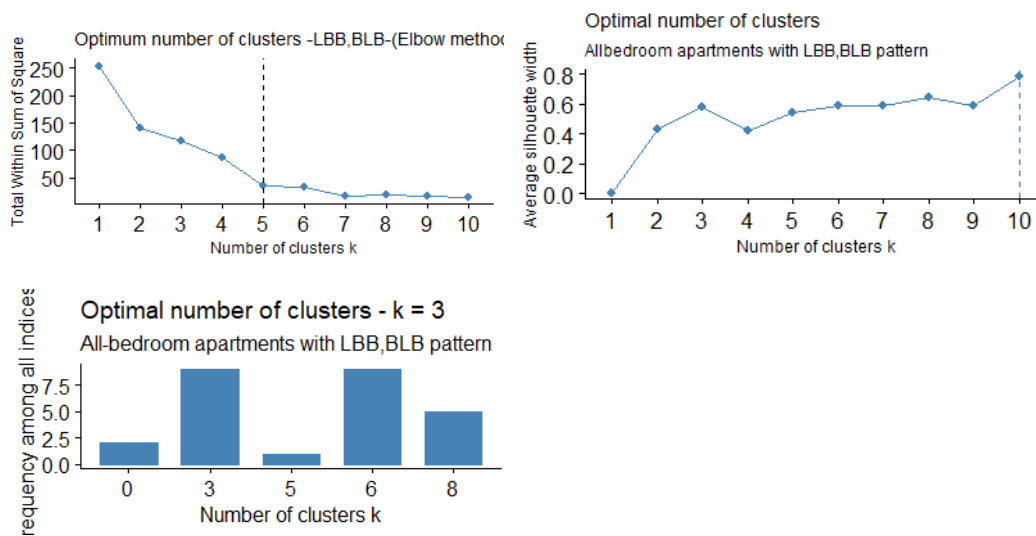


Figure 73- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on apartments architectural layouts design (Living room and two bedrooms)

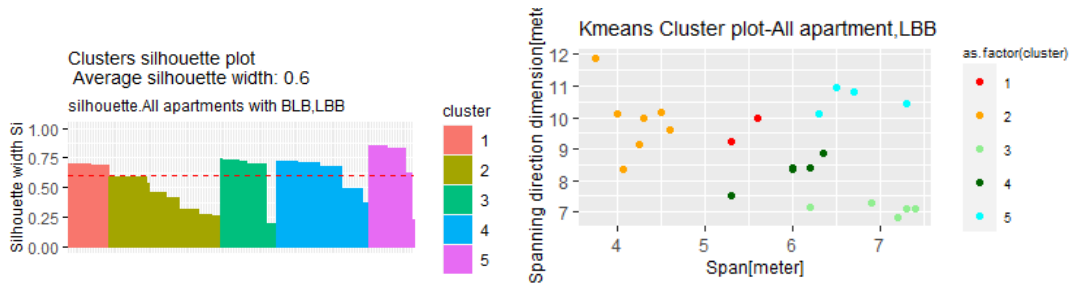


Figure 74- Cluster validation and scatter plots in analysing data based on apartments architectural layouts design (Living room and two bedrooms)

Table 37- Optimal number of clusters in analysing data based on the apartments architectural layouts design

Method	Elbow method	Average silhouette	Frequency among 30 indices	Number of final clusters
Spatial voids arrangement aligned with apartments spanning direction				
Living room	5	8	4	5
Bedroom and Livingroom	4	4	5	4
Livingroom and two bedrooms	5	10	3	5

▪ Optimal number of clusters for vertical design analysis

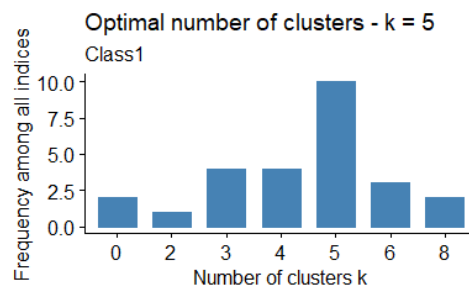
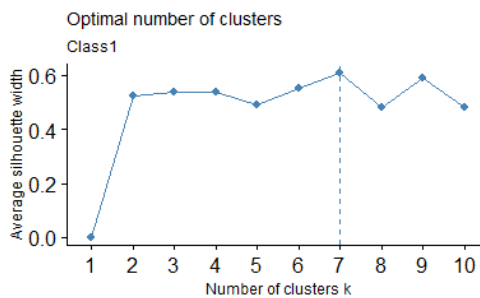
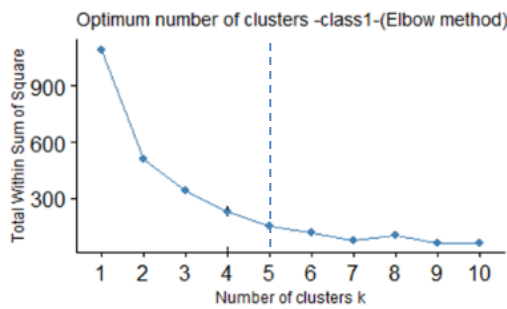


Figure 75- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on vertical design (building class1, i.e buildings with less than 5 storey)

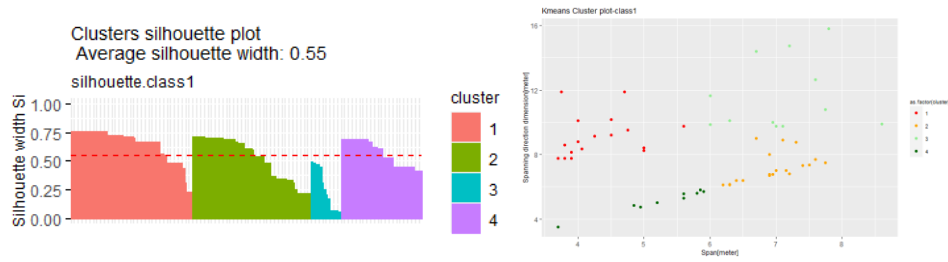


Figure 76- Cluster validation and scatter plots in vertical design data analysis (building Class1, i.e., buildings with less than 5 storey)

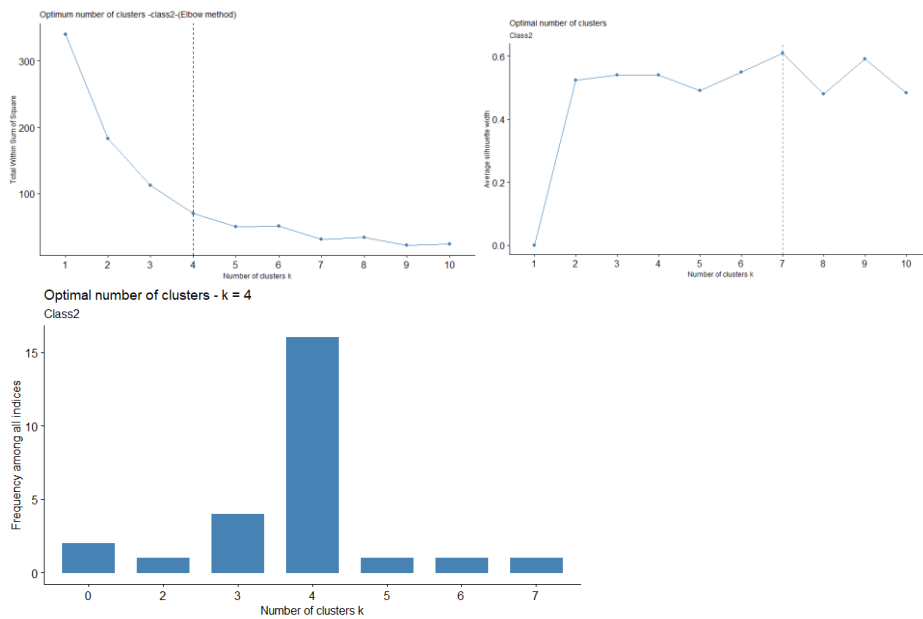


Figure 77- Optimal number of clusters with Elbow, Silhouette, and Frequency among 30 indices methods in analysing data based on apartments architectural layouts design (building Class2, i.e. buildings with between 5 to 10 storey)

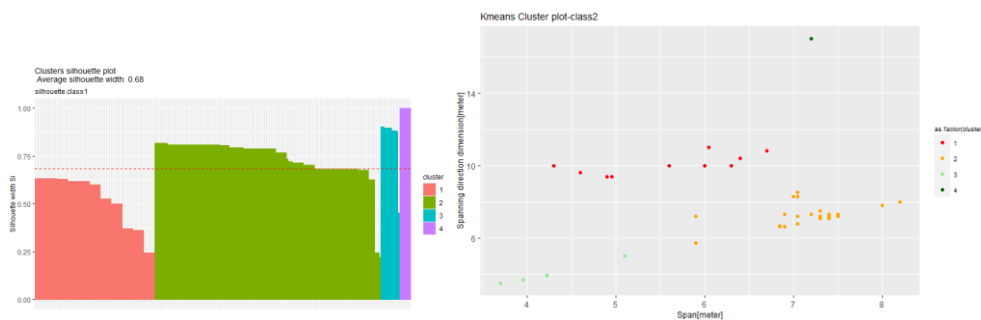


Figure 78- Cluster validation and scatter plots in vertical design data analysis (building Class2, i.e buildings between 5 to 10 storey)

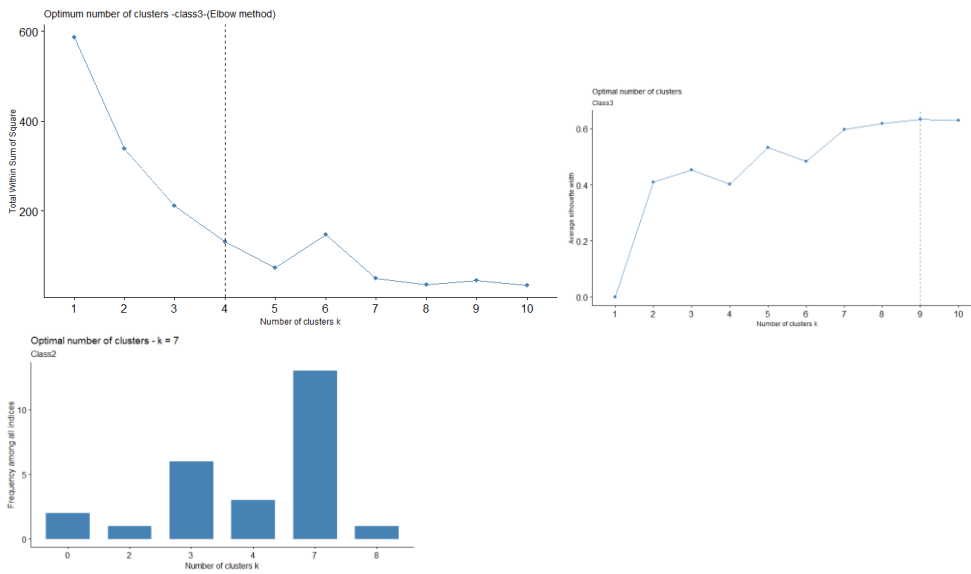


Figure 79- Cluster validation and scatter plots in vertical design data analysis (building Class 3, i.e buildings with more than 10 storey)

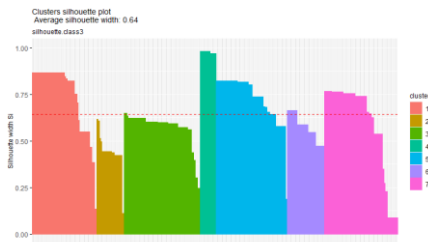


Figure 80- Cluster validation and scatter plots in vertical design data analysis (building class3, i.e., buildings with more than 10 storey)

Table 38- Optimal number of clusters in analysing data based on vertical designs

Method Building Class	Elbow method	Average silhouette	Frequency among 30 indices	Number of final clusters
Class 1	5	7	5	5
Class 2	4	7	4	4
Class 3	4	9	7	7

- A part of clustering coding in R studio (Spatial voids)

```

59
60 #scaling the data for clustering
61 Scale.Liv.L.W.AR.Area<-scale(Liv.L.W.AR.Area)
62 Scale.Liv.L.W.AR<-scale(Liv.L.W.AR)
63
64 #optimum number of clusters
65 library(factoextra)
66 #1: Elbow method
67 fviz_nbclust(Scale.Liv.L.W.AR, kmeans, method = "wss") +
68   geom_vline(xintercept = 5, linetype = 2)+labs(title = "Optimum number of clusters for Living data
with L,W,AR")
69
70 fviz_nbclust(Scale.Liv.L.W.AR.Area, kmeans, method = "wss") +
71   geom_vline(xintercept = 5, linetype = 2)+labs(title = "Optimum number of clusters for Living data
with L,W,AR,Area")
72
73 #2: silhouette method
74 # packages and function for determining the optimal number of clusters:
75 #fviz_nbclust() function in factoextra R packag : this function just provide elbow, silhouette and gap
statistic while Nbclust()function provide 30 indices for determining the numbr of clusters
76 install.packages("NbClust")
77 library(factoextra)
78 library(NbClust)
79
80 #Silhouette method
81 fviz_nbclust(Scale.Liv.L.W.AR, kmeans, method = "silhouette")+
82   labs(subtitle = "Livingroom.L.W.AR")
83
84 fviz_nbclust(Scale.Liv.L.W.AR, kmeans, method = "silhouette")+
85   labs(subtitle = "Livingroom.L.W.AR.Area")
86
87 #3: Gap statistic method
88 set.seed(123)
89 fviz_nbclust(Scale.Liv.L.W.AR, kmeans, nstart = 25, method = "gap_stat", nboot = 500)+
90   labs(subtitle = "Livingroom.L.W.AR")
91
92 set.seed(123)
93 fviz_nbclust(Scale.Liv.L.W.AR, kmeans, nstart = 25, method = "gap_stat", nboot = 500)+
94   labs(subtitle = "Livingroom.L.W.AR.Area")
95
96 #NbClust() function: 30 indices for choosing the best number of clusters
97 library("NbClust")
98 Number.Liv.L.W.AR <- NbClust(Scale.Liv.L.W.AR, distance = "euclidean", min.nc = 2,
99   max.nc = 8, method = "kmeans")
100
101 Number.Liv.L.W.AR.Area <- NbClust(Scale.Liv.L.W.AR.Area, distance = "euclidean", min.nc = 2, max.nc =
102   10, method = "kmeans")
103
104 library("factoextra")
105 fviz_nbclust(Number.Liv.L.W.AR.Area)+
106   labs(subtitle = "Livingroom.L.W.AR.Area")
107
108 #Kmeans- Living room based on Length,width,AR
109 set.seed(123)
110 Km.Liv.L.W.AR <- kmeans(Scale.Liv.L.W.AR, 8, nstart = 25)
111 AddKm.Liv.L.W.AR<- cbind(Liv.L.W.AR, cluster = Km.Liv.L.W.AR$cluster)
112
113
114 Kmean.Living.L.W.AR<-aggregate(Liv.L.W.AR, by=list(cluster=Km.Liv.L.W.AR$cluster), mean)
115
116 Km.Liv.L.W.AR[["size"]]
117
118
119 #Kmeans- Living room based on Length,width,AR,Area
120 set.seed(123)
121 Km.Liv.L.W.AR.Area <- kmeans(Scale.Liv.L.W.AR.Area, 8, nstart = 25)
122
123 AddKm.Liv.L.W.AR.Area<- cbind(Liv.L.W.AR.Area, cluster = Km.Liv.L.W.AR.Area$cluster)
124 Kmean.Living.L.W.AR.Area<-aggregate(Liv.L.W.AR.Area, by=list(cluster=Km.Liv.L.W.AR.Area$cluster), mean
125 )
126 Km.Liv.L.W.AR.Area[["size"]]
127
128 #####Clustering validation
129
130 # Silhouette coefficient of observations
131 library("cluster")
132 Sil.Km.Liv.L.W.AR <- silhouette(Km.Liv.L.W.AR$cluster, dist (Scale.Liv.L.W.AR))
133 library(factoextra)
134 fviz_silhouette(Sil.Km.Liv.L.W.AR)+
135   labs(subtitle = "silhouette.Livingroom.L.W.AR")
136
137
138 Sil.Km.Liv.L.W.AR.Area <- silhouette(Km.Liv.L.W.AR.Area$cluster, dist (Scale.Liv.L.W.AR.Area))
139 fviz_silhouette(Sil.Km.Liv.L.W.AR.Area)+
140   labs(subtitle = "silhouette.Livingroom.L.W.AR.Area")
141
142
143 #plot based on selected variables(standardized)
144 #standardize Liv Length and Width plot
145 library('factoextra')
146 fviz_cluster(object=Km.Liv.L.W.AR.Area,data=Liv.L.W.AR.Area,choose.vars = c("LivLength", "Livwidth"),
147   ellipse.type = "convex",
148   star.plot = TRUE, # Add segments from centroids to items
149   repel = TRUE, # Avoid label overplotting(slow)

```

```

150 ggtheme = theme_minimal()
151 )+
152 labs(title = "kmeans clustering plot-Livingroom.L.W.AR.Area",
153 x="Livingroom Length(standardize)",
154 y="Livingroom Width(standardize)")+
155 theme(title = element_text(size = 9))+
156 theme(legend.text = element_text(size=7))+
157 theme(legend.title = element_text(size = 7))+
158 scale_color_manual(values = c("red", "orange", "green", "dark green", "cyan", "blue", "purple", "pink"))
159
160
161 library('factoextra')
162 fviz_cluster(object=Km.Liv.L.W.AR,data=Liv.L.W.AR,choose.vars = c("LivLength", "Livwidth"),
163 ellipse.type = "convex",
164 star.plot = TRUE, # Add segments from centroids to items
165 repel = TRUE, # Avoid label overplotting(slow)
166 ggtheme = theme_minimal()
167 )+
168 labs(title = "kmeans clustering plot-Livingroom.L.W.AR".

```

- A part of clustering coding in R studio (Modular design scenario)

```

28 #optimum number of clusters
29 library(factoextra)
30 #1: Elbow method
31 fviz_nbclust(Scale.Allbed.LB.S.SDD, kmeans, method = "wss") +
32 geom_vline(xintercept = 5, linetype = 2)+labs(title = "Optimum number of clusters -(Elbow method)")+
33 theme(title = element_text(size = 9))
34
35 #2: silhouette method
36 # packages and function for determining the optimal number of clusters:
37 #fviz_nbclust() function in factoextra R packag : this function just provide elbow, silhouette and gap
38 #statistic while Nbclust()function provide 30 indices for determining the number of clusters
39 library(factoextra)
40 library(NbClust)
41
42 #####Silhouette method
43 fviz_nbclust(Scale.Allbed.LB.S.SDD, kmeans, method = "silhouette")+
44 labs(subtitle = "Allbedroom apartments with living room and bedroom pattern")+
45 theme(title = element_text(size = 9))
46
47 #3: Gap statistic method
48 set.seed(123)
49 fviz_nbclust(Scale.Allbed.LB.S.SDD, kmeans, nstart = 25, method = "gap_stat", nboot = 500)+
50 labs(subtitle = "all apartments with living room and bedroom pattern")+
51 theme(title = element_text(size = 9))
52
53 #NbClust() function: 30 indices for choosing the best number of clusters
54 library("NbClust")
55 Number.Allbed.LB.S.SDD <- NbClust(Scale.Allbed.LB.S.SDD, distance = "euclidean", min.nc = 3, max.nc =
56 8, method = "kmeans")
57
58 library("factoextra")
59 fviz_nbclust(Number.Allbed.LB.S.SDD)+
60 labs(subtitle = "All-bedroom apartments with living room and bedroom pattern")
61
62 #Kmeans-
63 set.seed(123)
64 Km.Allbed.LB.S.SDD <- kmeans(Scale.Allbed.LB.S.SDD, 5, nstart = 25)
65
66 AddKm.Allbed.LB.S.SDD<- cbind(Allbed.LB.S.SDD, cluster = Km.Allbed.LB.S.SDD$cluster)
67 library(psych)
68 KmGroupsSummaryAllbed.LB.S.SDD <- describeBy(AddKm.Allbed.LB.S.SDD,group = AddKm.Allbed.LB.S
69 .SDD$cluster)
70
71 Kmean.Allbed.LB.S.SDD<-aggregate(Allbed.LB.S.SDD, by=list(cluster=Km.Allbed.LB.S.SDD$cluster), mean)
72 Ksd.Allbed.LB.S.SDD<-aggregate(Allbed.LB.S.SDD, by=list(cluster=Km.Allbed.LB.S.SDD$cluster), sd)
73 Km.Allbed.LB.S.SDD[["size"]]
74
75 #####Clustering validation
76 # Silhouette coefficient of observations
77 library("cluster")
78 sil.Km.Allbed.LB.S.SDD <- silhouette(Km.Allbed.LB.S.SDD$cluster, dist (Scale.Allbed.LB.S.SDD))
79 fviz_silhouette(sil.Km.Allbed.LB.S.SDD)+
80 labs(subtitle = "silhouette.All apartments with living room and bedroom pattern")+
81 theme(title = element_text(size = 9))

```

Appendix D

Figure 81- Problem coding in Matlab environment

```

EDITOR PUBLISH VIEW
New Open Save Find Files Compare Go To Comment % Breakpoints Run Run and Run Section Run and
FILE NAVIGATE EDIT BREAKPOINTS RUN
Costm x +
1 function [Z,Sol]=Cost(AllSols)
2 %% Inputs
3 %The number of spans
4 I=5;
5 %Recycling cost per cubic meter
6 Recyclingcost=100;
7
8 H=10;
9
10 % Press waiting time for each different billet layer number
11 FWTime=10;
12
13 %Penaty value for violating the billet length
14 PBL=1000000;
15
16
17 %Penaty value for violating the footprint length
18 PFL=1000000;
19
20 % The number of different billet lengths needed
21 %NUMBEROFBILL=2;
22
23 % Maximum revenue demanded by the client
24 MaxRev=70000;
25
26 %Building length
27 BuildingLength=30;
28 BilletLength=12;
29
30 %SetupTime=X;
31
32 Li=[6.8;5.8;4.1;5.9;6.8]; %Lower bound of spans
33 Ui=[7.2;6.2;4.5;6.3;7.2]; %Upper bound of spans
34 Ranges=[Li, Ui];
35
36 %Lengths at which the width to use will change
37 LL=[2.8000 3.4000 4.1000 4.2000 4.9000 5.1000 5.4000 5.9000 6.2000 6.4000 6.6000 6.8000 7.2000 7.4000 7.6000 7.8000];
38
39 %Number of panels in each span
40 XP=7;
41
42 %Billet Thicknesses in order
43 Th=[0.085 0.105 0.115 0.125 0.135 0.145 0.160 0.175 0.195 0.205 0.225 0.245 0.265 0.275 0.295 0.315];
44
45 %Billet revenue per square meters
46 R=[122 136 149 164 177 192 209 230 256 272 301 323 357 367 398 422];
47
48
49 %Billet cost for each billet
50 C=[2164 2448 1320 2682 2952 3186 3456 3762 4140 4608 4896 5418 6426 6606 7164 7596];
51
52 %Pressing stage process time
53 PT=zeros(1,numel(R));
54 PT(1:25/5)=91;
55 PT(25/5+1:55/5)=102;
56 PT(55/5+1:80/5)=110;
57
58 %% Creating solution matrices
59 LB=[LL;Th];
60
61 Xhat=AllSols(1:I);
62 Rand=AllSols(I+1:2*I);
63
64 %% Random Generation of lengths conforming to the Building desired length
65 Ints=Ranges;
66
67 Floor=zeros(1,numel(Ints)/2);
68
69 for i=1:numel(Ints)/2
70
71     Floor(i)=Ints(i,1)+Xhat(i).*(Ints(i,2)-Ints(i,1));
72
73 end
74
75 X=zeros(size(Floor));
76 FLength=zeros(size(Floor));
77 for i=1:numel(X)
78
79     X(i)=Floor(i)/sum(Floor);
80     FLength(i)=round((X(i).*BuildingLength)*10)/10;
81     FLength(i)=max(FLength(i),Li(i));
82     FLength(i)=min(FLength(i),Ui(i));
83
84 end
85
86 %Total length of all spans
87 SumLength=sum(FLength);
88

```

```

89  %% Choice of thicknesses
90  Lengths=FLength;
91
92  % Freallocations
93  Possible=zeros(numel(Lengths),numel(LL)); %Possible thicknesses for all Lengths
94  Non=zeros(1,5);
95  % Rand=zeros(1,numel(Lengths));
96  WidthInd=zeros(size(Rand));
97  Widths=zeros(size(Rand));
98
99
100 %All the Lengths and their possible thicknesses in one function
101 %LLs=[min(Li):1:max(Ui)];
102 % PossLen= @(LLs) Possibles(LLs);
103
104 % Generating the possible thickness matrix
105 for i=1:numel(Lengths)
106
107     for j=1:numel(LL)
108
109         if Lengths(i)<=LB(1,j)
110
111             Possible(i,j)=LB(2,j);
112
113         end
114
115     end
116
117     %Random number for choosing the billet
118     Non(i)=numel(nonzeros(Possible(i,:)));
119
120     %Count from the end%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Main Variable
121     % Rand(i)=randi([0,Non(i)]); % Take this to Xhat form
122
123
124
125 -end
126
127
128 Rand=round(1+Rand.*max(0,(Non-1)));
129 for k=1:numel(Non)
130
131
132
133     %Index of the chosen widths
134     WidthInd(k)=numel(LL)+1-Rand(k);
135
136
137     %Widths themselves
138     Widths(k)=Th(WidthInd(k));
139
140 -end
141
142 %% From here, can be moved to another function, having widths and lengths as inputs and cutting plan as output
143 Uniques=unique(Widths);
144
145 Npanels=numel(Uniques);
146
147 Ncount = histc(Widths, Uniques);
148
149 %Clean output
150 % [SortWtest,WIndtest]=sort(Widths);
151 [SortW,WInd]=sort(WidthInd);
152 Lsort=Lengths(WInd);
153
154 Rmat=R(SortW);
155 Cmat=C(SortW);
156 % PTmat=PT(SortW);
157 WLS=[SortW;Lsort;Widths(WInd);Rmat;Cmat];
158
159
160
161
162 % The cutting plan can be defined before anything.
163 Cutmat=cell([1,Npanels]);
164 Tripled=3*ceil(XP*Ncount/3);
165 %Preallocation
166
167 %Random solution generation
168 Input=cell([Npanels,1]);
169
170 %NB is going to be a matrix showing the number of widths in the cutting plan assigned to each of the widths
171
172
173 BB=[];
174 % Tool=zeros(1,Npanels);
175 % Arz=zeros(1,Npanels);
176 % CutPlan=cell(size(Cutmat));
177
178 LS=cell(size(Cutmat));
179 solution=cell(1,Npanels);
180 Lengthsbil=cell(1,Npanels);
181 Numbil=zeros(1,Npanels);

```

```

182- NumCuts=cell(1,Npanels);
183- PFCnc=zeros(1,Npanels);
184- PFCNC=cell(1,Npanels);
185- Span=1;
186
187- Arz=XF*Ncount;
188- Tool=1;
189- RealBillet=zeros(1,Npanels);
190- for ii=1:Npanels
191-     LS{ii}=zeros(Arz{ii},Tool);
192-
193- end
194
195
196- for ii=1:Npanels
197-
198-     if Ncount(ii)==1
199-
200-         %Tool calculation
201-
202-         %Length matrix for multiplication to cut matrix
203-         LS{ii}=repmat(Lsort(Span),[XF,Tool]);
204-         Span=Span+1;
205-         elseif Ncount(ii)==2
206-
207-             LS{ii}=[repmat(Lsort(Span),[XF,Tool]); repmat(Lsort(Span+1),[XF,Tool])];
208-             Span=Span+2;
209-         elseif Ncount(ii)==3
210-
211-
212-             LS{ii}=[repmat(Lsort(Span),[XF,Tool]); repmat(Lsort(Span+1),[XF,Tool]); repmat(Lsort(Span+2),[XF,Tool])];
213-             Span=Span+3;
214-
215-         elseif Ncount(ii)==4
216-
217-
218-             LS{ii}=[repmat(Lsort(Span),[XF,Tool]); repmat(Lsort(Span+1),[XF,Tool]); repmat(Lsort(Span+2),[XF,Tool]); repmat(Lsort(Span+3),[XF,Tool])];
219-             Span=Span+4;
220-
221-         elseif Ncount(ii)==5
222-
223-             LS{ii}=[repmat(Lsort(Span),[XF,Tool]); repmat(Lsort(Span+1),[XF,Tool]); repmat(Lsort(Span+2),[XF,Tool]); repmat(Lsort(Span+3),[XF,Tool]); repmat(Lsort(Span+4),[XF,Tool])];
224-             Span=Span+4;
225-         end
226-

```

```

226
227- %     LS{ii}=LS{ii}(:,1);
228
229
230
231- Input{ii}=LS{ii}';
232- [solution{ii},Numbil{ii},Lengthsbil{ii},NumCuts1{ii}]=Greedy(Input{ii},BilletLength);
233- %     Cutmat{ii}=zeros(size(solution{ii}));
234- %     Cutmat{ii}(solution{ii}>0)=1;
235- RealBillet{ii}=ceil(Numbil{ii}/3)*3;
236
237- Cutmat{ii}=zeros(RealBillet{ii});
238- Lengthsbil{ii}=zeros(1,RealBillet{ii});
239- NumCuts{ii}=zeros(1,RealBillet{ii});
240
241- [ms,ns]=size(solution{ii});
242- [ml,nl]=size(Lengthsbil{ii});
243- [mn,nn]=size(NumCuts1{ii});
244
245
246
247
248- Cutmat{ii}(1:ms,1:ns)=solution{ii};
249- Lengthsbil{ii}(1:ml,1:nl)=Lengthsbil{ii};
250- NumCuts{ii}(1:mn,1:nn)=NumCuts1{ii};
251
252
253
254
255
256- TL{ii}=sum(Lengthsbil{ii});
257
258- Realwaste{ii}= RealBillet{ii}*12-TL{ii};
259
260
261
262
263
264
265- % RNP Total number of panels cut from each billet
266- % RRR Total length cut from each billet
267- for i=1:RealBillet{ii}/3
268
269-     %Total number of panels cut on each billet
270-     RNP{ii}(i)=sum(NumCuts{ii}(3*(i-1)+1:3*i));
271-

```

```

272 %Total length of all cuts on each big billet
273 RRR(ii)(i)=sum(Lengthsbil{ii}(3*(i-1)+1:3*i));
274
275
276 end
277
278 % NP{ii}=sum(CutsNum{ii})
279
280 %Process Time and cost for panels (PTCNC)
281 % BigsInd{ii}=[1:Used2{ii}];
282 % Bigs{ii}=rem(BigsInd{ii},3);
283 % Bigs{ii}=find(Bigs{ii}~=0);
284 %
285 % Set{ii}=(Used2{ii)+sum(Sortedused{ii}(Bigs{ii}))/3;
286
287 %Calculation of set variable
288 for i=1:RealBillet(ii)/3
289
290
291 Set{ii}(i)=(sum(Lengthsbil{ii}(3*(i-1)+1:3*i))-min(Lengthsbil{ii}(3*(i-1)+1:3*i)+numel(nonzeros(Lengthsbil{ii}(3*(i-1)+1:3*i))))/3;
292
293
294
295 end
296
297
298
299 end
300 AA=unique(WLs(1,:));
301 PTmatrix=PT(AA);
302 UU=unique(WLs(5,:));
303 for ii=1:Npanels
304
305 BilletCost(ii)=ceil(Numbil(ii)/3).*UU(ii);
306
307 end
308 %% Revenue of selling each square meter of billets
309 Rev=TL.*unique(WLs(4,:));
310 Revenue=sum(Rev);
311
312 %% Recycling cost of billets' waste
313 Recycle=Realwaste.*unique(WLs(3,:)).*Recyclingcost;
314
315 %% Process Time and cost for billet (PTpress)
316 AA=unique(WLs(1,:));
317 PTmatrix=PT(AA);
318 ProcessTime=RealBillet/3.*PTmatrix;
319
320 ProcessCost=ProcessTime*H;
321
322
323 WW=unique(WLs(3,:));
324
325 for ii=1:Npanels
326 for i=1:RealBillet(ii)/3
327
328 if WW(ii)<0.136
329
330 PTCNC{ii}(i)=1.13+(9.77*RNP{ii}(i)+0.525*(3*12-RRR{ii}(i))+2.567*Set{ii}(i))/RNP{ii}(i);
331
332 elseif WW(ii)>0.135&&WW(ii)<0.226
333
334 PTCNC{ii}(i)=14.33+(9.77*RNP{ii}(i)+0.525*(3*12-RRR{ii}(i))+2.567*Set{ii}(i))/RNP{ii}(i);
335
336 elseif WW(ii)>0.225&&WW(ii)<0.316
337
338 PTCNC{ii}(i)=25.09+(9.77*RNP{ii}(i)+0.525*(3*12-RRR{ii}(i))+2.567*Set{ii}(i))/RNP{ii}(i);
339
340 end
341
342 end
343 PTCnc(ii)=sum(PTCNC{ii});
344
345 end
346 PTCnc=H*sum(PTCnc);
347
348 %% Billet length constraint
349
350 % ii=1;
351 % WASTE=sum(Waste);
352 % WASTE{i}(j)=12-Waste{i}(j);
353
354 % WASTE=12-Billsmat;
355
356 %% Violation of building length constraint
357 LengthDev=BuildingLength-SumLength;
358
359 % PT(1:25/5)=91;
360 % PT(25/5+1:55/5)=102;
361 % PT(55/5+1:80/5)=110;
362 Different=0;
363 PressCost=0;
364 A1=0;

```

```

365 - A2=0;
366 - A3=0;
367 - for j=1:numel(unique(WLs(3,:)))
368 -     if WLs(1,j)<=5
369 -         A1=A1+1;
370 -
371 -     elseif WLs(1,j)>5 && WLs(1,j)<=11
372 -         A2=A2+1;
373 -
374 -     elseif WLs(1,j)>11
375 -         A3=A3+1;
376 -
377 -     end
378 - end
379 - Differents=numel(nonzeros([A1, A2, A3]));
380 -
381 - PressCost=Differents*PWTime*H;
382 -
383 - %Things that are still needed:
384 - % TL, WLs, RealWaste
385 -
386 - %     SetupCost=Setuptime.*numel(unique(WLs(3,:)));
387 -
388 -
389 - %% Objective function
390 - % Objective with constraint on the number of different billets
391 - % Z=-(Revenue-sum(BilletCost)-sum(Recycle)-sum(ProcessCost)-PTcnc-sum(WASTE)-PFL*abs(LengthDev)-BillDev);
392 -
393 - % Objective "without" constraint on the number of different billets
394 - %1 Z=-(Revenue-sum(BilletCost)-sum(Recycle)-sum(ProcessCost)-PTcnc-PFL*abs(LengthDev));
395 -
396 - % objective with a setup cost associated with different billet thicknesses
397 - % Z=-(Revenue-sum(BilletCost)-SetupCost-sum(Recycle)-sum(ProcessCost)-PTcnc-sum(WASTE)-PFL*abs(LengthDev)-BillDev);
398 -
399 - % Objective with setup cost
400 - Z=-(Revenue-sum(BilletCost)-sum(Recycle)-sum(ProcessCost)-PTcnc-max(0,PFL*abs(LengthDev))-PressCost-1000000*max(0,(Revenue-MaxRev)));
401 - %Z=-(Revenue-sum(BilletCost)-sum(Recycle)-sum(ProcessCost)-PTcnc-max(0,sum(WASTE))-max(0,PFL*abs(LengthDev))-PressCost);
402 -
403 - %% Outputs
404 - Sol.CutPlan=solution;
405 - Sol.Solution=WLs;
406 - Sol.NumberOfCutsOnBillets=RNP;
407 - Sol.TotalCutLengthForBillet=RRR;
408 - Sol.TotalNumberOfBillets=Numbil;
409 - Sol.TotalLengthOnBillets=Lengthsbil;
410 -
411 - Sol.TotalLengthOnBillets=Lengthsbil;
412 - Sol.TotalNumberOfCutsOnBillets=NumCuts;
413 - Sol.Revenue=Revenue;
414 - Sol.BilletCost=BilletCost;
415 - Sol.Recycle=Recycle;
416 - Sol.ProcessCost=ProcessCost;
417 - Sol.PTcnc=PTcnc;
418 - Sol.Differents=Differents;
419 -
420 - end
421 -
422 -

```