A Development Cost Comparison between a Multi-Storey Mass Timber and Reinforced Concrete Building in South Africa

by

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ABSTRACT

A study was conducted investigating the economic viability of a multi-storey mass timber building for South Africa through a development cost comparison. First, the research investigated whether South African plantations can provide sustainable volumes of high-grade (S7, S10) timber for a multi-storey mass timber building market. This was followed by the design of two 8 storey commercial buildings, consisting of a mass timber frame and of a reinforced concrete frame, respectively. A focus group workshop, conducted with industry professionals, assisted in the development of the construction schedules. In the subsequent step, a financial model was used to determine the overall development cost and financial feasibility of the ventures. Finally, a sensitivity analysis was conducted to investigate the effect of certain variables on the overall profitability of the mass timber frame development. The research also served as a case study for the implementation of Building Information Modelling (BIM) in a project team. Through this, an assessment was made regarding the benefits and limitations of BIM.

The research revealed that mass timber products would need to be imported to satisfy a rapid growth in the multi-storey mass timber building market in South Africa as current timber supplies (S5, S7, S10) are oversubscribed. Studies suggest that future log resources could be added to the market through the development of new plantations, however, these plantations will only become available after 24 to 30 years. The focus group workshop identified that the construction of the reinforced concrete frame building and mass timber frame building will take 42 weeks and 21 weeks, respectively. The total capital investment required for the mass timber frame development was 10% more than that of the reinforced concrete frame development (R115 691 000 versus R105 118 000).

A 5 year internal rate of return (IRR) of 20.9% and 25.7% was calculated for the mass timber frame and reinforced concrete frame developments, respectively. Notably, the 5 year IRR of both developments is above the 15% minimum acceptable rate of return (MARR), indicating that they are both financially feasible. A significant finding of the sensitivity analysis was that the mass timber frame building proved to generate a higher 5 year IRR than that of the reinforced concrete frame once the mass timber building achieved a rental premium of 7.8% or more. The sensitivity analyses further showed that the importation of the mass timber elements remains an expensive option, with a 16.4% 5 year IRR for the imported mass timber frame (R17:€1 exchange rate). The study highlighted a number of aspects, particularly in the manufacturing sector, that can be addressed in order to develop a sustainable multi-storey mass timber building market. This includes improvement in the sourcing of high-grade structural timber (S7, S10) and investment into equipment to enable the large-scale production of large beams/columns typically required in multi-storey mass timber structures.

Shortcomings were observed in the all-round implementation of BIM, particularly regarding the information provided by South African suppliers of mass timber elements. Nonetheless, a number of the BIM benefits were realised, with the main advantages being 3D visualisation and clash detection.

OPSOMMING

'n Studie is uitgevoer om die ekonomiese lewensvatbaarheid van 'n multi-verdieping massahoutgebou vir Suid-Afrika te ondersoek, deur middel van n ontwikkelingskoste benadering. Die volhoubare volumes van hoë-gehalte (S7, S10) hout wat deur Suid-Afrikaanse plantasies gelewer kan word vir multi-verdieping massahoutgeboue, is eerstens ondersoek. Dit is gevolg deur die ontwerp van twee kommersiële geboue van 8 verdiepings elk, bestaande uit 'n massahoutraamgebou en 'n gewapende betonraamgebou, onderskeidelik. 'n Fokusgroep werkswinkel, onderneem met professionele persone in die boubedryf, het gehelp met die ontwikkeling van die konstruksieskedules. In die daaropvolgende stap is 'n finansiële model gebruik om die algehele ontwikkelingskoste en finansiële uitvoerbaarheid van die ondernemings te bepaal. Laastens, is 'n sensitiwiteitsanalise uitgevoer om die effek van bepaalde veranderlikes op die algehele winsgewendheid van die ontwikkeling van die massahoutgebou te ondersoek. Die ondersoek het gedien as 'n gevallestudie vir die implementering van ‘Building Information Modelling’ (BIM) in 'n projek. Die voordele en beperkings van BIM is sodoende bepaal.

Daar is gevind dat massahoutprodukte ingevoer sal moet word om 'n vinnige toename in die multi-verdieping massahout mark in Suid-Afrika te bevredig, aangesien die huidige houtvoorraad (S5, S7, S10) onvoldoende is. Die studie bevind dat toekomstige houtbronne tot die mark toegevoeg kan word deur die ontwikkeling van nuwe plantasies, maar hierdie plantasies sal eers na 24 tot 30 jaar beskikbaar word. Die fokusgroep werkswinkel het geïdentifiseer dat die konstruksie van die betonraamgebou en massahoutraam gebou onderskeidelik 42 weke en 21 weke sal duur. Die totale kapitale belegging benodig vir die ontwikkeling van die massahoutraam-ontwikkeling was 10% meer as dié van die gewapende betonraam-ontwikkeling (R115 691 000 teenoor R105 118 000). 'n 5 jaar interne opbrengskoers (IOK) van 20,9% en 25,7% is onderskeidelik bereken vir die massahoutraam- en gewapende betonraam-ontwikkelings. Die 5 jaar IOK van albei ontwikkelings is hoër as die 15% minimum aanvaarbare opbrengskoers (MAOK), wat daarop dui dat albei ontwikkelings finansïeel haalbaar is. 'n Belangrike bevinding van die sensitiwiteitsanalise is dat die massahoutgebou 'n hoër 5 jaar IOK het as dié van die gewapende betonraamgebou indien die massahoutgebou 'n huurpremie van 7,8% of meer behaal het. Die sensitiwiteitsanalise toon verder dat die invoer van massahoutelemente 'n duur opsie bly, met 'n 5 jaar IOK van 16,4% vir die ingevoerde massahoutgebou (R17: € 1 wisselkoers). Die studie het 'n aantal aspekte identifiseer, veral in die vervaardigingsektor, wat aangespreek kan word om 'n volhoubare mark vir massahoutgeboue te ontwikkel. Dit sluit in die verbetering in beskikbaarheid van hoëgraadse struktuurhout (S7, S10) en investering in toerusting wat die grootskaalse produksie van groot balke/kolomme moontlik maak vir multi-verdieping massahoutstrukture. Tekortkominge is waargeneem in die algehele implementering van ‘BIM’ veral met betrekking tot inligting van verskaffers van massahoutelemente. Daar is egter ‘n aantal van die BIM-voordele bevestig, met die belangrikste voordele die 3D-visualisering en identifiseering van botsings tussen elemente/dienste.

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A2 Timber

BART SENEKAL INC.
Consulting Civil & Structural Engineers

ISIPANI CONSTRUCTION

HOLZBAU HESS
We Roof Namibia!

MDA
MITCHELL DU PLESSIS ASSOCIATES

XLAM
CROSS LAMINATED TIMBER: SAFE. FAST. SUSTAINABLE.

rothoblaas

Abland

CAPEX
PROJECTS

SAWPA

UNIVERSAL PLYWOODS

NRF
National Research Foundation

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AEC – Architecture Engineering Construction

BCTH – Brock Commons Tallwood House

BIM – Building Information Modelling

CBD – Central Business District

CLT – Cross Laminated Timber

FLS – Fire Limit State

Glulam – Glued-laminated Timber

GFA – Gross Floor Area

HVAC – Heating Ventilation and Air Conditioning

IBC – International Building Code

IPD – Integrated Project Delivery

IRR – Internal Rate of Return

LCA – Life Cycle Analysis

LVL – Laminated Veneer Lumber

LSL – Laminated Strand Lumber

MAR – Minimum Acceptable Rate of Return

MEP – Mechanical, Electrical and Plumbing

MTC – Mass Timber Construction

OSL – Oriented Strand Lumber

P&G – Preliminary and General

PSL – Parallel Strand Lumber

SA pine – South African pine

SANS – South African National Standard

SAWPA – South African Wood Preservatives Association

SCL – Structural Composite Lumbar

SLS – Serviceability Limit State

STC – Sound Transmission Class

ULS – Ultimate Limit State

Chapter 1

1 Introduction

1.1 Background

The materials used for the construction of multi-storey buildings have been dominated by concrete, masonry and steel for several decades (American Institute of Steel Construction, 2018; BCSA, 2019). Before the development of these materials many multi-storey buildings were constructed out of timber. The inherent anisotropic and combustible nature of timber were considered as some of the main drawbacks of using it as a building material (ARUP, 2019). The combination of an increased concentration of high-rise timber buildings in cities and the combustible nature of timber resulted in the break out of a number of catastrophic fires. Evidence of such a fire is The Great Chicago Fire of 1871 which killed an estimated 300 people and destroyed more than 17 000 structures (Marx, 2004). In a response to these dangers, building regulations were implemented to mitigate the risks involved with timber construction (London Assembly Planning and Housing Committtee, 2010). During this time great strides were being made in the steel and concrete industry. The disadvantages of timber paired with the clear advantages of using steel and concrete in high-rise buildings led to the virtual demise of multi-storey timber buildings for a number of decades (ARUP, 2019).

The technology involved in the manufacturing and finishing of timber has vastly improved over the years with new products such as mass timber elements entering the market. These new products claim to have addressed many of the aspects that have limited the growth of multi-storey timber buildings over the past century, such as improved fire resistance and increased isotropic properties. As a result of this, high-rise timber buildings have experienced a resurgence during the past decade (Salvadori, 2017). An example of such a structure is the Mjøsa Tower in Brumunndal, Norway. The 18 storey Mjøsa Tower is labelled as the world’s tallest timber building, standing 85 metres tall (Walter, 2018). The growth in the market share of multi-storey mass timber building has sparked interest among South African property developers and architecture, engineering and construction (AEC) professionals. Questions have arisen regarding the potential development cost of multi-storey mass timber buildings and how this would compare to a typical building system applied in South Africa. Moreover, concerns were raised regarding the potential to supply enough raw timber to sustain a multi-storey mass timber building market. The new-found interest in timber construction among South African industry professionals serves as an indication of the need for research in mass timber construction. A development cost comparison between a multi-storey mass timber and reinforced concrete building in South Africa was therefore undertaken in an attempt to address the questions raised within the property and AEC industry.

1.2 Problem Statement

The World Cities Report of 2016 stated that 54% of the world's population reside in cities and that the number would increase to 66% by 2050 (UN Habitat, 2016). Africa's population is expected to increase to approximately 2.5 billion people by 2050, while the urban population is expected to increase by 920 million people within the next 30 to 35 years (UN, 2018). Architects and engineers are therefore constantly challenged to design more high-rise buildings due to urbanisation and spatial constraints. This calls for a better understanding of the materials used in the construction process of these multi-storey buildings. In addition to the challenge of urbanisation, the environmental impact of buildings remains a key factor in the design process. Developers are constantly in search of building solutions that satisfy the triple bottom line namely; the economic, social, and environmental aspects for sustainable development (Hammer and Pivo, 2017).

The built environment, which consists of the construction, infrastructure and transportation sectors, is a central component of economic and social development. As such, these sectors consume large amounts of energy, being responsible for 62% of the global final energy consumption in 2009 (IEA, 2011) and 55% of global greenhouse gas emissions in 2004 (Metz *et al.*, 2007). Moreover, reports have indicated that energy consumption is set to increase by up to 44% in the period of 2009 to 2035 (Anderson, Wulfhorst and Lang, 2015). Total CO_2 emissions from the global construction sector were found to be 5.7 billion tons in 2009, forming 23% of the global economic sectors (Huang *et al.*, 2018). From these findings it is evident that the built environment contributes on a large scale to global greenhouse gas emissions and that these emissions are set to increase if alternative construction materials and techniques are not considered.

Rising awareness and interest in environmental and global warming challenges have grown tremendously in recent years, leading to a call for sustainable housing technology and methods within the construction industry. This has sparked renewed interest in the use of timber for construction worldwide. Timber remains unique as it is one of few construction materials with a negative carbon footprint before processing (Green, 2012). During its 'manufacturing period' (growth) it takes in atmospheric CO_2 and releases O_2 during photosynthesis. This is in contrast to steel and cement which were responsible for approximately 5% (2003) and up to 7% (2002) of global greenhouse gas emissions, respectively (Anderson, Wulfhorst and Lang, 2015). Recently, South Africa initiated a green building rating tool – the first of its kind in Africa – which has spawned a number of green rated building projects (Crafford and Wessels, 2016). Presently, 70% of all sawn timber in South Africa is used for construction and in recent studies the use of timber over small, light gauge steel has shown a 40% lower impact on the environment across all assessment categories (Crafford and Wessels, 2016). As such, timber construction can be labelled as a more environmentally friendly construction material as opposed to steel, concrete, and masonry when sustainable forest management is practiced. Although timber has all the structural characteristics to be a sustainable alternative to steel and concrete high-rise buildings, a study investigating the economic viability of multi-storey mass timber buildings for South Africa has yet to be conducted. In order to adapt to the growing requirements of urbanisation and climate change, it is vital that mass timber be considered as a viable alternative for steel and concrete. It would be of interest to see how the application of mass timber compares to that of reinforced concrete, since reinforced concrete is the most dominant construction material used in South Africa (Drennan, 2017). As such, a comparative analysis of development costs of a typical multi–storey reinforced concrete and mass timber building is required to assess the economic viability of mass timber construction in South Africa.

1.3 Research Objectives

The aim of the research is to perform a development cost comparison between a multi-storey mass timber and reinforced concrete building in South Africa. To this end the research objectives of this dissertation can be defined as:

a) To briefly investigate and comment on the economics surrounding the timber industry in South Africa.
b) To investigate different concepts and designs for multi-storey mass timber buildings and elaborate on alternative mass timber construction techniques.
c) To design and model a mass timber frame building and a reinforced concrete frame building, followed by the development of construction schedules in order to perform a timber/concrete development cost comparison.
d) To develop a financial model which can be used to investigate the effect of certain variables on the internal rate of return of the multi-storey mass timber development through a sensitivity analysis.
e) To use the design project as a case study for the development, implementation and use of BIM, in order to identify the potential benefits and limitations thereof.

1.4 Methodology

In order to meet the objectives of this dissertation, information and results were predominantly gathered through comprehensive literature studies and interviews conducted with industry professionals. Software was used to model the design and to provide output for analysis where applicable. A financial model was developed to perform a financial feasibility study for both the reinforced concrete and mass timber frame buildings, respectively.

An in-depth literature review investigating various aspects of mass timber construction and popular mass timber design systems is conducted in Chapter 2. The chapter provides a brief overview of the South African forestry industry while commenting on recent global and local construction market trends. Moreover, a simple analysis is performed based on existing literature to determine whether South Africa can supply enough timber from current resources for a potential multi-storey mass timber building market. A materials research section is added which elaborates on the various materials used in multi-storey mass timber buildings. The chapter further provides the necessary background knowledge of the fire performance of timber. Chapter 2 concludes by introducing the concept of Building Information Modelling (BIM) and elaborates on the potential benefits through the implementation thereof.

Chapter 3 presents the design methodology by making reference to the various software packages used throughout the design process. The chapter eludes to a number of improvements that were made to the design delivery process due to the integrated design process which was followed. A number of limitations regarding the use of BIM were encountered during the course of the project. The chapter concludes by highlighting and discussing the main limitations of BIM from that which was experienced for this particular research project.

Chapter 4 presents the conceptual designs for the 8 storey reinforced concrete frame building and mass timber frame building, respectively. The reinforced concrete design was performed by consulting engineering firm, Bart Senekal & Partners Inc. Three timber frame/floor & core combinations were considered for the mass timber building namely; GL24h glulam frame/C24 CLT floor & core (imported timber), S7 glulam frame/S7 CLT floor & core (South African timber), and S10 glulam frame/S7 CLT floor & core (South African timber). The design of the GL24h/C24 mass timber building was performed by European consulting engineering firm, A^2 Timber. A cost comparison (Chapter 6 and Appendix H) showed that S7 grade timber would prove to be the most cost effective solution as opposed to GL24h or S10 timber. As such, a design of an S7 glulam frame was performed by the author. C24 CLT (imported CLT) was assumed to be equivalent to S7 CLT in terms of mechanical properties. A separate design of the S7 CLT floor and core was thus not required as it was the same as that of the C24 floor and core design performed by A^2 Timber. Table 1.1 contains a summary of the designs that were performed by A^2 Timber and the author.

Table 1.1: Mass timber building design summary

Designer	Glulam Frame	CLT Core	CLT Floor
A^2 Timber	GL24h: ULS/SLS/FLS	C24: ULS/SLS/FLS	C24: ULS/SLS/FLS
Author	S7: ULS/FLS/SLS S10: Cost check (Chapter 6)	S7: Equivalent to C24 S10: Not considered	S7: Equivalent to C24 S10: Not considered

Chapter 4 also presents the findings of an interview which was conducted with the executive director of the South African Wood Preservatives Association (SAWPA) regarding the treatment of mass timber. The chapter concludes with a summary of the total mass of each structural frame in Section 4.4, followed by a comparison of the foundation sizes.

The focus of Chapter 5 is the development of construction schedules for both the reinforced concrete and mass timber frame building. Extensive discussions during a focus group workshop resulted in the development of the construction schedules for both buildings. The focus group comprised of 5 industry professionals with expertise in project management, civil engineering, construction, carpentry, architecture and mass timber manufacturing. During the course of the focus group workshop a number of concerns regarding the timber industry were raised. The chapter therefore concludes by highlighting and discussing the current limitations/concerns regarding mass timber construction in South Africa.

Chapter 6 comprises of a comprehensive development cost comparison of the two buildings. A financial model was developed to gauge the feasibility of each development. Through this, Chapter 6 comments on aspects such as total construction cost, total capital investment, interest incurred during construction, and presents the expected 'S-curve' for each building during construction. Internal rate of return is the primary metric used to gauge the potential profitability of the developments.

A sensitivity analysis is performed in Chapter 7 to investigate the effect of a number of variables on the overall development cost and internal rate of return of the mass timber frame building. Finally, Chapter 8 comprises the dissertation conclusion, followed by recommendation for future investigations and prospects.

1.5 Scope and Limitations

This section aims to define the scope and limitations of the research study to ensure an accurate and feasible comparison between the two buildings. Various comparisons between mass timber and reinforced concrete buildings can be considered which include, but are not limited to:

- structural performance comparison
- environmental impact and life cycle analysis (LCA) comparison
- social impact comparison
- cost comparison

Structural Performance Comparison

The buildings in this study are designed according to national codes by independent structural engineering firms. However, the designs remain conceptual and are considered to be conservative (have not been optimised). A more detailed design process would require subsequent design reviews that extend beyond the available resources of this study. As a result of this, the study refrains from entering into a detailed structural analysis for each building. This is because the main aim of the research is to focus on the total development cost and construction schedules.

The following terms need to be defined before commencement of the research:

Multi-storey building: Multi-storey refers to buildings that are between 2 and 20 storeys for this particular study. Buildings that have more than 20 storeys can be regarded as tall multi-storey buildings and generally require different design principles as to that of typical low multi-storey buildings in South Africa (Tata Steel, SCI and BCSA, 2015). The desired classification for the timber building in this study was a Type IV-C structure in accordance to the recently revised 2021 International Building Code (IBC) (refer to Section 2.1.2). This classification allows for the majority of mass timber within the building to be left exposed, which is appealing from an architectural perspective. The 2021 IBC allows for a maximum of 9 storeys, 25.9 m and approximately 37 625 square feet for Type IV-C buildings (Breneman, Timmers and Richardson, 2019). Given this information, an 8 storey building with a total height of 24 m was initially envisaged for this particular study. Design reviews with consulting engineers revealed that the floor-to-floor height needed to be increased from 3.0 m to 3.5 m. The final design therefore has a total height of 28 m.

Mass Timber: Mass timber (also known as heavy timber, engineered timber, and *massivholz* (German)) is a category of framing styles used in timber buildings which is characterised by the use of large solid wood panels for wall, floor and roof construction (reThink Wood, 2016; ARUP, 2019). The main timber products commonly found within the mass timber family include; cross laminated timber (CLT), glued-laminated timber (glulam), and structural composite lumbar (SCL) (reThink Wood, 2016). Mass timber systems, as seen in the 8 storey structure in this study, compliment light wood-frame and post/beam systems (reThink Wood, 2016).

Structural Alternatives: The aim of the study was to compare a multi-storey mass timber structure to that of a dominant building system in South Africa. Reinforced concrete construction is the most popular system for commercial buildings in South Africa (Drennan, 2017). Hence, a multi-storey mass timber structure is compared with a reinforced concrete flat slab structure. The study is limited to these two structural alternatives. Studies comparing other structural alternatives in South Africa have been conducted (refer to the work of Drennan (2017)).

Environmental and Social Impact Comparison

The study regarding the environmental and social impact of the two buildings is mainly based on existing literature and case studies. The focus of this section is to determine which building material is superior from an environmental impact perspective through a comprehensive literature study. The study comparing the social impact of each building went beyond the scope of this particular research.

Cost Comparison

The main focus of the research is the cost comparison of the two buildings. It was decided to limit the research to a development cost comparison, which includes; the structural frame cost, non-structural costs, and total capital investment cost. In other words, all the cost which would be incurred by a property developer to allow for the occupation of tenants. The operation and maintenance costs of the buildings are not considered as this extends beyond the information available in this study.

Main Assumptions

Numerous assumptions had to be made during the development of the designs, construction schedules, Bill of Quantities, and financial feasibility study. These assumptions are clearly stated within every chapter. One assumption which had a significant impact on the thesis is that of the current manufacturing capabilities of mass timber suppliers. Interviews conducted with South African mass timber manufacturers indicated that current manufacturing limitations within South Africa prevent the large-scale production of large cross-sectional beams/columns typically required in multi-storey mass timber structures. As such, a fictitious situation is assumed where large mass timber products can be manufactured within South Africa. Furthermore, the mechanical properties of S7 SA pine cross laminated timber (CLT) have yet to be tested. It was thus assumed that the mechanical properties of S7 SA pine CLT are approximately equivalent to that of CLT made up of C24 grade timber. During the development of the construction schedule, it was assumed that the mass timber industry in South Africa is an established industry. Artisans are thus familiar with the construction technique and manufacturers are capable of supplying material regularly and on-time. This assumption was made to ensure that a fair comparison was made between the mass timber and reinforced concrete construction techniques.

Chapter 2

2 Literature Review

Chapter 2 presents the necessary background knowledge required for mass timber construction. Before this, a brief investigation of the economics surrounding the South African timber industry is required.

2.1 Forestry Industry and Timber Construction

South Africa is by nature a water scarce country with a mean annual rainfall of 450 mm (DWS, 2011). The global mean annual rainfall of 870 mm makes South Africa the 30th driest country in the world (DWS, 2011). With the required mean annual rainfall to sustain timber plantations being approximately 750 mm, it can be expected that timber plantations in South Africa are limited to only a number of high rainfall areas (Sabie, 2018). South Africa’s total plantation area is approximately 1 212 383 ha, which represents about 1% of the country’s total land area (Forestry Economic Services CC, 2018). Figure 2.1 shows the percentage that various countries contribute to the world total forested area. The size of the forestry industry in a country is directly correlated to the popularity of timber construction, due to an abundance or deficit in structural timber supply. Clearly South Africa ranks among countries with a low total forested area. This raises the question as to whether local plantations can sustainably supply timber for multi-storey mass timber buildings construction in South Africa.

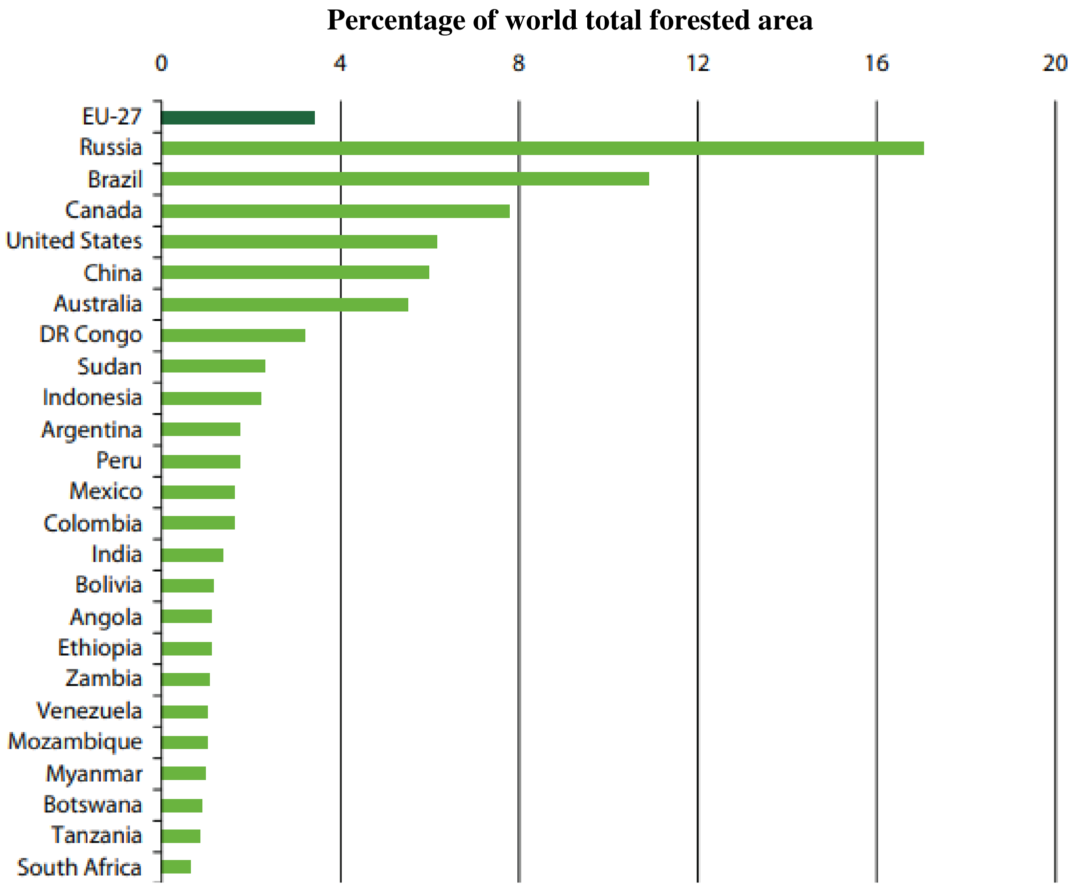


Figure 2.1: Percentage of world total forests and other wooded land area in 2010 (Eurostat, 2011)

The three main timber species found in timber plantations in South Africa are South African (SA) pine (49.6%), eucalyptus (43.0%) and wattle (7.0%) (DAFF, 2019). Figure 2.2 illustrates the distribution of timber plantations in South Arica. From this figure it is evident that up to 81% of timber plantations are found in Mpumalanga and KwaZulu-Natal province. This causes logistical challenges for the industry as the majority of the manufacturing plants are located close to the plantations.

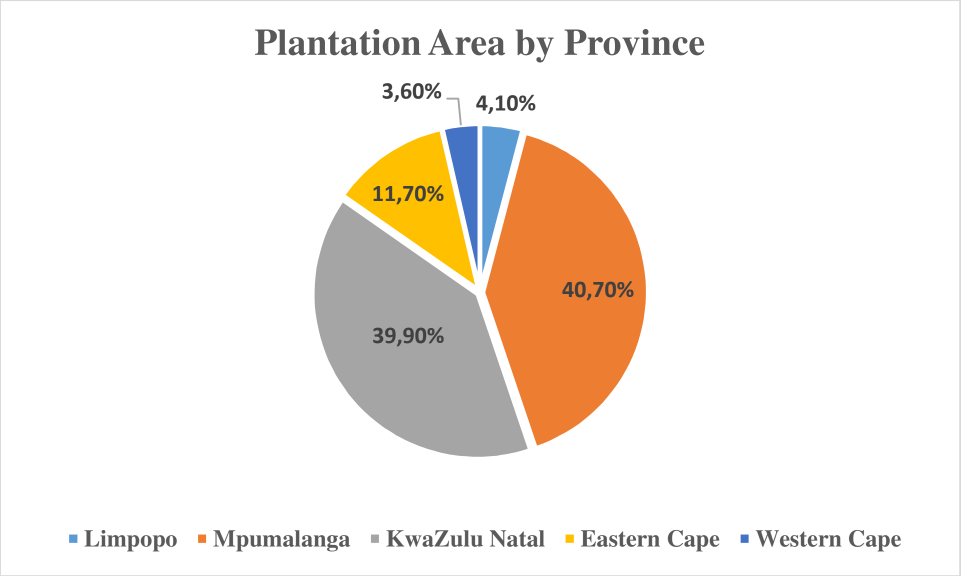


Figure 2.2: Plantation area by province in South Africa (DAFF, 2019)

A single tree in a planation can be transformed into a vast array of end products depending on the species and characteristics of the tree. SA pine is the main species used for construction purposes in the form of rafters and trusses in roofing systems as well as timber composites for walls and floors. Studies conducted by Crafford and Wessels (2016), investigating the utility of young eucalyptus for structural timber, yielded positive results with the effect that young eucalyptus timber is also considered for structural timber. Eucalyptus is the main species used for the production of mining poles in South Africa, whereas wattle is predominantly used for pulp and paper production (Forestry South Africa, 2019).

Trees in plantations are selectively felled (cut down) to form round logs. The thickest and best quality bottom section of the round log is used as a sawlog whereas the remaining section is generally turned into veneers and plywood having multiple end uses. The sawlog is sawn to produce lumber which has various end uses including structural timber (Forestry South Africa, 2019). The sawlog is of particular interest for this study since the majority of the timber composites used in multi-storey timber buildings are produced from sawlogs. For more information regarding the processing chain of timber products refer to Appendix A.

During the 2016/2017 year, 37% of the total plantation area was mainly managed for sawlog purposes, 57% for pulpwood production and 2% for mining purposes (Forestry Economic Services CC, 2018). South Africa is perceived as a timber scarce country, which raises the question if an increase in the market share of timber construction is at all sustainable due to a potential lack of local resource availability.

A study undertaken by Crickmay and Associates in 2004 concluded that the demand of softwood sawlog resource in South Africa well exceeds the supply thereof. The sawlog shortage, which stood at 27% of the demand in 2004 (1 438 500 m^3 per annum), was expected to increase to 53% in a 30 year period. This is mainly due to increases in sawn board sales of up to 17% per annum, overfelling and increased plantation loss due to fire (Crickmay and Associates, 2005). Although the economic recession resulted in the demand for sawn timber to decrease, favourable economic growth will likely result in demand exceeding supply once again (Crafford and Wessels, 2016). Figure 2.3 shows that the roundwood intake over the past 8 years has slightly decreased with roundwood production reaching 17.7 million m^3 in 2017. Additionally, the sawlog sales have increased slightly over the past 8 years.

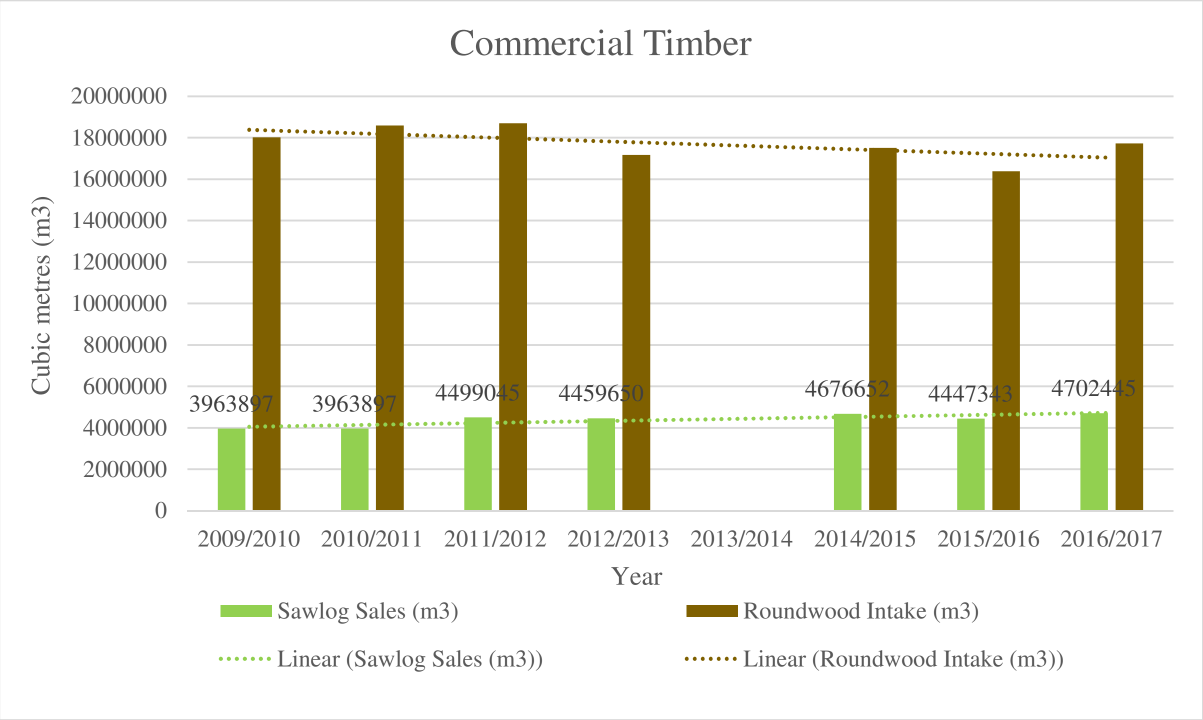


Figure 2.3: Annual roundwood production and sawlog sales from 2009 to 2017 (Forestry Economic Services CC, 2018)

Figure 2.4 on the following page shows that the production and sales of sawn timber for building purposes have on average increased over the past decade. In years 2014/2015 and 2015/2016, the sales even exceeded the production, serving as evidence that sawn timber resources are oversubscribed. Crafford and Wessels (2020) noted that it is unlikely that current sawmilling resources could supply additional structural timber for future house construction within South Africa. As such, other wood resources may be required to meet the growing demand for structural timber. It remains difficult to determine how the production and sale of timber within South Africa may change as a mass timber market develops. A comparison with the Australian forestry industry – who have an established mass timber market – may be of use in determining future market trends.

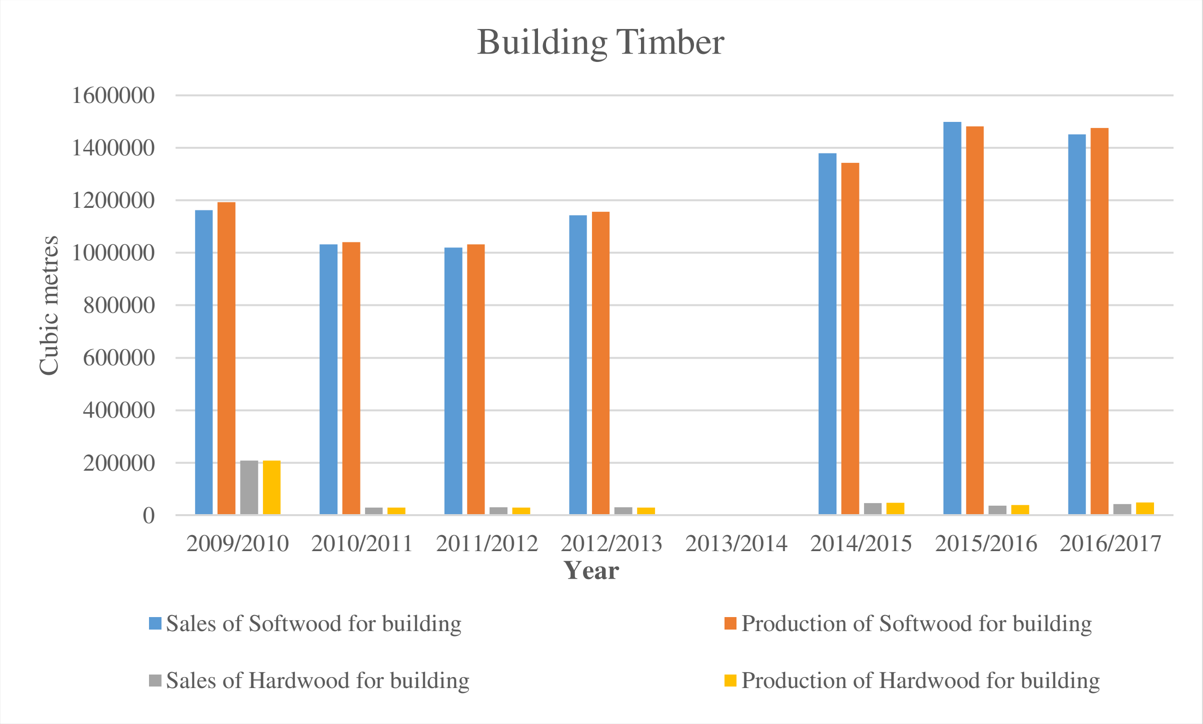


Figure 2.4: Annual production and sale of sawn building timber from 2009 to 2017 (Forestry Economic Services CC, 2018)

South Africa's 17.7 million m^3 of roundwood intake in the 2016/2017 year is overshadowed by the 28.7 million m^3 of logs harvested from Australia's commercial plantations in the 2017/2018 year (ABARES, 2018). Australia produced a total of 3.9 million m^3 of softwood sawn timber in 2017/2018 of which 85% was used for building. This is more than double the 1.4 million m^3 which South Africa produced in the 2016/2017 year (ABARES, 2018). From this it is evident that Australia has a much larger timber supply than South Africa. According to Evison and Kremer (2018), mass timber construction (MTC) only occupies a niche position in Australia. A large portion of the mass timber products used in MTC are imported (Evison and Kremer, 2018). Australia imports approximately 25 000 – 40 000 m^3 of cross laminated timber (defined in Section 2.3.1) per year and only has one local producer of cross laminated timber with a production capacity of 60 000 m^3 per year (Evison and Kremer, 2018). XLAM South Africa – which is the only producer of CLT in South Africa – can currently produce up to 2500 m^3 per year (XLAM SA, 2020). There is thus a high possibility that South Africa, like Australia, will be forced to import materials required for MTC, since South Africa is a smaller supplier of timber and an even smaller producer of materials used in MTC. It therefore remains essential to look at both the locally produced mass timber products as well as those which are imported.

2.1.1 Future Expansion in South Africa

Current supply of structural timber can be increased if a multi-storey mass timber market develops in South Africa. A recent study by Crafford and Wessels (2016) investigated potential future log resources in South Africa – specifically for sawn timber and board products that are used in timber housing. These potential resources included using chip exports for construction components. Chip exports account for approximately 17% of roundwood production (Crafford and Wessels, 2016). Other new potential resources include investing in new plantations. Table 2.1 provides a summary of the potential future log resources for timber construction, as well as the number of years required before these resources become available. Approximately 6.2 million m^3 of log resources could be added to the market for timber housing components, considering imports and current pulp, board and other log resources are excluded (Crafford, 2019).

Table 2.1: Potential future log resources (Crafford, 2019)

Future Log Resource	Log Volume (m^3/year)	Availability (years)	Data Source
Current chip export resource	2 600 000	Immediate	(FSA, 2015)
Current pulp, board and other logs	11 850 000	Immediate	(FSA, 2015)
Import logs or products	N. A	Immediate	
Afforestation Eastern Cape/KZN 140 000 ha	2 070 000	24	(DEA, 2017)
Dryland Afforestation Western Cape 170 000 ha	1 557 500	30	(Von Doderer, 2012)

Crafford and Wessels (2020) went on to calculate the amount of sawn timber that could be processed from the additional 6.2 million m^3 of roundwood logs. Calculations showed that an additional 2.9 to 4.9 million m^3 of sawn timber could be added to the South African market (Crafford and Wessels, 2020). Approximately 0.3 m^3 of processed timber products is required for one square metre of timber construction (Pajchrowski *et al.*, 2014). Given this information, a total of 9.6 to 16.3 million square metre of timber housing could be constructed out of the additional 2.9 to 4.9 million m^3 of sawn timber. This translates into 84 210 and 142 982 houses with a total floor space of 114 m^2 each which could be constructed on an annual basis (Crafford and Wessels, 2020). In South Africa, an average of 54 111 houses of 114 m^2 were constructed on an annual basis from 2000 to 2016 (Statistics SA, 2017). Crafford and Wessels (2020) state that this serves as an indication to the resource potential for an increase in wood-based construction market in South Africa.

The 8-storey mass timber building considered in this study contains approximately 1600 m^3 of structural timber (Chapter 4). 5472 m^2 of office space is available within the commercial building. This also translates into 0.3 m^3 of mass timber product which is required per square metre of office space, the same as that of Pajchrowski *et al.* (2014). By following a similar calculation procedure to Crafford and

Wessels (2020), it was calculated that a total of 1810 to 3060 similar 8-storey mass timber buildings could be constructed on an annual basis. Upon investigation it was discovered that the calculation procedure for multi-storey mass timber buildings was not completely accurate. High grade structural timber (S7 and S10) is required for multi-storey mass timber buildings. In 2011, visual and mechanical grading tests were conducted by Crafford and Wessels (2011) on 1833 random timber samples from 6 South African sawmills. Results showed an average of 31% of the samples graded as S7 for the visual grading tests (Crafford and Wessels, 2011). Given this information, approximately 31% of the additional 2.9 - 4.9 million m^3 of sawn timber can effectively be used in the mass timber products used in multi-storey mass timber buildings. Approximately 560 to 950 similar 8-storey multi-storey mass timber buildings is therefore a more accurate reflection of what could potentially be constructed from the 6.2 million m^3 of future roundwood production. Importantly, the 3.63 million m^3 of the potential future roundwood production only becomes available within 24 to 30 years after plantation. Furthermore, the 2.6 million m^3 of chip export resource needs to classify at least as S7 timber, which may prove to be difficult. This serves as further indication that mass timber products will need to be imported to satisfy a rapid growth in the multi-storey timber building market in South Africa in the current and near term.

2.1.2 Multi-storey Building Market

2.1.2.1 International Market

For a number of decades the preferred construction material for multi-storey buildings has been steel in both the United States of America (USA) and Great Britain (American Institute of Steel Construction, 2018). Figure 2.5 shows that in the USA, structural steel was the dominant building material in 2017 with a 46% market share for residential and non-residential multi-storey buildings (American Institute of Steel Construction, 2018). Concrete and timber construction managed to capture a market share of 34% and 10%, respectively.

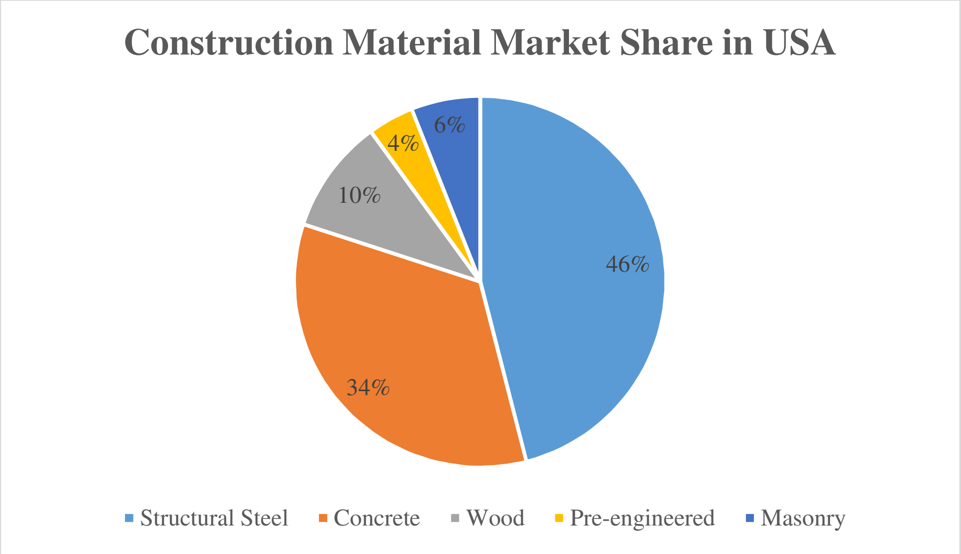


Figure 2.5: Market share of multi-storey construction materials in the USA (American Institute of Steel Construction, 2018)

Similar market shares can be seen in Great Britain where the market share for structural steel, in-situ concrete and timber was approximately 65%, 18%, and 6%, respectively, in 2018 (BCSA, 2019). The low market share of multi-storey timber buildings is the effect of building policies which regulated the number of storeys allowed in timber buildings in the 20th century, due to a lack of knowledge regarding fire resistance (Kuzman and Sandberg, 2017). This restriction caused a negative perception regarding timber and fire, which has carried over into the 21st century.

In 1988, material neutral regulations were introduced, which are functional-based regulations. In other words, if any construction material meets the minimum functional criteria it may be used (Kuzman and Sandberg, 2017). Breneman, Timmers and Richardson (2019) note that mass timber buildings in the USA "have been constrained by a strong reliance on prescriptive building code limits and less willingness to use performance-based fire protection engineering". However, this is set to change following the approval of proposals to allow tall wood buildings as part of the 2021 International Building Code (IBC) (Breneman, Timmers and Richardson, 2019). These proposals addressed requirements for mass timber construction types as well as allowable mass timber building size limits. The 2021 IBC will make provision for different mass timber construction types namely; Type IV-A, IV-B, and IV-C. For example, Type IV-A mass timber commercial buildings are allowed a total of 18 stories with a maximum height of 270 feet (82.3m) (Breneman, Timmers and Richardson, 2019). Table 2.2 shows the allowable heights, total stories, and floor areas for selected occupancies of different building types in the 2021 IBC. Occupancy 'A', 'B' and 'R' stand for 'Assembly', 'Business' and 'Residential', respectively.

Table 2.2: IBC 2021 allowable building sizes for occupancy (Breneman, Timmers and Richardson, 2019)

		I-A	I-B	IV-A	IV-B	IV-C	IV-HT
Occupancies	**Value**	**Allowable Building Height above Grade Plane, Feet (IBC Table 504.3)**					
A, B, R	S	Unlimited	180	270	180	85	85
		Allowable Number of Stories above Grade Plane (IBC Table 505.4)					
A-2, A-3, A-4	S	Unlimited	12	18	12	6	4
B	S	Unlimited	12	18	12	9	6
R-2	S	Unlimited	12	18	12	8	5
		Allowable Area Factor (At), Feet^{2} (IBC Table 506.2)					
A-2, A-3, A-4	SM	Unlimited	Unlimited	135,000	90,000	56,250	45,000
B	SM	Unlimited	Unlimited	324,000	216,000	135,000	108,000
R-2	SM	Unlimited	Unlimited	184,500	123,000	76,875	61,500

The positive regulatory changes relating to timber construction over the past two decades has resulted in a steady increase in multi-storey mass timber buildings internationally (Salvadori, 2017). Approximately 20 mass timber buildings, which are six storeys and higher, have been completed internationally since 2010 (Forestry Innovation Investment, 2017). In 2017 more than 13 multi-storey mass timber buildings (7 stories and higher) were underway (Forestry Innovation Investment, 2017).

2.1.2.2 South African Market

Information regarding the exact market share of construction materials in South Africa is not currently available. Nevertheless, extensive interviews with South African industry professionals, conducted by Drennan (2017), gathered vital information regarding the preferred construction material in South Africa.

It was found that concrete was overwhelmingly the most popular building material, followed by steel and precast concrete (Drennan, 2017). Concrete buildings were described as the 'default' option with regards to framing materials. Furthermore, from the interviews there was a perception that concrete structures are less expensive than steel, and that steel framed structures pose a more challenging construction route. South African industry professionals believe that designing concrete structures is less complex than steel, with more flexibility during construction (Drennan, 2017). It became evident that there is a lack of knowledge regarding steel construction, and that a shift in mind-set is required in order for steel to be more successful. This notion indicates that South Africa is less advanced in this area in relation to global construction trends. Globally, concrete was the first dominant construction material, followed by steel. The market share of timber has also been growing steadily as seen in Section 2.1.1.1. In South Africa, concrete is still the dominant material and has yet to undergo its steel 'revolution'. As of yet, timber construction for multi-storey buildings is not even considered as no such buildings exist in South Africa. The estimated market share for timber residential housing (not multi-storey timber buildings) in South Africa is approximately 1%, which is a major contrast to the UK and Germany, where timber frame housing reached a market share of 28% and 18%, respectively (Crafford and Wessels, 2016; Adamson and Browne, 2017; Alfter, Lüdtke and Maack, 2017).

2.1.2.3 SA Commercial Market Trend

A commercial office building was chosen for this particular study. The reason why an office building is considered, as opposed to residential, is due to the fire rating requirements as stipulated by SANS 10400-T. According to SANS 10400-T, a 3 to 10 storey office block has a more achievable fire rating of 60 minutes, whereas other types of occupancies require fire ratings of 90 and 120 minutes. For more information regarding timber in fire refer to Section 2.6.

The Rode's report for the state of the property market in the fourth quarter of 2018 in South Africa stated a national nominal rental growth of 3%. Interestingly, the vacancy rate for Green certified Prime&A – grade offices in South Africa was 5.9% lower than non-green certified offices despite demanding a premium of 13.6% (SAPOA, 2018). It thus shows that there is a drive among businesses to move to Green certified office spaces.

2.2 Materials Research

The focus of this section is to provide background on the main mechanical properties of timber, as well as various advantages and disadvantages of timber as a building material. This is followed by a description of the main structural timber components used in multi-storey timber buildings. The type of connections of these structural components and popular timber design systems are discussed in Section 2.7 of the thesis.

2.2.1 Mechanical Properties of Timber

Figure 2.6 shows the different stress strain diagrams for steel, concrete and timber. Steel shows similar behaviour in compression as well as tension. The steel initially shows linear elastic behaviour before yielding. Once yielding occurs it enters the plastic region, showing very ductile behaviour (Buchanan and Abu, 2016). In contrast to steel, concrete performs very poorly under tension, thus the need for steel reinforcing (Buchanan and Abu, 2016). The high compressive strength of concrete is followed by brittle failure as seen in Figure 2.6.

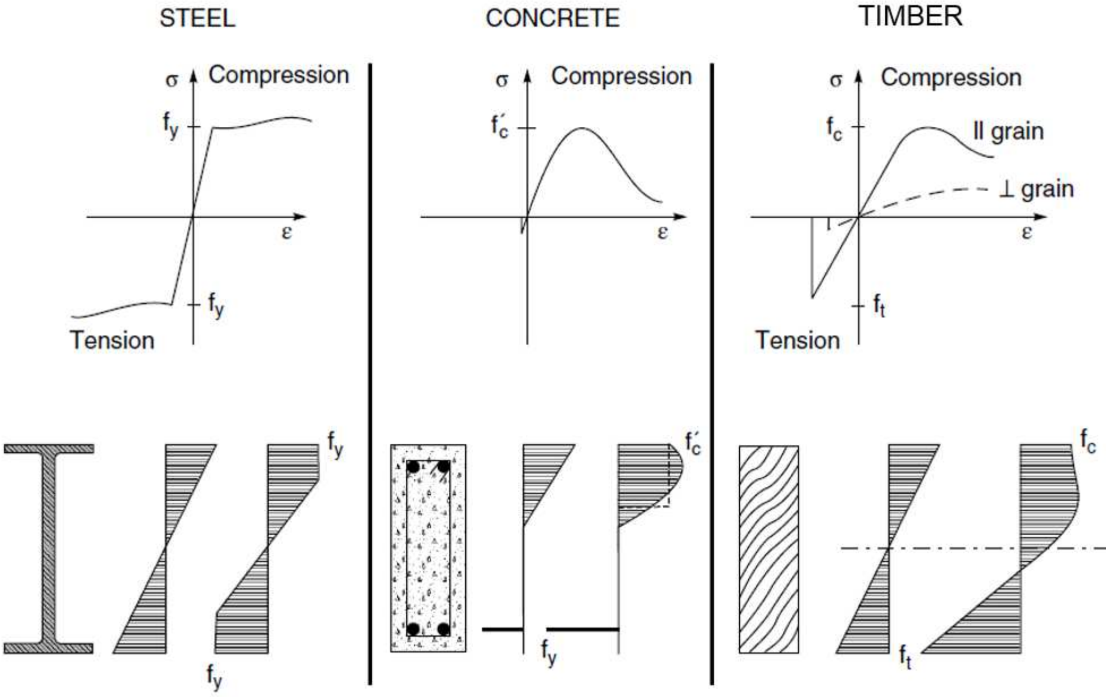
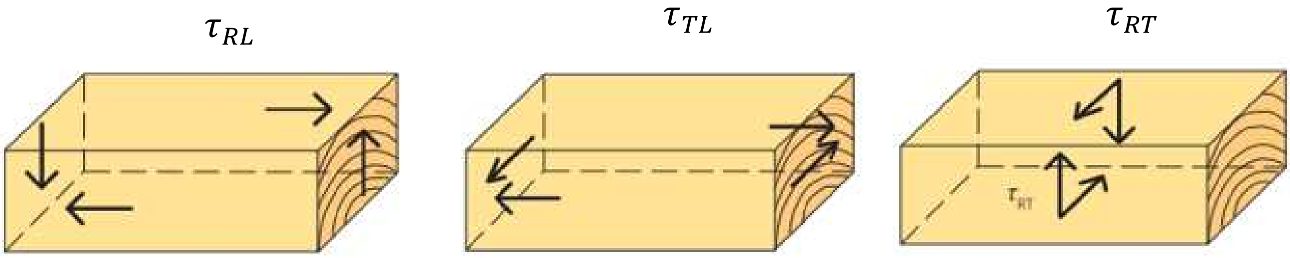


Figure 2.6: Stress-strain relationship of different materials. (Buchanan and Abu, 2016)

The stress strain diagram of timber is much more complex as it depends on grain direction. A pure tension test in the grain direction exhibits an almost linear stress-strain relationship up to failure (Johansson, 2016). The tension strength of clear timber in the grain direction is very high, with failure stress normally at around 100 MPa (Johansson, 2016). Timber loaded in tension perpendicular to its grain has a very low strength of 0.5 MPa or lower (Johansson, 2016). This has significant design implications as designers continually need to consider the grain direction of elements. Clear timber has high compression strength when loaded parallel to its grain with a compression strength of approximately 80 MPa. However, compression perpendicular to the fibre direction results in the crushing of timber fibres. As such, the strength as well as stiffness of timber is low in this direction. The compression strength perpendicular to the grain direction of clear timber is typically between 3 to 5 MPa (Johansson, 2016). "Wood is ductile in compression, but exhibits brittle failure in tension" as stated by Buchanan & Abu (2016). Timber exhibits splitting failure in tension perpendicular to grain and crushing failure in compression perpendicular to grain. Loading timber perpendicular to grain should evidently be avoided. Effectively, this is what makes connection design particularly complex with timber elements, as beams often experience point loads perpendicular to grain.



Shear longitudinal-radial **Shear longitudinal-tangential** **Rolling Shear**

Figure 2.7: Shear in timber (Carling *et al.*, 1992)

Shear strength of timber is the greatest in the direction parallel to the grain (Johansson, 2016). Shear in the τ_{RL} and τ_{TL} directions are the two most common types of shear experienced within timber buildings (Figure 2.7). Rolling shear is typically not considered with square beams, but should be checked for glulam I-beams (later discussed in Section 2.3.2). Typical shear strength values for shear in the τ_{RL} and τ_{TL} direction range from 5 MPa to 8 MPa, while rolling shear strength (τ_{RT}) ranges between 3 MPa and 4 MPa (Johansson, 2016). Shear strength in the τ_{RL} direction is generally greater than in the τ_{TL} direction, but it remains difficult to distinguish between the two for the purpose of structural engineering. As such, the lower of the two is typically applied in design codes.

Several natural characteristics of wood result in anomalies or defects within timber such that the mechanical properties of clear timber cannot simply be applied to the sawn timber used in structures. Some of the main defects within sawn timber include knots, spiral grain angle, and differences in strength between juvenile wood and mature wood. All of these defects decrease the mechanical properties of sawn timber (Johansson, 2016). As a result of these natural characteristics of wood the strength, stiffness and density vary greatly, thus requiring the timber to be graded based on machine strength grading and visual grading techniques (Johansson, 2016). The designer can then choose a specific grade of timber and know with reasonable certainty what the mechanical properties of the timber will be (Kliger, 2016).

2.2.2 Advantages of Timber

Timber holds several advantages over traditional building materials. These advantages stem from the structure and chemical composition of wood, which has made it an attractive material to build with. From a structural and architectural perspective, timber is known for its high strength-to-weight ratio, high insulation capacity due to low thermal conductivity, high resistance to corrosion, good processability, and aesthetic appearance (Brischke, 2019). The environmental benefits, health benefits and seismic response are briefly discussed below.

2.2.2.1 Environmental Benefits

Life Cycle Analysis (LCA) is the standard and internationally recognised approach for evaluating climate change impact. During such an analysis the input and output is measured for different phases in the lifetime of products (Berge, Nord and Stehn, 2017). Timber has the unique advantage of having a negative carbon footprint before manufacturing processing is undertaken, due to the storage of carbon in wood (Brischke, 2019). Variations in LCA results of wood products are typically ascribed to researchers not taking into account the carbon sequestration of wood. In this context carbon sequestration refers to the removal of atmospheric carbon and the storage thereof in timber through the process of photosynthesis. Taking this into consideration, research has shown that timber is renewable, and is the best performer across most environmental impact factors when compared to building materials such as steel and concrete, with particularly good performance in terms of greenhouse gas emissions (Petersen and Solberg, 2005; Werner and Richter, 2007; Upton *et al.*, 2008; Sathre and O'Connor, 2010; Wang, Toppinen and Juslin, 2014; Crafford and Wessels, 2020). Forte Living is a 10 storey multi-storey timber building in Melbourne constructed out of 759 cross laminated timber (defined in Section 2.3.1) panels. After completion it was estimated that the building has a 22% lower carbon footprint as compared to similar reinforced concrete constructions (ARUP, 2019). In light of such case studies, timber construction is advertised as a more environmentally friendly and sustainable building material (as opposed to steel and concrete) when sustainable forest management is practiced.

Illegal logging accounts for up to 30% of all wood traded globally (WWF, 2017). An increase in the demand for timber products may result in a rise of illegal timber trade. In a recent report titled *The State of the World's Forest 2018,* the world's forest area recorded a decreased in global land area from 31.6% to 30.6% between 1990 and 2015 (Food and Agriculture Organization of the United Nations, 2018). This accounts to a total area of 129 million hectares – approximately the size of South Africa. The largest loss of natural forests takes place in the tropics, specifically South America and Africa. The rate of annual net loss of forest from 2010 to 2015 was 0.08% which is significantly less than the 0.18% recorded in the 1990s (Food and Agriculture Organization of the United Nations, 2015). Deforestation is a key factor to consider for the potential growth of the multi-storey mass timber building industry, especially in third world countries throughout Africa (where illegal logging is extensive). Sustainable forest management is therefore an essential requirement for timber to be considered as an sustainable environmentally friendly building material for the future (ARUP, 2019).

2.2.2.2 Mental Well-being

Studies have been conducted on the possible positive effect of timber on the well-being of the residents in timber structures. This comes from the concept that human beings have an instinctive bond with other living systems, known has biophilia (Xue *et al.*, 2019a). Consequently, human physical and mental well-being is largely affected by our contact and experience with nature in everyday life. By incorporating natural elements such as exposed timber in buildings, the human-nature connection is increased, therefore contributing positively on the well-being of residents (Xue *et al.*, 2019b). Moreover, a study was undertaken to investigate the restorative properties of wood in the human environment. After analysing the heart rates and skin conductance of 119 office workers, it was concluded that wood provided stress reducing effects in the office environment (Fell, 2010).

2.2.2.3 Seismic Response

The strength-to-weight ratio of timber is one of its major advantages. This property renders timber as structurally efficient where a large majority of the load to be resisted is the self-weight of the structure (Ramage *et al.*, 2017). Heavier structures such as reinforced concrete structures tend to experience larger inertia forces during earthquakes. The resulting outcome is that light timber residential buildings have performed well during earthquakes, as opposed to concrete, as exhibited during the Christchurch earthquakes of 2011 (Ramage *et al.*, 2017). Furthermore, during the 1999 earthquakes in Turkey, reinforced concrete buildings showed high levels of damage, whereas traditional timber buildings remained intact (Doğangün *et al.*, 2006). In a study conducted by Ceccotti *et al.* (2013), on a 3D shaking table test of a full-scale seven storey CLT building, it was found that the CLT building performed adequately for earthquake prone regions. This serves as evidence that timber shows favourable seismic characteristics. No literature regarding the seismic performance of South African timber buildings could be obtained.

2.2.3 Disadvantages of Timber

As with most materials, timber has certain disadvantages which need to be discussed in order to mitigate possible risk/hazards in timber buildings and timber construction. Various negative prejudices exist in the construction industry regarding the combustibility, robustness, durability, acoustic insulation, and weathering of timber. Importantly, the majority of these aspects can be addressed through appropriate design. The three main aspects that affect the serviceability of timber are discussed below and include; moisture, decay fungi and bacteria, and insects.

2.2.3.1 *Moisture*

Moisture negatively affects timber in various manners which include:

- Reduction in strength, hardness, durability and surface quality.
- Dimensional changes due to shrinking and swelling.
- Increase in dead loads due to an increase in mass.
- Changes in thermal, acoustic and electrical properties.
- Increase possibility of biological degradation through decaying organisms (Brischke, 2019).

As a result of this, the service life of a timber building can be significantly increased by reducing the changes of exposing timber members to moisture.

2.2.3.2 *Bacteria and Decay Fungi*

Timber products can undergo biological degradation or discoloration due to certain decaying fungi and bacteria growing and feeding on the timber (Brischke, 2019). Degradation has severe effects on the mechanical properties of the timber, whereas discoloration is unappealing from an aesthetic point of view. The nutrients, presence of water, temperature, light and pH are all factors which fungal growth and degradation are dependent on (Brischke, Bayerbach and Otto Rapp, 2006). In an attempt to mitigate the risk of fungal growth one of these variables need to be controlled. This usually comes in the form of moisture protection or impregnation of toxic preservatives (Brischke, 2019). A very high moisture content is a typical condition at which bacteria degrades timber (Kretschmar *et al.*, 2008).

2.2.3.3 *Insects*

Beetles and termites are known to be destructive when it comes to timber. Beetles typically require higher temperature and less moisture for growth, whereas termites require warmth and moisture (Brischke, 2019). Termites are found in South Africa since their preferred temperature ranges between 26°C and 32°C. Termites are known to cause severe structural damage, and attacks by termites often go unnoticed.

2.2.4 Protection Measures

Various methods are employed to protect timber from the above-mentioned hazards. These include wood preservatives and modification techniques to enhance durability and stability. The South African Wood Preservers Association (SAWPA), SABS and industry representatives established a Hazard Classification system which assists in deciding what treatment is required for purchased timber. The chemicals used for treatment include Copper Chrome Arsenate (CCA), Creosote, Boron, and Tributyltin naphthenate – permethrin (TBTNP) (SAWPA, 2019a). Table 11.1 in Appendix B shows the different hazard class symbols and typical end use applications. Protecting wood by design is of particular interest for this study. Protection from decaying organisms is achieved by ensuring no access, or that crucial parameters such as moisture, oxygen, and temperature are either above or below the minimum and maximum for activity (Brischke, 2019). Appropriate selection of material to meet required durability is the starting point for 'protection by design'. Removing water from the structure is also vital to reduce moisture-induced risk of decay or biotic attack (Brischke, 2019). Exposure to moisture can be prevented by implementing physical barriers and regular maintenance. Section 4.2.2.2 contains an interview conducted with the executive director of SAWPA regarding the treatment of timber in South Africa.

2.3 Timber Composites

The development of timber composites has attempted to address certain mechanical deficiencies of timber such as anisotropy and creep. Two of the main components used in mass timber post-beam building systems are cross laminated timber (CLT) and glued-laminated timber (glulam) (Salvadori, 2017). CLT is the most recent timber product, and has been one of the main reasons for the increase in popularity in multi-storey mass timber buildings (Lindt *et al.*, 2013).

2.3.1 Cross Laminated Timber

CLT comprises of wood lamina stacked into odd numbers of layers in an orthogonal pattern as shown in Figure 2.8. These laminations are glued and compressed together to make a single, durable solid wood panel (Burback, Pei and Asce, 2017). The number of layers for a CLT panel typically ranges from 3 to 7 layers, depending on the function of the panel. CLT panels are used as load bearing walls and floors in timber buildings (Song and Hong, 2018). Wall panels generally consist out of 3 to 5 layers, whereas floor panels are 5 to 7 layers. CLT addresses the inherent anisotropic nature of timber through the cross wise layering of the timber. The resultant effect is a more isotropic material with a high dimensional stability in-plane (Brandner *et al.*, 2016).

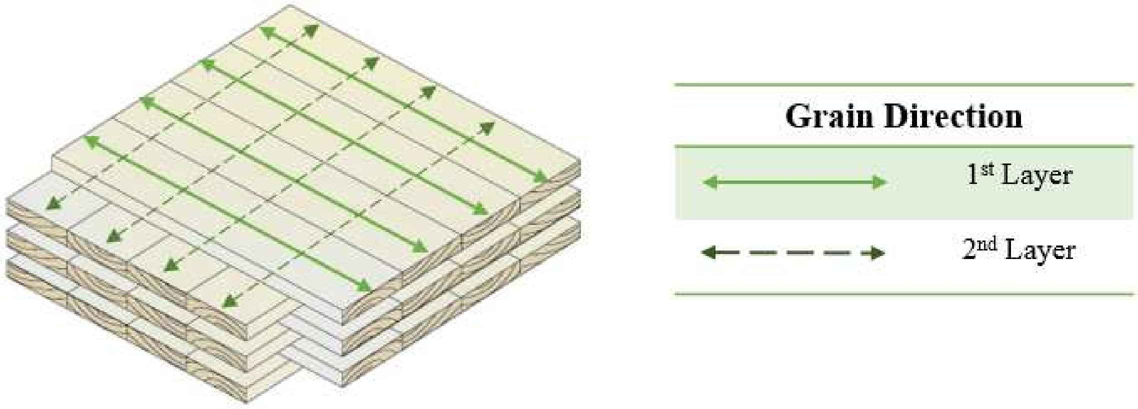


Figure 2.8: Cross laminated timber (Brandner *et al.*, 2016)

SABS standards for performance rated CLT was published in 2019. This standard is the identical implementation of the American Standard ANSI/APA PRG 320-2012 with some adaptation to make it applicable for South African timber. According to the standard, a common lamination thickness in the CLT layup is 35 mm.

Cross laminated timber (CLT) is a relatively new engineered wood structural component first developed and used in Germany and Austria in the early 1990s (Burback, Pei and Asce, 2017). During the past decade, CLT has become a product of global interest, with increased production seen outside of Europe. In 2012, the worldwide production volume of CLT was approximately 500 000 m^3/annum, which increased to 625 000 m^3/annum in 2014 – an increase of nearly 25% (Plackner, 2014). As shown in Figure 2.9, a further increase of 700 000 m^3/annum was forecast leading up to 2015. According to Ebner (2017), CLT production in Europe is expected to double from 2016 to 2020. The total CLT production volume will be approximately 1.2 million m^3/annum. The two main suppliers of CLT in Europe are Binderholz and Stora Enso – with a combined CLT production capacity of 275 000 m^3/annum. This is set to increase to 420 000 m^3/year in 2020 following expansions and the construction of new production sites. Evidently, Binderholz and Stora Enso are also the two main suppliers of CLT for large multi-storey mass timber buildings world-wide (Salvadori, 2017).

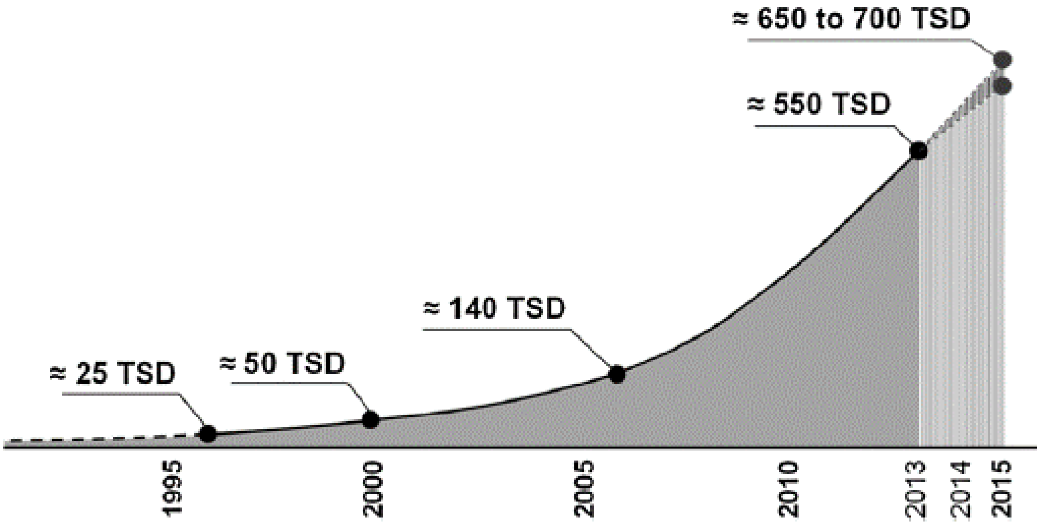


Figure 2.9: Development of the worldwide production volume of CLT in m^3 (Brandner *et al.*, 2016)

Until recently, CLT has only been produced on a very small scale in South Africa as it is a relatively new product. XLAM South Africa is the only CLT manufacturer in South Africa. SA pine (softwood) is typically used to produce their CLT products. This can be expected since Europe and North America, generally constructed CLT from typical softwoods such as Douglas fir (*Pseudotsuga menziesii*), spruce (*Picea spp*.) and lodgepole pine (*Pinus contorta*) (Liao *et al.*, 2017). Recent studies carried out by Stellenbosch University investigated the possible use of eucalyptus for CLT. Results of the analysis showed good bonding, successful shear tests, and satisfactory fire tests thereby demonstrating eucalyptus to be a viable alternative to SA pine (Dugmore, 2018; van der Westhuyzen, Walls and de Koker, 2020). This significantly improves the potential of local CLT production. As a result of these successful tests, XLAM South Africa have started to produce CLT products manufactured out of eucalyptus. The current production capacity of XLAM South Africa is approximately 2250 m^3/year. It is anticipated that current production output of XLAM South Africa would not be able to sustainably supply CLT for the entire construction of a large multi-storey mass timber building. Importing of CLT would therefore have to be considered for large projects due to current manufacturing limitations.

2.3.2 Glued-Laminated Timber

Glued-laminated timber (glulam) is one of the oldest timber composites used for structural purposes, and a material that most construction professionals in South Africa will be familiar with. Its use in timber construction dates back to 1890, while the first patent for straight beams composed of multiple laminations bonded with adhesives was issued in 1901 (Rhude, 1996). Glulam comprises of wood laminations that are arranged and bonded with adhesive so that the grains of the individual planks run parallel to one another (APA, 2018a). This is in contrast to CLT, where adjacent laminations are perpendicular (Kuzman, Oblak and Vratuša, 2010). Glulam is typically used for the long spanning beams and columns in mass timber buildings and can be bent to serve specific structural or architectural purposes (Kuzman, Oblak and Vratuša, 2010). In South Africa the manufacture of glulam is regulated by various standards including SANS 1460:2015.

2.3.3 Structural Composite Lumber

Structural composite lumber (SCL) is engineered wood products which are manufactured by stacking graded veneers, strands and flakes, and bonding them with adhesive to form structural framing members including columns, beams and studs. SCL includes; laminated veneer lumber (LVL), laminated strand lumber (LSL), parallel strand lumber (PSL), and oriented strand lumber (OSL) (APA, 2018b). Figure 2.10 provides an illustration of each SCL component.

2.3.3.1 Laminated Veneer Lumber

Veneers are thin slices of wood (2.5 mm to 4.8 mm) generally produced by rotary cutting/peeling a roundlog. Multiple layers of veneers can be laminated together using an adhesive to form laminated veneer lumber (LVL) (Green, 2012). Typical application of LVL is shuttering, furniture and flooring in the form of plywood.

2.3.3.2 Laminated Strand Lumber

Strands of wood – that were too weak, small, or misshapen for structural use – are blended with adhesive and oriented parallel to the length of the member (Green, 2012). These strands, which typically have a length-to-thickness ratio around 150, are then pressed to form a single timber composite known as laminated strand lumber (LSL). LSL has a wide range of applications which include framing boards for floor joists, support beams, columns, and door cores.

2.3.3.3 Parallel Strand Lumber

The veneers are cut into long strands (typical length-to-thickness ratio of 300) which are then laid parallel and bonded using an adhesive (APA, 2018c). PSL is often used as load-bearing columns, beams and headers. It is preferred over glulam for the heavy loaded structural columns, beam and header applications where high bending strength is needed.

2.3.3.4 Oriented Strand Lumber

OSL is similar to both laminated strand lumber and parallel strand lumber with the main difference being the length-to-thickness ratios between the composites. OSL has an approximate length-to-thickness ratio of 75 (APA, 2018c). As the length-to-thickness ratio increases so does the overall structural capacity of the member.

The reason why glulam and CLT are preferred over structural composite lumber in multi-storey timber buildings is ascribed to the high fire resistance rating that must be satisfied for the products. Glulam beams and CLT panels are typically thicker than SCL. As a result of this, glulam and CLT can meet the necessary fire ratings whereas the thinner SCL products have an insufficient fire resistance for multi-storey timber buildings unless passive protection is provided.

Figure 2.10: 1- LVL main beam; 2- PSL main beam; 3- LSL; 4- OSL (APA, 2018c)

2.4 Case Studies

One of the major benefits of multi-storey mass timber construction is an increase in construction speed due to the prefabricated nature of timber products. This may result in a shorter construction schedule for the entire project and prove beneficial from a cost point of view. The ensuing section discusses case studies where mass timber structures were studied in order to determine the potential benefits that mass timber construction may have on cost and schedule. A comparison between typical concrete buildings is also made to see how mass timber compares to conventional construction techniques.

2.4.1 Tallwood

A comprehensive report prepared by mgb Architecture and Design analysed different possible mass timber designs for a potential 12 storey and 20 storey mass timber building in Canada (Green, 2012). A replica concrete frame building was also designed to form part of the cost comparison. Since fire protection is a significant cost component of timber construction, two different fire protection methods were also considered, which included the charring method and encapsulation method. Fire protection for timber is discussed in detail in Section 2.6. Different regions for the buildings in Canada were also considered as this would influence cost. Figure 2.11 demonstrates how the cost of constructing with timber was very competitive in comparison to reinforced concrete. In all of the cases the 12 storey timber building designed using the charring method was found to be the least expensive (Green, 2012). Similar results were obtained for the 20 storey building comparison. Figure 2.11 does not encompass the possible cost reduction that a shorter construction schedule may have.

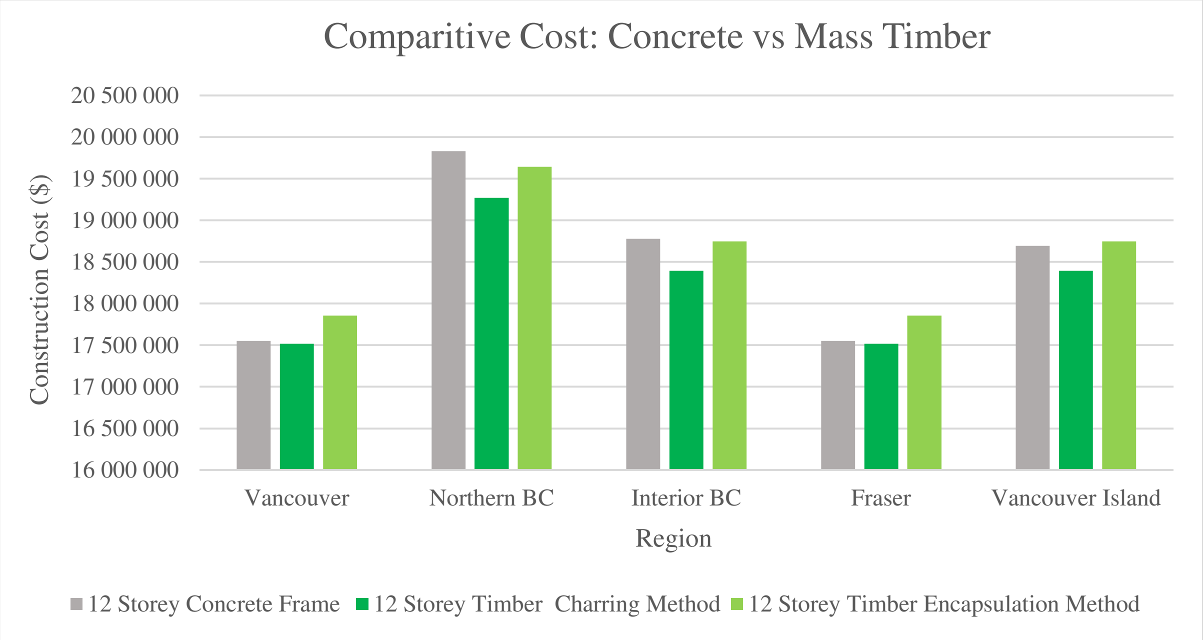


Figure 2.11: Comparative cost: concrete vs timber (Green, 2012)

A 15% and 11% reduction in construction schedule was calculated for the 12 and 20 storey timber buildings, respectively, when compared to the schedule of the concrete base cases (Green, 2012). Back propping of newly poured floors and columns, as well as the construction of a concrete core, are some of the major reasons for a longer schedule in concrete construction (Green, 2012). This reduction in schedule will result in cost savings as it enables earlier sales, resulting in less interest payments due to earlier loan repayments.

2.4.2 Rethinking Apartments

A multi-disciplinary Australian research project team had the objective of designing a model timber apartment building and, in so doing, determine the potential cost and construction schedule benefits of tall timber buildings. An 8 storey hybrid timber building was developed with a height of 25.9 m. The basement and ground floor levels would consist of concrete, while the remaining 7 floors would be constructed using mass timber (Timber Development Association NSW, 2015). The main reason for the concrete basement and ground floor was for protection from moisture and termite activity. Additionally, car park basements and retail buildings require a higher fire resistance according to the Australian National Construction Code (NCC), which would easily be satisfied with concrete (Timber Development Association NSW, 2015).

Table 2.3 summarises the cost plan for the developed timber building and compares it to a concrete base case. The timber solution was found to be approximately 2% cheaper than the concrete alternative. A major area of cost saving was the concrete transfer slab and the load bearing structure (walls, floors, columns, roof) originating from the lighter weight of timber. Fire and termite protection were some of the major additional costs for the timber option (Timber Development Association NSW, 2015).

Table 2.3: Cost plan for timber and concrete models (Timber Development Association NSW, 2015)

Element	Timber ($)	Concrete ($)	Variance ($)
Columns	28 305	306 130	-277 825
Level 1 Concrete Transfer slab	312 660	480 340	-167 680
Upper Floors	1 132 287	1 180 395	-48 108
Roof	147 135	205 530	-58 395
External Walls	1 087 910	1 098 327	-10 417
Internal Walls	939 037	954 955	-15 918
Wall Finishes	867 998	414 416	453 582
Ceiling Finishes	792 373	486 090	306 283
Termite & Fire Engineering	35 000	0	35 000
Preliminaries	-312 000	Base	-312 000
Total	$ 5 030 705	$ 5 126 183	-$ 95 478 (1.9%)

The construction schedule for the timber building was estimated using the actual construction time of similar projects (as seen in Table 2.4) and interviews with experienced professionals. The estimated construction time was 12 weeks for the timber building, while the concrete building was estimated to be completed within 18 weeks. This 33% reduction in construction schedule resulted in savings of up to $ 312 000 in preliminary and general costs – translating to a 6% reduction in cost.

Table 2.4: Mass timber projects (Timber Development Association NSW, 2015)

Project Name	Location	Apartments	Floors	Construction Time
Murray Grove	Hackney, London	29	9	17 weeks
Bridport House	Hackney, London	42	8	12 weeks
Forte	Victoria Harbour, Melbourne	27	10	12 – 16 weeks

Other areas of cost savings which were excluded in this specific study are:

- **Foundation/Footing costs**: The timber building is lighter than the concrete building and therefore requires a smaller and cheaper foundation.
- **Scaffolding:** Significantly less scaffolding is used in timber buildings.
- **Crane Size:** A smaller more mobile crane (which is much cheaper) can potentially be used since timber building components comprise lighter material.
- **Internal Works:** The process of installing services, linings and finishes is easier to carry out with timber as opposed to concrete due to the softer material and 'anywhere' fixing point. The installation of these services can also occur at a much faster rate (Timber Development Association NSW, 2015).

2.4.3 Mass Timber Buildings

A study completed by the University of Utah collected cost and schedule data for 18 mass timber buildings (Smith *et al.*, 2018). Of the 18 mass timber case studies, only 7 comparative projects of similar size and scope that were built using conventional construction material, could be identified. The 7 mass timber buildings were then compared to the conventional construction material buildings that were identified in terms of cost and schedule. On average, the mass timber construction projects showed a 4.2% average cost saving over conventional construction techniques (Smith *et al.*, 2018). However, Smith *et al.* (2018) stated that the determination of cost for the traditional buildings was difficult due to the high level of design. An average construction schedule of 15.4 months was calculated for the conventional construction materials, whereas an average construction schedule of 12.7 months was obtained for mass timber construction (Smith *et al.*, 2018). This translates into an average construction schedule reduction of 21%. Figure 2.12 shows how in 5 out of the 7 case studies, timber was found to be cheaper than traditional buildings. The 2 timber buildings that were more expensive were the first of their kind and subsequently resulted in higher costs. It is expected that the overall price will decrease as designers and contractors become more familiar with the material.

Figure 2.12: Mass timber versus traditional construction: cost (Smith *et al.*, 2018)

Figure 2.13 illustrates how timber construction generally results in a shorter construction schedule as opposed to conventional concrete construction.

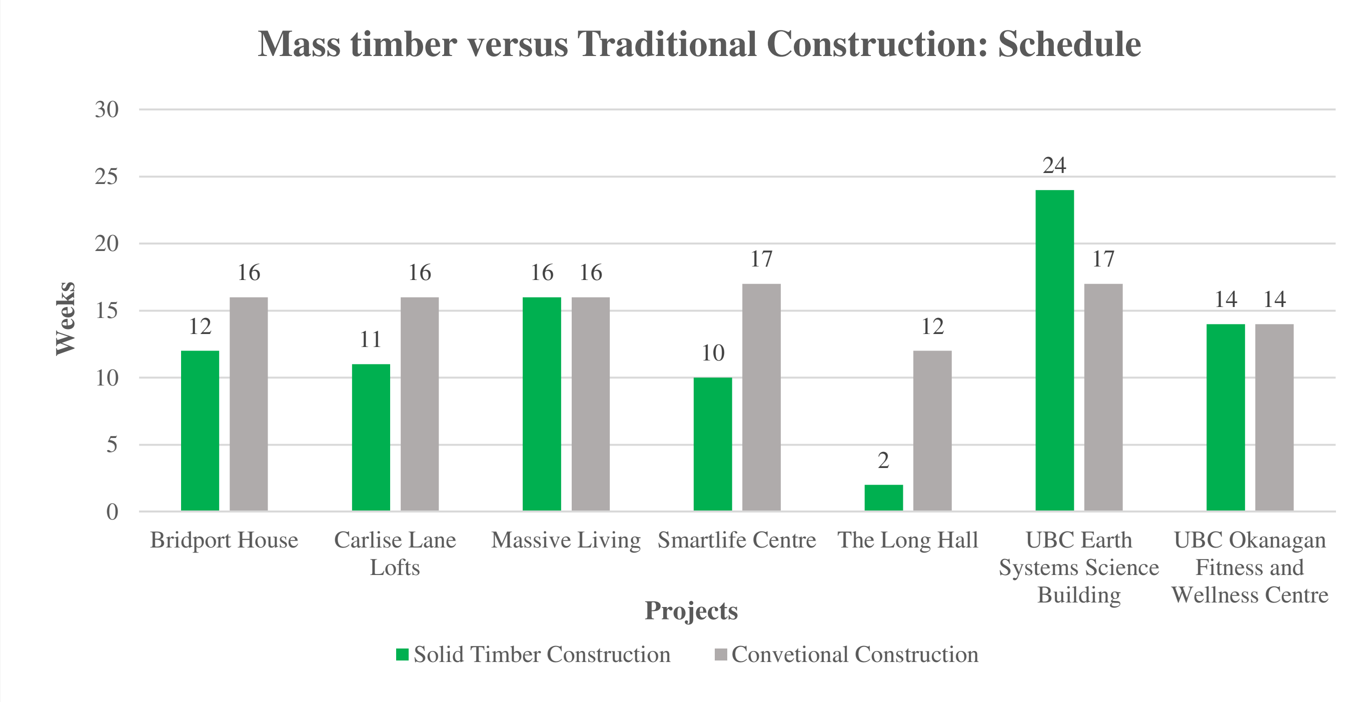


Figure 2.13: Mass timber versus traditional construction: schedule (Smith *et al.*, 2018)

These international case studies serve as evidence of the potential cost and schedule benefit that exist with timber construction. Given the above information, it may be of interest to see how a multi-storey mass timber building in South Africa compares to that of a typical reinforced concrete building in terms of cost and schedule.

2.5 Market Factors

2.5.1 Electricity

Various market factors need to be taken into consideration for timber construction. In the case of South Africa – where the cost of electricity is continually rising – developers need to acknowledge that the cost of concrete frame construction will continue to rise. The latter directly impacts several manufactured components including concrete manufacturing, steel reinforcement, formwork, mechanical vibrators and concrete pumps etc. On the contrary, timber is advantageous (over concrete) as it involves fewer electricity dependant components during construction (Green, 2012). However, the manufacture of the mass timber elements is heavily dependent on electricity. It therefore remains difficult to quantify which building system is superior from an increasing electricity cost perspective.

2.5.2 Labour

Timber construction has significantly less on-site labour as opposed to steel and concrete due to the prefabricated nature of the product (Green, 2012). Timber is easier to handle and fix, meaning less labour is required to construct the building. Off-site labour is however increased as most of the products are manufactured in factories. The aspect of labour in South Africa is elaborated on in Section 5.6.5.

2.5.3 Material Cost

Green (2012) emphasises the fact that more CLT manufacturers are needed worldwide to promote a competitive market place. South Africa is home to only one CLT manufacturer, meaning that the current material cost of CLT may not be a true reflection of its value. Similarly, in 2012 Canada had only 3 manufacturers of CLT. An increase in CLT manufacturer resulted in more competitive CLT costs.

2.5.4 Insurance

Since timber is combustible, insurance companies deem timber buildings to carry more risk as opposed to concrete and steel. The resulting effect is that the cost of insuring timber buildings is higher when compared to conventional construction (Green, 2012). It can be expected that as research into the fire resistance of timber increases, paired with an increase in timber buildings globally, so will the confidence of insurance providers.

2.5.5 Government Policy

Governments across the world are moving towards imposing carbon tax. Carbon tax is an incentive to protect the environment from greenhouse gasses by decreasing the usage of carbon fuels (Bondarenko, 2015). Carbon tax is based on the CO_2 emissions of a firm's operations. In other words, the greater the carbon footprint of a firm, the more tax it will pay. As mentioned previously, timber buildings have an advantage over conventional buildings due to their lower carbon footprint. In essence, timber building owners may pay significantly less carbon tax once the carbon tax policy is implemented (Green, 2012).

2.6 Timber in Fire

Fire remains one of the major concerns for timber structures due to the combustible nature of the material. When timber burns a charcoal layer is formed on the fire exposed surface (Buchanan, 2002). The underlying timber is insulated by this charcoal layer due to its low effective thermal conductivity (Lineham *et al.*, 2016). Charring rate can be defined as the depth which timber chars (mm) in one minute. Timber chars at fairly constant rates, irrespective of the heat intensity of the fire (SANS, 2012). This is considered a major advantage of timber over steel since the structural capacity of steel is very dependent on the heat intensity of the fire. Tests have verified steel to have only 11% of its ambient temperature strength at a temperature of 800 °C (Association for Fire Protection Specialists, 2004). Due to the slow predictable charring rate of thick timbers members, experiments have shown timber to achieve high fire resistance ratings, irrespective of fire intensity (Dagenais, White and Sumathipala, 2012). Although timber is combustible and experiences a reduction in cross sectional area during a fire, the section which is not burning (the interior of the member) still provides the same resistance as before the fire. This allows heavy timber systems to maintain significant structural capacity for prolonged periods of time during fires (Dagenais, White and Sumathipala, 2012).

Timber buildings can therefore be as safe as conventional buildings provided that fire engineering is applied throughout. Various methods have been recommended by national codes to design for fire. The two methods for calculating the load bearing capacity of mass timber during fire, as per Eurocode 5, are; (a) the reduced cross section method and (b) the reduced properties method. Essentially, designers need to ensure that the timber members are thick enough to maintain structural capacity for a specified period of time (as per the national code).

Similarly, fire protection is of equal importance in timber structures. Fire protection can be divided into two categories, namely; active fire protection and passive fire protection. Active fire protection consists of smoke detectors, alarms, and sprinklers, while passive fire protection refers to insulating structural members by using fire protection materials (Steel Alliance, 2010). Fire protection materials include boards, sprays and intumescent coatings – all of which increase the overall cost of the structure (Steel Alliance, 2010).

Every building in South Africa is required to meet a specific fire resistance rating as specified by SANS 10400 – T. One of the major concerns up to now has been that the mass timber products produced in South Africa will not satisfy the necessary fire resistance ratings for multi-storey buildings. Recent furnace fire tests conducted by Stellenbosch University obtained satisfactory fire ratings for CLT wall panels (van der Westhuyzen, Walls and de Koker, 2020). Research regarding the fire resistance of locally produced CLT members and steel connection is currently in progress.

2.7 Popular Timber Design Systems

The focus of the following section is to discuss the main design systems currently employed in multi-storey mass timber buildings. This is achieved by investigating two existing high-rise timber buildings, namely the Brock Commons Tallwood House (Appendix C) located in Vancouver, Canada, and the Mjostarnet (Appendix D) in Brumundal, Norway (also known as the Mjøsa Tower).

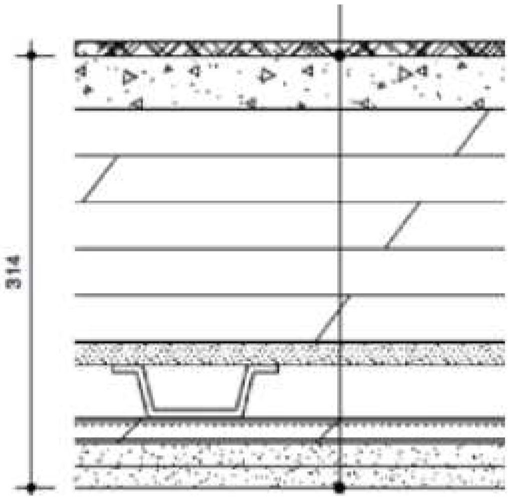
2.7.1 Brock Commons Tallwood House

The Brock Commons Tallwood House (BCTH) was completed in 2017 and held the accolade as the tallest mass timber building in the world from late 2017 to early 2019 (Hasan, 2017). This 53 metre high residential building was constructed using a combination of concrete and various timber composites. It was estimated that a total of 679 metric tonnes of greenhouse gas (GHG) emissions were avoided through the use of timber instead of concrete (Pilon *et al.*, 2016a). The literature for the BCTH was obtained from a case study prepared by Pilon *et al.* (2016). The construction and commission phase stretched from November 2015 to September 2017, a total construction time of approximately 68 weeks.

2.7.1.1 Foundation and Structural Frame

The total building footprint was 15×56 m^2, a total surface area of 840 m^2. The concrete foundation of the building consists of reinforced spread footings (2.8×2.8×0.7 m^3), a perimeter strip footing (600 × 300 mm^2) and raft slabs (1.6 m thick) that includes soil anchors below the building concrete cores. A reinforced cast-in-place concrete structure was used for the ground floor, second floor transfer slab and building elevator cores. The main reason for the choice of concrete over timber for the cores was ascribed to tight approval deadlines. As a first of its kind in Canada, separate tests would have had to be conducted to see if timber cores provided the necessary lateral stability. In addition, high clearances and large spans in ground floor public spaces was made possible by using concrete, as well as meeting the necessary fire resistance requirements for certain types of occupancies. The concrete cores provide the needed rigidity in order to resist the lateral loads imposed by earthquakes as stipulated by national building codes.

Floors 2 to 18 were constructed out of mass timber slabs and columns interconnected with steel connections. A steel perimeter beam was added to each floor to increase stiffness and to support the building envelope. The timber slabs comprised of CLT panels that were 5 layers thick (169 mm) and screwed together using a plywood spline. The acoustic, water resistance, and fire resistance properties of each floor was increased by adding a concrete screed layer of 40 mm. The panels were 2.85 m wide, while 4 different lengths were used in the floor layout namely; 6, 8, 10, and 12 m lengths. To further improve fire resistance, moisture resistance and acoustic performance, various materials were incorporated to the CLT floor. The CLT floor assembly had a fire resistance rating of 120 minutes, while acoustic insulation was between 52 and 54 STC (Sound Transmission Class). Figure 2.14 illustrates the CLT panel floor assembly used in the BCTH.



Assembly (Top to Bottom):

- Floor finish
- 40 mm concrete screen layer
- 5 layer CLT slab panel
- 16 mm Type X gypsum – moisture resistant
- 38 mm steel hat track
- 19 mm steel res bar
- 16 mm Type X gypsum
- 16 mm Type X gypsum
- Interior finish

Figure 2.14: CLT floor panel assembly

Glulam columns were used throughout the building except for columns that experienced significant loading, such as in the case for specific columns on floor 2, 3, 4 and 5. PSL columns were utilized in such cases since they demonstrate improved load capacity. General cross section dimensions for columns were 265×265 mm^2 on floors 2 to 9, and 265×215 mm^2 on floors 10 to 18. The glulam column grid was 4×2.85 m^2 from floor 2 to 18, whereas the concrete column grid was 5×5 m^2. This specific design did not require the use of any beams in the building.

2.7.1.2 Building Envelope and Connections

All of the timber elements, steel connections and facade panels were prefabricated off-site. The prefabricated panels where hoisted with a crane and simply slotted and bolted into place as can be seen in Figure 2.15. Special care was taken to keep timber components dry on-site by using various sealant and 'peel and stick' products. According to the Brock Common fact sheet, a staggering 2 floors were completed per week.

Figure 2.15: Left: Simple column to column connection Right: Prefabricated panels (Pilon et al.*, 2016b)*

Various different types of steel connections were required to join different building components for the BCTH. Figure 2.16 shows two of the four main structural connections used throughout the building. The connections are relatively simple and can be connected in a matter of minutes. It took an average of 6-12 minutes to install one CLT panels and 5-10 minutes to install one glulam column.

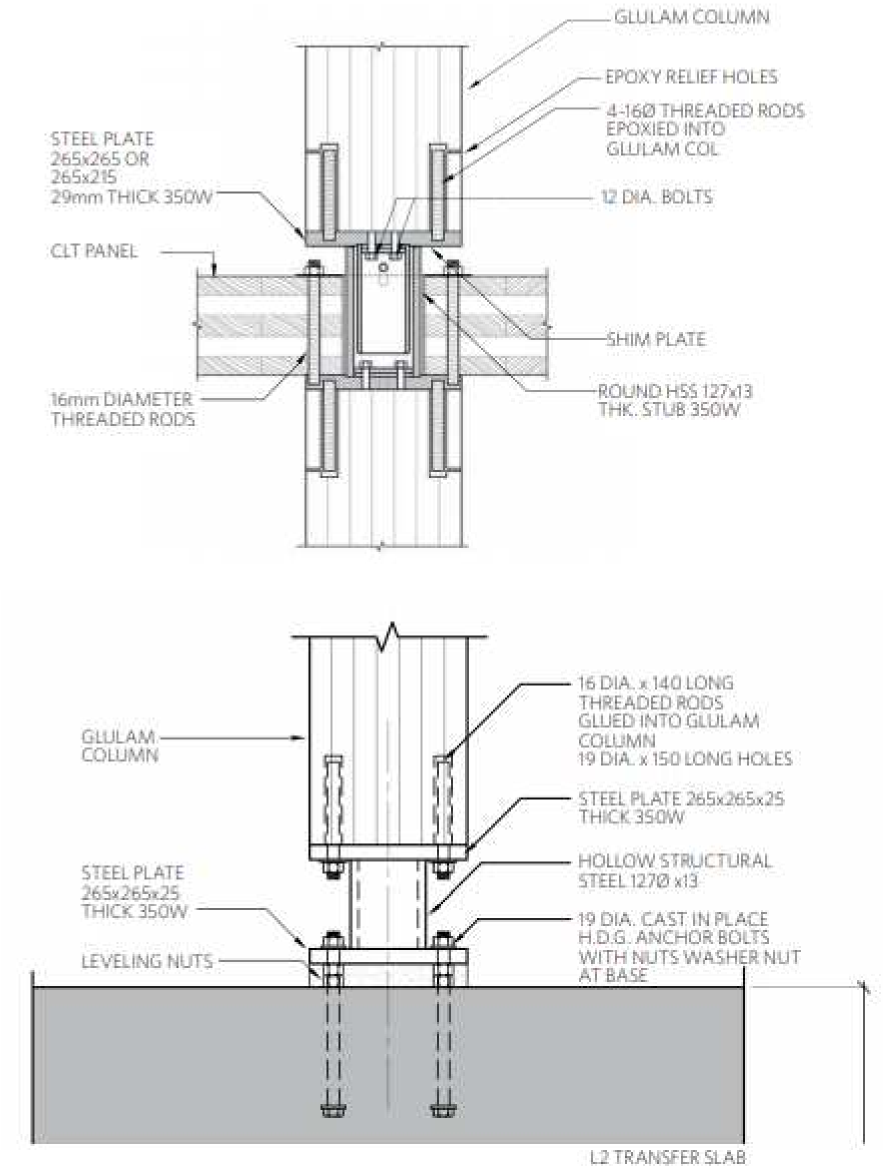


Figure 2.16: Structural connections for Brock Commons (Pilon *et al.*, 2016b)

2.7.1.3 *Fire Protection*

The active fire protection for the BCTH comprised of fire alarms and a sprinkler system. The sprinkler system had a 20 000 litres backup water tank in the event that the building is cut off from the city's water supply. Passive fire protection included covering the wooden components with type X gypsum, which is a common fire protective cladding for timber (Stora Enso, 2012). All necessary fire resistance ratings were satisfied as per the national codes. Refer to Appendix C for 3D renders of the BCTH.

2.7.2 Mjostarnet

The following information on the Mjostarnet was obtained from two conference papers written by Abrahamsen (Abrahamsen, 2017, 2018). The Mjostarnet is an 18 storey timber building which stands approximately 85 m tall – making it the tallest mass timber building in the world in 2019. The building is located in the town of Brumundal, Norway, and was opened on 1 March 2019. Groundwork on the building site started in April 2017, while assembly of the building frame commenced in September 2017. The building frame was completed in September 2018, 18 months after groundwork started. Appendix D contains 3D renders of the Mjostarnet mass timber structure.

2.7.2.1 Foundation and Structural Frame

A different structural system was employed for the Mjostarnet when compared to the BCTH. The foundation size was approximately 17×37 m^2 consisting of a main concrete slab supported by driven piles. The ground floor slab was concrete while floors 2 to 11 were timber. The remaining floors (12 to 18) were concrete floors with a thickness of 300 mm. Tests showed that additional mass was required higher up in the building to satisfy the necessary comfort criteria, hence the decision to use concrete instead of timber. Lateral stability was provided by bracing the structure with diagonal glulam beams as opposed to the concrete cores used in BCTH. In essence, the diagonal glulam beams form a structure that resembles a horizontal truss system rotated 90 degrees. In contrast to the BCTH, the elevator cores were constructed out of CLT. Studies have shown CLT shear walls to provide the necessary lateral stability required in structures (Hashemi, Valadbeigi and Masoudnia, 2016).

Mjostarnet also used a completely different flooring system as opposed to the BCTH. Instead of the typical CLT used in multi-storey timber building, designers chose to use Moelven's TRA8 flooring elements. The TRA8 system, as illustrated in Figure 2.17, uses a combination of thin glulam girders and flanges with a LVL plate glued to the top. Rockwool was placed in between girders and flanges to achieve a R90 fire rating. Rockwool constitutes stone wool and galvanised steel mesh, which improves fire resistance and acoustic properties of flooring systems (Rockwool Ltd, 2019).

Figure 2.17: Moelven's TRA8 flooring system (Abrahamsen, 2017)

According to the designers, the flooring elements use less timber compared to CLT decks and floors and can span up to 10 m. For this particular building the floor spanned a maximum of 7.5 m. The majority of the flooring elements also have a 50 mm concrete screed layer on top.

Maximum compression and tension forces of 11 500 kN and 5500 kN, respectively, were calculated in the columns. The maximum dimensions for the external glulam columns are 1485×625 mm^2, whereas internal column dimensions are 725×810 mm^2 and 625×630 mm^2. The Mjostarnet incorporates glulam beams of 395×585 mm^2 and 395×675 mm^2 to support the timber floors. The columns' cross sections were substantially larger than that of BCTH, which is possibly due to the extra height of the building and absence of concrete columns on the ground floor. Concrete floors were supported with thicker glulam beams with sizes ranging between 625×585 mm^2 and 625×720 mm^2. A maximum dimension of 625×990 mm^2 was used for the diagonal glulam beams.

2.7.2.2 Building Envelope and Connections

Similar to BCTH, the building envelope consisted of prefabricated wooden cladding, and facade elements which already had insulation installed. Slotted in steel plates and dowels were used to connect the glulam elements. The steel connections were high capacity connections typically used in bridges and large buildings. Figure 2.18 is an image of one of the steel connections used to connect the foundation to the first vertical and diagonal glulam column. The steel connections were installed at depths exceeding 85 mm into the timber for fire resistance purposes. Additionally, any gaps between building elements resulting from the steel connections were fitted with intumescent fire strips to protect connections during fires.

Figure 2.18: Steel connection for foundation and vertical/diagonal column connection (Abrahamsen, 2017)

2.7.2.3 Fire Protection

The structural frame of the building had to be designed for a 120 minute fire rating, whereas floors had to achieve a 90 minute fire rating. The fire resistance of the members was calculated by using the reduced cross section method. To further enhance fire resistance, visible timber in the main stairwell and elevators received a layer of fire retardant. CLT panels were also covered using plasterboard (probably type X gypsum although not specified). The entire building had a sprinkler system that was installed with several fire stops in the facades. Figure 2.19 displays a typical beam-column connection. As illustrated, the steel is installed with a timber cover of at least 85 mm to prevent exposure during a fire.

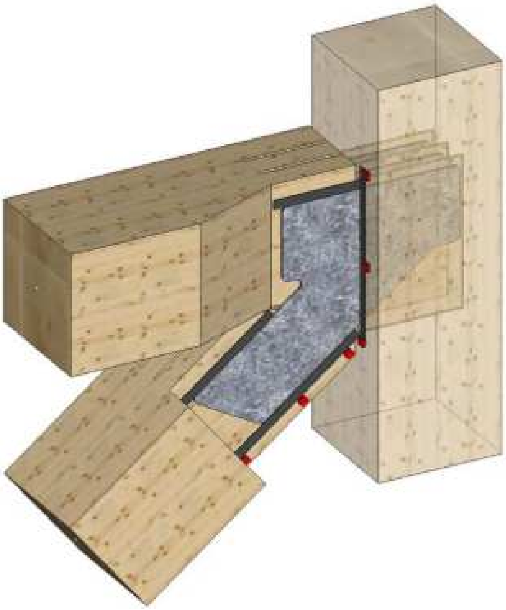


Figure 2.19: 3D render of a Beam/Column connection (Abrahamsen, 2017)

2.7.2.4 Construction Schedule

The majority of the components were prefabricated off-site and assembled on-site. Following assembly, the building sections were lifted and installed using a crane and manual labour. The tolerances in the production of the timber composites were very small. The timber was not protected against moisture during the construction of the building. According to designers this exposure to weather did not harm the structure as it was allowed to dry before installation of cladding. The LVL in the flooring system did experience some form of moisture damage and should be kept dry in future projects. In terms of treatment, the glulam elements received a layer of varnish, while visible members are to be painted again at a later stage. Epoxy was also used to seal the ends of columns where applicable.

The above-mentioned literature pertaining to the respective multi-storey mass timber building examples substantiates the potential of implementing mass timber construction within South Africa. A development cost comparison between multi-storey mass timber buildings and that of reinforced concrete is thus required to investigate the economic viability of mass timber within South Africa.

2.8 Building Information Modelling

Building Information Modelling (BIM) was implemented throughout the design delivery process. The ensuing section aims to define and discuss the term *building information modelling (BIM)* and makes reference to the application thereof in the AEC industry. Numerous advantages relating to the application of BIM are presented followed by a discussion of the disadvantages and current limitations associated with BIM.

2.8.1 Current Design Delivery Process

The planning, design, construction, operating and maintenance processes involved in engineering projects are complex processes guided by multi-disciplinary, multi-organizational teams. The planning and design processes are iterative by nature – continuously undergoing changes by the project teams. These changes, or variation orders (VOs) as they are commonly known, are generally classified as design changes initiated by owner or architect (DCO), design changes initiated by engineer/consultant (DCP), or design changes caused by improvements from design reviews (DCI) (Mohammad *et al.*, 2010). Each design team typically works on a different software package since each package offers a different primary function. As such, similar virtual models are created by different design teams, but with each model containing different information. Figure 2.20 provides a graphical illustration of the conventional project design delivery process. This form of communication in engineering projects generates additional costs, time delays, and lawsuits due to errors and omissions by different stakeholders (Eastman *et al.*, 2008). It often results in design clashes as a result of a lack of collaboration between design teams (Eastman *et al.*, 2008). A study conducted by the National Institute of Standards and Technology (NIST) attempted to calculate the additional costs generated in the construction industry in the USA as a consequence of a lack of collaboration and interoperability between stakeholders (see Table 2.5). From their findings, a total additional cost of $ 15.8 billion was calculated.

Table 2.5: Cost of inadequate interoperability in the construction industry in 2002 ($ millions) (Eastman *et al.*, 2008)

Stakeholder	Planning, Engineering, Design Phase	Construction Phase	O&M Phase
Architects and Engineers	$ 1,007.2	$ 147.0	$ 15.7
General Contractor	$ 485.9	$ 1265.3	$ 50.4
Special Contractor and Supplier	$ 442.4	$ 1762.2	-
Owner and Operators	$ 722.8	$ 898.0	$ 9027.2
Total	**$ 2,658.3**	**$ 4,072.4**	**$ 9,093.3**
Applicable square foot in 2002	1.1 billion	1.1 billion	39 billion
Cost/square foot	**$ 2.42/sf**	**$ 3.70/sf**	**$ 0.23/sf**

A different project design delivery process was required in an attempt to address this unnecessary additional cost. This new process should allow for stakeholder engagement throughout project delivery, and facilitate a more integrated design and construction process.

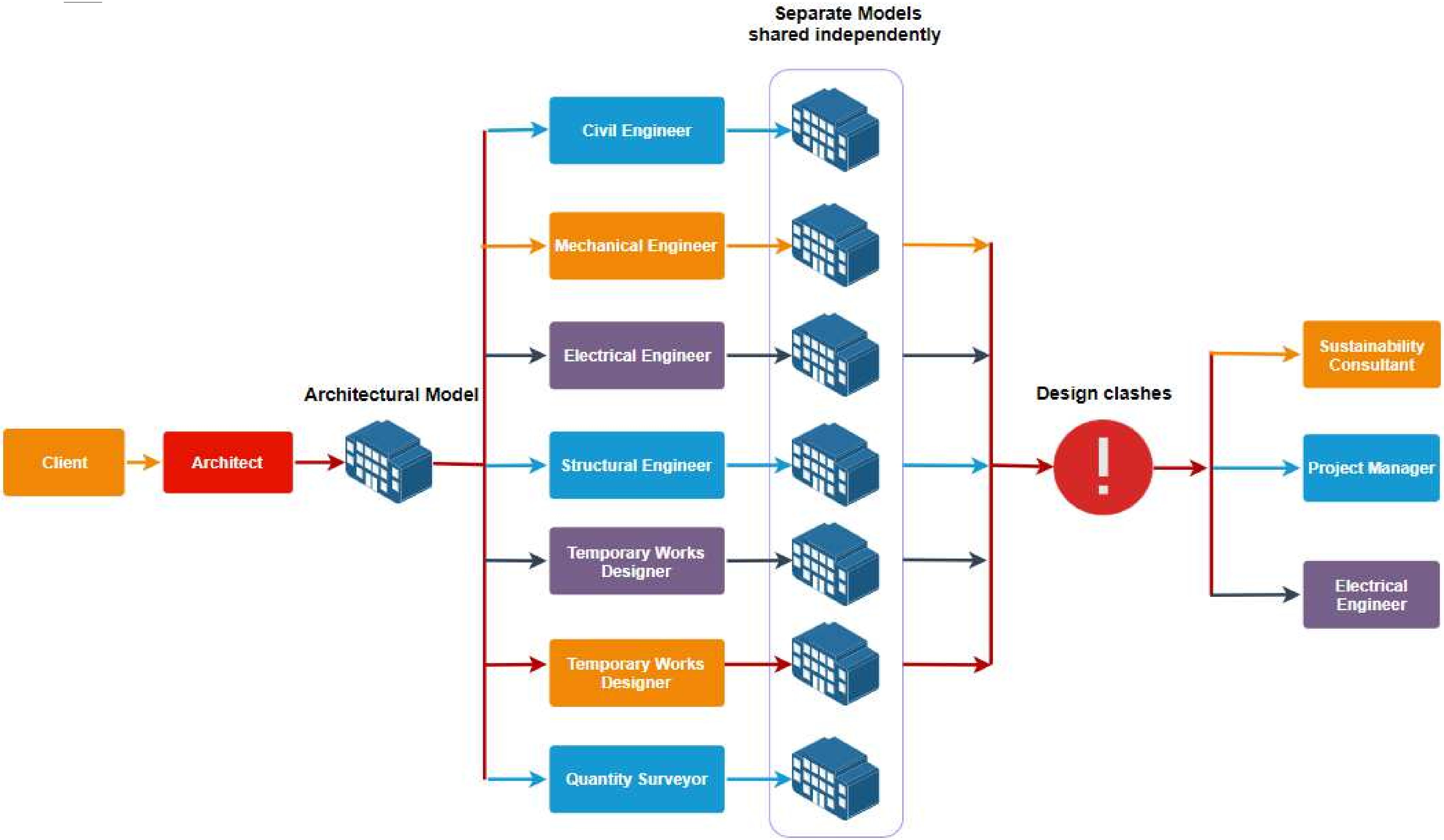
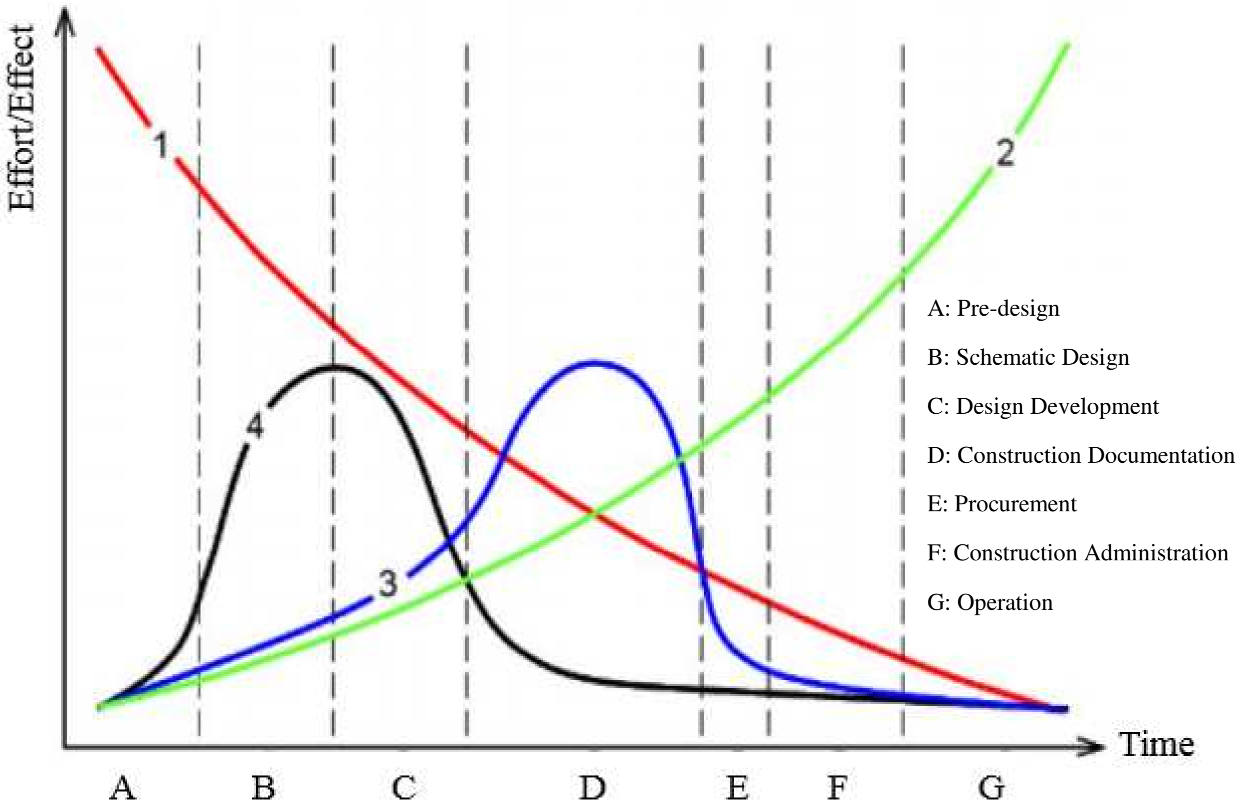


Figure 2.20: Conventional design delivery process

2.8.2 Integrated Project Delivery Process

Integrated Project Delivery (IPD) is a method of managing large engineering projects by focusing on the early collaboration of project stakeholders throughout all phases of the project. In essence, IPD alters the traditional design process by shifting the work volume required for the project to earlier stages of design (Ilozor and Kelly, 2012).

Principles of trust, collaboration, transparency, open information sharing, shared project risk and project reward are some of the key principles that IPD project team members are guided by. This is in contrast to the traditional process where information is often withheld between stakeholders due to a lack of trust. The Macleamy curve presented in Figure 2.21 illustrates the consequence of implemented IPD as opposed to the traditional approach. During early stages of the project development, the cost of alterations (line 2) are still very low. As such, error detection and design clashes between different stakeholders during the early stages of the project is one of the key focusses of the IPD process. The Macleamy curve suggest that the total construction time of the project will be reduced by shifting a large portion of the work volume to the schematic design and design development phases (line 4). This differs from the traditional process (line 3) where most of the work is completed during the construction phase.



Line 1: Ability to impact cost and functional capabilities

Line 2: Cost of design changes

Line 3: Traditional Design Approach

Line 4: Preferred Design Approach

Figure 2.21: Macleamy Curve (Ilozor and Kelly, 2012)

2.8.3 Building Information Modelling

BIM attempts to address the flaws in the current AEC model by creating a single accurate 3D parametric model of the project that all of the design teams can work on simultaneously (Azhar, 2011). Furthermore, BIM rectifies the current project delivery processes by providing a platform whereby different design teams can access and contribute to the same virtual model in real-time as illustrated in Figure 2.22. BIM is therefore an amalgamation between software and project delivery processes. The project delivery process implemented by BIM is largely inspired by integrated project delivery. Ilozor and Kelly (2012), noted that a large portion of BIM literature "makes reference to potential synergies and benefits associated with coupling BIM with IPD". BIM should be regarded as an activity instead of simply being a virtual object (Goldswain, 2016). BIM, as defined by Azhar (2011), is "a virtual process that encompasses all aspects, disciplines, and systems of a facility within a single, virtual model, allowing all design team members (owners, architects, engineers, contractors, subcontractors and suppliers) to collaborate more accurately and efficiently than using traditional processes".

The typical process followed when incorporating BIM in a project is as follows:

1. A 3D parametric model of the building/facility/infrastructure is created using software. A 3D parametric model is made up of parametric objects. A parametric object is a 3D digital object represented by parameters and rules that determine the geometry, as well as non-geometric properties and features of that object (Eastman *et al.*, 2008). The 3D model contains all information of the project including structural components, architectural component, HVAC system, civil works, interior and exterior finishes, etc.
2. The 3D model is stored on a central cloud server which can be accessed by project team members. The project design team (as well as other stakeholders) can continually access and review the model throughout the design and construction process. This significantly improves collaboration throughout the project.
3. The 3D parametric model is typically imported to additional software that extends the current capabilities of the model. These additional software packages include clash detection software, construction simulation, project scheduling software, and quantity take-off software. All of these capabilities allow project stakeholders to optimise the design, identify errors, improve coordination, as well as various other benefits (Eastman *et al.*, 2008).
4. Once construction is complete the 3D model can be imported into facility management and operation software.

BIM implementation yields several benefits for engineering projects. These benefits are discussed in Section 2.8.3.1

Figure 2.22:BIM design and project delivery process

2.8.3.1 *Benefits of BIM*

Table 2.6 lists a few of the main benefits that incorporating BIM in a project may yield as discussed by Eastman *et al.* (2008) and Azhar (2011). For more information concerning BIM, please refer to the book written by Eastman *et al.* (2008) titled the *BIM Handbook.*

Table 2.6: Benefits of BIM (Eastman *et al.*, 2008) (Azhar, 2011)

Project Phase	BIM Benefits
Design Concept	Easier to identify best design option for owner
	Assists in determining overall feasibility of design
	Allows for a more accurate code review by regulating authorities
Design	Early visualization of design
	Early collaboration of multidisciplinary design team
	Easy initial quantity take-offs and cost estimates from model
	Energy efficiency and sustainability improvement through analysis software
	Clash detection of key components before construction
Fabrication	Accurate element fabrication as suppliers can export accurate 3D elements from model.
Construction	Linking construction schedule with 3D model allows for animations of construction stages.
	Early identification of constructability issues
	Synchronise procurement with design
Facility Management	3D model provides a detailed database of building components and systems allowing for real time monitoring of systems and detailed asset management
	Assists in forensic analysis

2.8.3.2 *Challenges with BIM*

BIM challenges are mainly ascribed to the AEC industry still finding itself in the transition phase of BIM. In other words, certain companies have moved towards complete digitalization, while others are reluctant and have remained with traditional paper-based drawings. This raises impediments regarding collaboration between different multi-organizational teams (Eastman *et al.*, 2008). Industry Foundation Classes (IFC) have been introduced as an open BIM standard that allows for easy transfer of models between different software packages (Afsari, Eastman and Shelden, 2017). Unfortunately, exporting models as IFC files may still result in some data loss between software packages. Legal issues have emerged since all of the data is shared on a single server. The issues pertaining the shared platform include; ownership of the information in the model, how the integrity of the information is protected, and who ensures the design accuracy (Eastman *et al.*, 2008). Systems have been put in place and are currently being addresses by practitioners. The final major challenges as noted by both Eastman *et al.* (2008) and Azhar (2011), is implementation of BIM within firms that are comfortable with their current practices and technology. Top level management are encouraged to develop BIM adoption plans in order to update their current practices and software packages.

2.8.4 BIM Summary

Internationally the use of BIM has become increasingly popular due to the numerous potential advantages it presents. Several leading firms have started to implement BIM within the AEC industry in South Africa. However, current perception is that a large number of South African firms have only partially implemented BIM within their firms for various reasons. Research is thus required to investigate how BIM is currently applied within the AEC industry in South Africa and to test whether any of the mentioned advantages and disadvantages are realised. The aspiration to acquire knowledge and skills regarding the development, implementation and use of Building Information Modelling (BIM) for the project was of significance.

The research project undertaken within this dissertation lends itself towards the use of BIM for a number of reasons. Firstly, both the design phase, costing phase, as well as construction phase, are focus areas during the project. 4D BIM allows for easy incorporation and scheduling of these different phases. Secondly, the project is a small pilot project which mainly focusses on the design of the structural works. As such, the project serves as an ideal project to introduce and explore the basic concepts of BIM. An investigation can therefore be undertaken to see to what extent the advantages and disadvantages are realised. Specific challenges can be identified and compared to those mentioned in Section 2.8.3.2. Finally, the project will involve a large number of stakeholders at various stages in the project. Accordingly, the project can be used to give an indication of the extent to which BIM is used within the South African AEC industry, and where areas of improvement can be achieved.

The research therefore explores the basic concepts of BIM through its implementation in the reinforced concrete frame and mass timber frame buildings. In so doing, current advantages, disadvantages and challenges of BIM can be identified, while also allowing for the implementation of BIM within the South African AEC industry to be explored.

2.9 Chapter 2 Conclusion

The literature study conducted in this chapter provided the necessary background knowledge required before commencement of the research. The chapter started by providing a brief overview of the South African forestry industry. Existing literature showed that current South African timber resources are oversubscribed and that mass timber elements may need to be imported for a rapid growth in the multi-storey mass timber building market.

The material research section showed that timber is the best performer across most environmental impact factors when compared to building materials such as steel and concrete. Additional advantages of timber also include positive effects on the mental well-being of building tenants, as well as improved seismic response due to timber’s high strength to weight ratio. However, timber is susceptible to damage from moisture, insects and beetles, as well as bacterial and fungi decay. These aspects have a significant effect on the serviceability of timber and need to be addressed through appropriate design measures.

An improved understanding of the materials used in mass timber construction was required before commencement of the designs. As such, timber composites commonly used in mass timber structures such as cross laminated timber (CLT), glued-laminated timber (glulam), and structural composite lumber (SCL) were defined in Chapter 2. CLT is the most recent mass timber product, and has been one of the main reasons for the increase in popularity in multi-storey mass timber buildings.

Chapter 2 also addressed the fire performance of timber in Section 2.6. One of the main findings of this section was that mass timber buildings can be as safe as conventional buildings provided that fire engineering is applied throughout.

The international mass timber case studies which were investigated showed the potential cost and schedule benefit that exist with mass timber construction. The case studies demonstrated how the cost of constructing with mass timber was very competitive in comparison to reinforced concrete. Furthermore, mass timber was found to be superior from a construction schedule point of view with a 33% reduction in construction schedule for the 'Rethinking Apartments' comparisons. The results found in the case studies thus served as justification for a development cost comparison between a multi-storey mass timber and reinforced concrete frame building in South Africa.

Section 2.7 introduced and discussed two popular mass timber design systems. The section was significant from a design point of view. It served as the primary investigation for a mass timber system which can be successfully constructed in South Africa.

Section 2.2 to 2.7 therefore provided the necessary knowledge and understanding required for the design of a multi-storey mass timber building for South Africa. It further provided the knowledge required to identify the main variables which need to be analysed during the sensitivity analysis. The final section, namely Section 2.8 – Building Information Modelling, differed in the sense that it provided the information required for the implementation of BIM in the project delivery process. The study could thus successfully commence as a result of the knowledge and understanding obtained in Chapter 2.

Chapter 3

3 Design Methodology – Application of BIM

An objective of the dissertation is the incorporation of BIM (Building Information Modelling) during the design phase of the project. As such, several different software packages were used to review and verify the designs of the two buildings. The focus of Chapter 3 is to elaborate on the BIM process applied throughout this project and to highlight the various software packages used.

3.1 Integration of Software Packages

Figure 3.1 illustrates the main software packages that were used during the design process. Each software package fulfilled a different primary function, which ranged from structural frame analysis to construction simulation and quantity take-offs. A brief description of each software package is provided as well as the role the software fulfilled in the project delivery process.

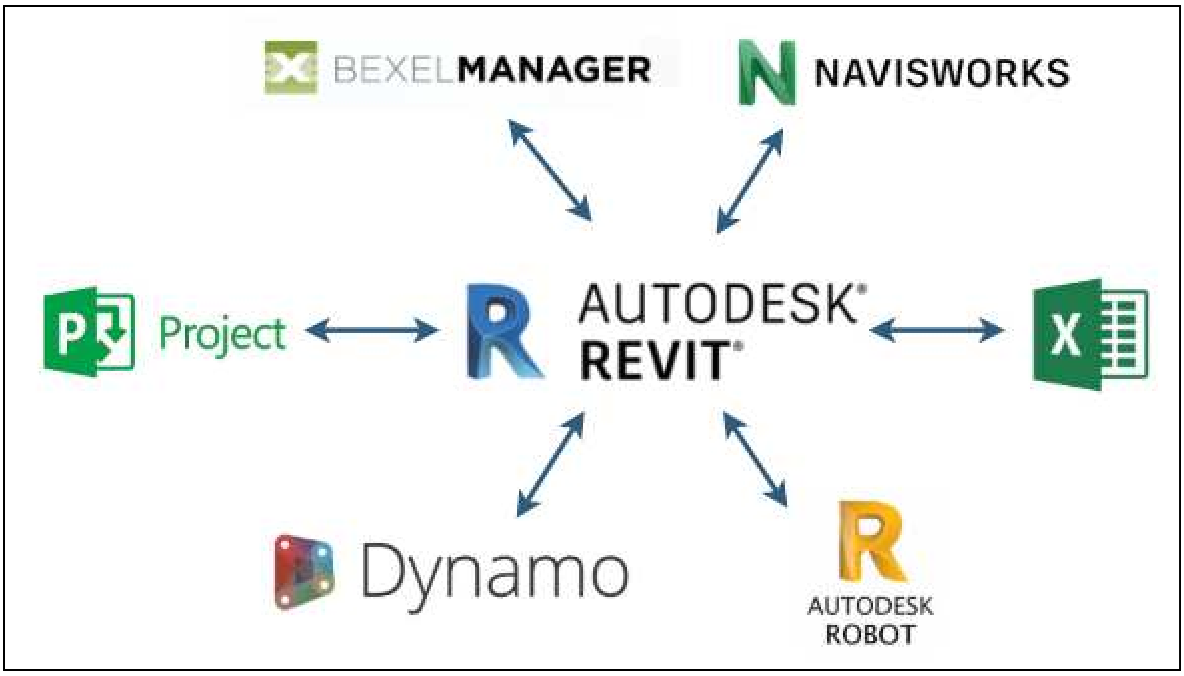


Figure 3.1: Application of software

The initial conceptual design of the timber frame building was inspired by the 25 King commercial timber frame building constructed in Brisbane, Australia. The first step of the design process comprised of hand sketches and calculation after inspection of 25 King. Following this, a 3D parametric architectural model was developed which formed the primary virtual model in the BIM process.

3.1.1 Autodesk Revit

Autodesk Revit software allows for designers to produce a 3D parametric model which can be exported and imported to various other software packages as IFC files. It forms the basis of the entire design process as illustrated in Figure 3.1. Revit has both architectural and structural templates, which in effect allows for structural models to be created simultaneously while the architectural model is drawn. Revit was used extensively throughout the entire design delivery process.

3.1.2 Autodesk Robot

Autodesk Robot is an advanced structural frame analysis software. The structural model produced in Revit was imported into Robot. This allowed for a basic structural frame analysis to be performed in order to determine the dimensions of the building elements. Independent structural engineering company, Bart Senekal & Partners Inc., assisted in the structural analysis of the reinforced concrete building whereas, A^2 Timber s.r.v, a European structural engineering firm, assisted in the structural analysis of the mass timber building.

3.1.3 Autodesk Dynamo Studio and Naviswork

Autodesk Dynamo Studio is “a stand-alone programming environment that enables designers to create visual logic to explore parametric conceptual designs and automate tasks” (Autodesk, 2020). In other words, it allows for designers to graphically program the 3D design created in Revit.

Autodesk Naviswork allows for clash detection of different building components. A common example is HVAC services clashing with structural components. The model that was designed only focused on the building frames and not any additional designs such as HVAC and MEP. As such, Naviswork was not required, but could serve well for a more complex design.

3.1.4 MS Project

Microsoft (MS) Project is software typically used by project managers and contractors for the scheduling of tasks. MS Project was initially used to create the construction schedule for both buildings. The 3D parametric models allowed for visualization of the project during the focus group workshop discussed in Chapter 5. The data captured during the focus group workshop was added to the project schedule in MS Project.

3.1.5 Bexel Manager

Similar to Naviswork, Bexel Manager adds multiple features to the 3D parametric models such as clash detection, scheduling and planning, construction simulation, and cost estimation/budgeting. These features are often referred to as the fourth and fifth dimensions of BIM. The project schedule and 3D model were imported into Bexel from MS Project and Revit, respectively. This allowed for the 4D and 5D capabilities of BIM to be utilised.

3.1.6 Excel

The data obtained from Bexel Manager and Revit, was exported into Excel for data interpretation purposes.

3.2 Integrated Design Outcome

The integrated design process that BIM offers allowed for a number of improvements to be made to the overall design process of the two buildings, when comparing it to the traditional design delivery process. The main improvements which are to be discussed are; stakeholder involvement and project delivery.

3.2.1 Stakeholder Involvement

The stakeholders that were involved throughout the project design and delivery process were as follows:

- **Bart Senekal & Partners Inc.**: Assisted in the structural analysis, design and foundation design of the reinforced concrete frame building.
- **A^2 Timber s.r.o**: Assisted in the structural analysis, design and costing of the mass timber frame building.
- **Rothoblaas South Africa (Pty) Ltd**: Assisted in the design and costing of the connections for the mass timber building.
- **Universal Plywood (Pty) Ltd**: Provided quotes for the imported glulam and CLT timber elements.
- **Capital Expenditure Projects (Pty) Ltd:** Assisted in the development of construction schedules.
- **Mitchell Du Plessis Projects (Pty) Ltd:** Assisted in the development of construction schedules.
- **Isipani Construction (Pty) Ltd:** Assisted in the development of the construction schedules.
- **XLAM South Africa (Pty) Ltd**: Provided quotes for the South African CLT elements and assisted in the development of the mass timber frame building construction schedule.
- **Holzbau Carpentry Hess CC:** Provided quotes for the South African glulam elements and assisted in the development of the mass timber frame building construction schedules.
- **Abland (Pty) Ltd:** Assisted in the feasibility study and development of the financial model.

The large number of stakeholders involved in the design process is an indirect result of the BIM models that were used. Interacting with the stakeholders was made easy by using BIM models as an interactive tool. It allowed for easy data sharing between different stakeholders and made information more accessible. In some cases it allowed for multiple reviews without the need for time-consuming redesigns.

3.2.2 Project Delivery

The use of BIM did not result in an improvement to project delivery, mainly as a result of a lack of accurate 3D BIM products available from South African suppliers. In theory, BIM allows for quantity take-offs, costing and scheduling of construction once the 3D parametric BIM model is complete. However, this is only possible if reliable, up-to-date 3D BIM products are available from suppliers. For this particular research, it was discovered that a large number of suppliers did not have reliable 3D BIM products especially within the South African timber industry.

As a result of this BIM could not be utilised to its full potential. This was also seen during the costing process, where work had to be repeated to formulate an accurate Bill of Quantities. Table 3.1 provides a summary of the potential benefits of BIM as proposed by Eastman et al. (2008) and Azhar (2011). The table shows whether the potential benefit was achieved within this particular study. The benefits which are not applicable to this particular case study have been omitted.

Table 3.1: Evaluation of BIM benefits

No.	BIM Benefits	Achieved
1	Easier to identify best design option for owner	YES
2	Assists in determining overall feasibility of design	YES
3	Early visualization of design	YES
4	Early collaboration of multidisciplinary design team	YES & NO
5	Easy initial quantity take-offs and cost estimates from model	YES & NO
6	Clash detection of key components before construction	YES
7	Accurate element fabrication as suppliers can export accurate 3D elements from model.	YES & NO
8	Linking construction schedule with 3D model allows for animations of construction stages.	YES
9	Early identification of constructability issues	YES

3 BIM benefits were only partially achieved as seen in Table 3.1. The following section briefly eludes to why the benefits were not completely achieved.

Early collaboration of multidisciplinary design team: A number of stakeholders within the design team did not have BIM compatible software. Furthermore, it was found that some data was lost between transferring the models through IFC files. In some cases, the traditional 2D pdf drawings were required to allow for collaboration from all stakeholders.

Easy initial quantity take-offs and cost estimates from model: Quantity take-offs and initial cost estimates are relatively easy once the 3D parametric model is complete. However, the cost estimate is only as accurate as the data contained within each parametric model. In the majority of cases the costs were omitted, therefore rendering the initial cost estimate completely inaccurate.

Accurate element fabrication as suppliers can export accurate 3D elements from model: In this particular project accurate 3D models were required from suppliers. A number of suppliers did not have the required 3D products which were required.

3.3 Current Limitations of BIM in SA

A number of limitations regarding the use of BIM were encountered within this particular study. The following sections highlight and discuss the main limitations from that which was experienced. The three main limitations of BIM discovered in this particular research project are discussed below.

3.3.1 BIM Knowledge

It was discovered that BIM as a concept is still not fully understood by all project members, including suppliers. This can be expected since the education surrounding BIM in South Africa remains limited. The knowledge surrounding BIM in the entire AEC industry – from the manufacturer to the client – requires improvement for successful implementation of BIM based projects. Through this, BIM can possibly be utilised to its full potential.

3.3.2 BIM Implementation

A number of stakeholders were found to have partially implemented BIM within their own organisations. Unfortunately, full utilisation of BIM within a project requires the project team to implement BIM as an entirety. It was found that a lack of implementation of BIM by certain project members resulted in a reduction of functionality of BIM. In fact, in some cases it was found to slow the project delivery process. This demonstrates the importance of full implementation of BIM by all stakeholders.

3.3.3 BIM Cost

The cost associated with BIM software packages is high. Some smaller firms encountered within this study believed that the high cost does not necessarily justify the advantages of BIM implementation. It remains difficult to quantify the financial benefit of BIM. However, if the AEC industry were to implement BIM on a full-scale, smaller firms need to be wary of becoming obsolete due to a lack of BIM implementation within their own respective firms.

3.4 Chapter 3 Conclusion

Based on this specific project, it is clear that the design delivery process and project delivery process can be greatly improved through the full implementation of BIM. However, a number of aspects, as seen in the discussion above, need to be addressed by project members before all the benefits regarding BIM can be realised.

4 Structural Development and Design

The aim of this chapter is to discuss and present the designs for both the mass timber and reinforced concrete frame buildings. The chapter is divided into two main sections namely; the timber frame building design and concrete frame building design sections. Each section presents a description of the building, followed by the design loads and limit states.

4.1 Conceptual Designs

The building is a fictitious 8 storey up-market commercial building situated in the Sandton central business district (CBD). One reason for choosing a commercial building, as opposed to a residential building, is due to the lower fire rating requirement of commercial buildings in South Africa as discussed in Section 4.3. The building footprint is 24×30 m^2 with a gross floor area (GFA) of 5472 m^2 for the 8 storeys. The floor-to-floor height is 3.5 m throughout the building resulting in a total height of 28 m. The building has a 6×6 m^2 column grid from floors 1 to 8 as seen in Figure 4.1. The external face of the building is covered by an aluminium glass façade. Figure 4.1 shows a large open office in the middle of the building with smaller offices on the sides. The smaller offices are separated by normal partitioning drywalls. The building core is separated into three sections namely, the elevator shaft, stairs shaft, and HVAC/MEP shaft. Allowance has been made for a bathroom and kitchen/lounge area for each floor. The timber and concrete buildings share the same basic layout for comparison purposes.

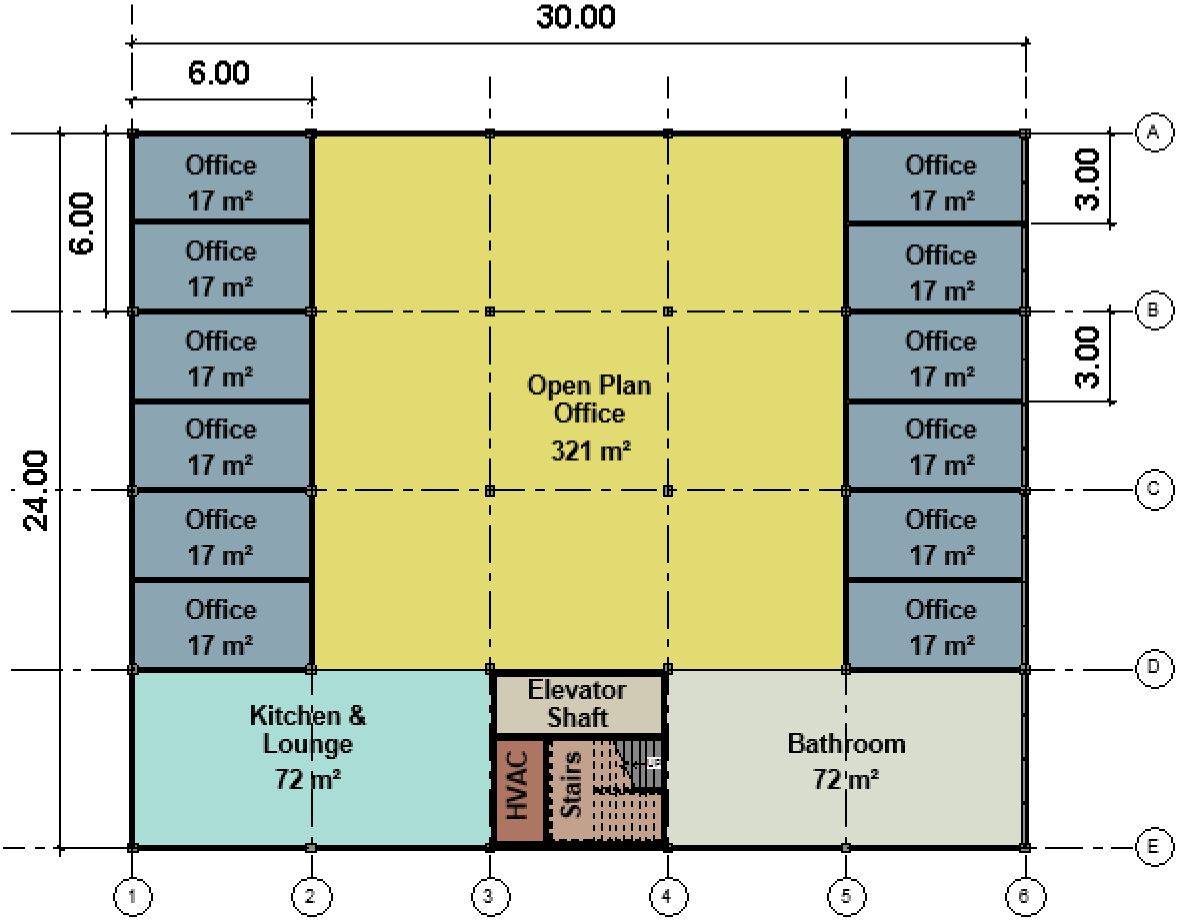


Figure 4.1:Floor plan for building

4.2 Design Loads and Limit States

The building experiences three loading types which include the permanent load, imposed load, and wind load. The floor loads were in accordance to SANS loading code and were determined as follows:

Permanent Load: The permanent loading for the building can be divided into the weight of the main structural components of the building frame, ceiling and services, as well as the imposed dead load on the floor (vinyl tiles). The loading for ceiling and services was assumed to be 0.3 kPa, while a dead load of 0.22 kPa was used for floor finishes.

Imposed Load: SANS 10160 – Part 2 prescribes a imposed load of 2.5 kPa for office areas for general use (SANS, 2011a).

Seismic Design: The buildings were not designed for seismic conditions as this was beyond the scope of the intended research. Section 2.2.2 does elude to timber structures showing improved seismic response as compared to reinforced concrete frame structures.

Soil Conditions: It was assumed that no piles are required due to shallow bedrock on-site. Normal foundation footings are sufficient for the buildings. The size of the concrete footings do differ as a result of the differences in structural/building dead weight. A soil bearing pressure of 200 kPa was applied.

Ultimate Limit State Design: The building has been designed for ultimate limit state. A brief summary of the prescribed partial factors according to the 2011 edition of SANS 10160 for STR and STR-P load combinations is:

STR-P: $\mathbf{1.35}G_k + \mathbf{1.0}Q_k$

STR: Imposed Load Leading:

Wind Favourable: $\mathbf{1.2}G_k + \mathbf{1.6}Q_k + 0.0W_k$

Wind unfavourable: $\mathbf{1.2}G_k + \mathbf{1.6}Q_k + 0.0W_k$

STR: Wind Load Leading:

Permanent and Imposed Favourable: $\mathbf{0.9}G_k + \mathbf{1.3}W_k$. (The 2019 edition of SANS 10160 uses a wind load factor of 1.6.)

Permanent and Imposed unfavourable: $\mathbf{1.2}G_k + \mathbf{1.3}W_k + \mathbf{0.3} \times \mathbf{1.6}Q_k$

Wind Load: The wind loads have been calculated using SANS 10160. The wind loading has been simplified for the sake of the design and is regarded as conservative. The wind loading is presented as a line load acting horizontally on the outer edge of each floor. Figures 4.2 and 4.3 summarise the notation used for the wind loading in both directions, while Tables 4.1 and 4.2 provide a summary of the line loads.

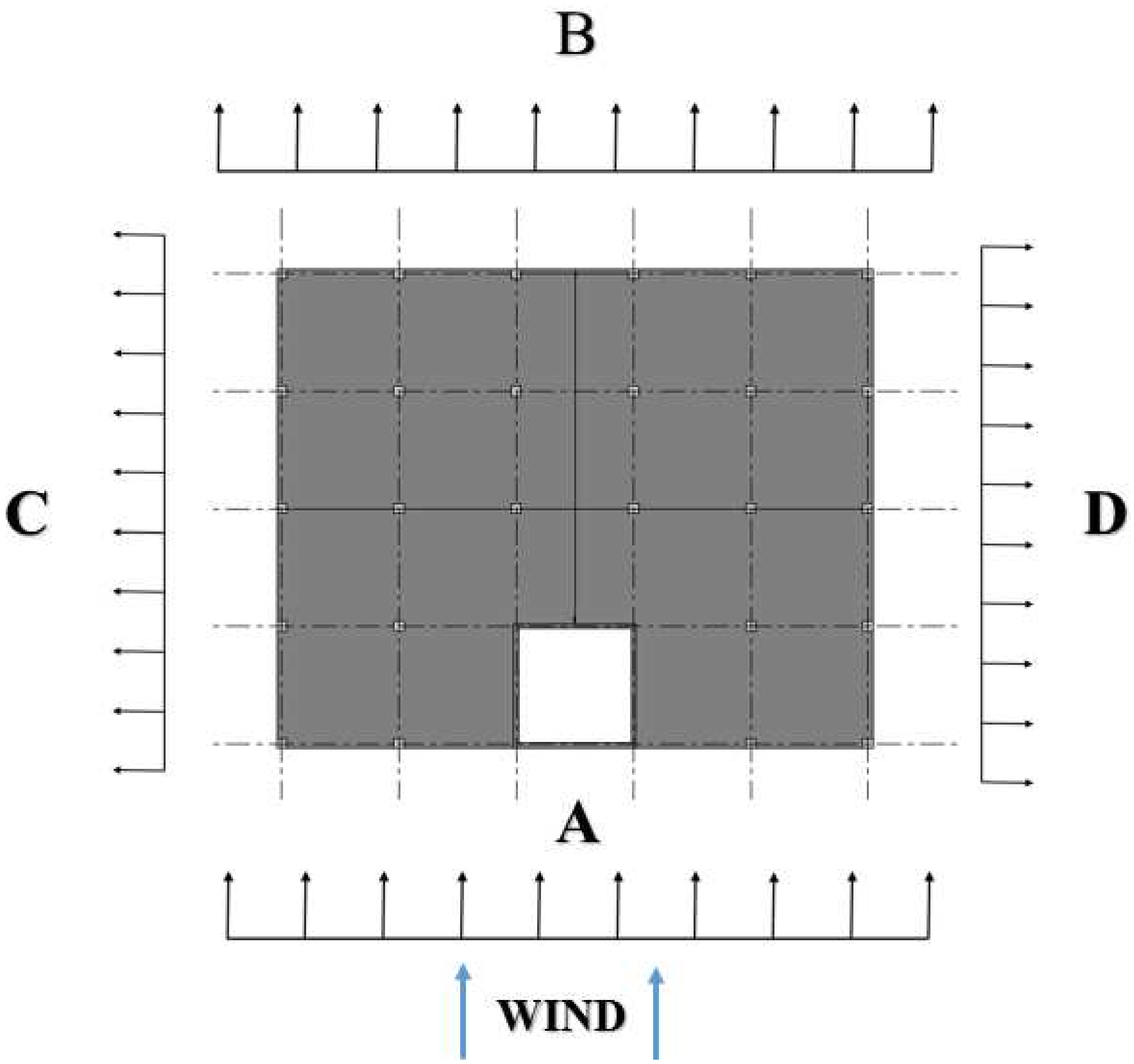


Figure 4.2: Wind direction at 0 degrees

Table 4.1: Wind loading at 0 degrees

Wind at 0 degrees				
Line load on floor beam (kN/m)				
Floor	**A**	**B**	**C**	**D**
1	1.97	-0.71	-1.69	-1.69
2	2.23	-0.80	-1.92	-1.92
3	2.42	-0.87	-2.07	-2.07
4	2.42	-0.87	-2.07	-2.07
5	2.56	-0.92	-2.20	-2.20
6	3.07	-1.10	-2.64	-2.64
7	3.07	-1.10	-2.64	-2.64
8	3.07	-1.10	-2.64	-2.64

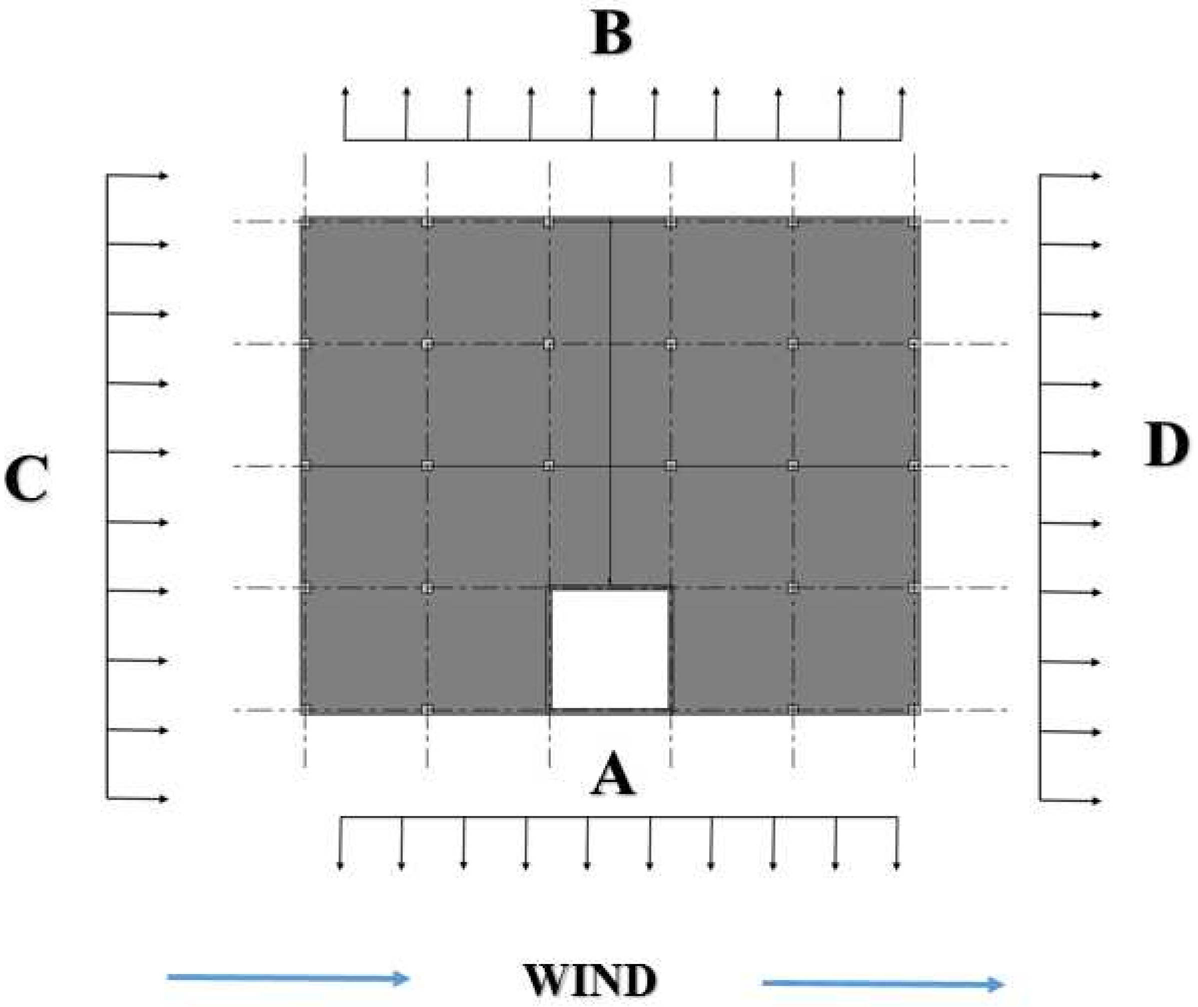


Figure 4.3: Wind Direction at 90 degrees

Table 4.2: Wind Loading at 90 degrees

Wind at 90 degrees				
Line load on floor beam (kN/m)				
Floor	**A**	**B**	**C**	**D**
1	-1.69	-1.69	1.97	-0.71
2	-1.92	-1.92	2.23	-0.80
3	-2.07	-2.07	2.42	-0.87
4	-2.07	-2.07	2.42	-0.87
5	-2.20	-2.20	2.56	-0.92
6	-2.64	-2.64	3.07	-1.10
7	-2.64	-2.64	3.07	-1.10
8	-2.64	-2.64	3.07	-1.10

4.2.1 Reinforced Concrete Frame Building

The detailed design for the reinforced concrete frame building is presented in this section. The structural analysis and design of the building was performed by independent consulting engineering firm, Bart Senekal & Partners Inc. Figure 4.4 is an image of the 3D Revit model of the concrete frame building. A steel roof structure was assumed for both the concrete and timber frame building alternatives.

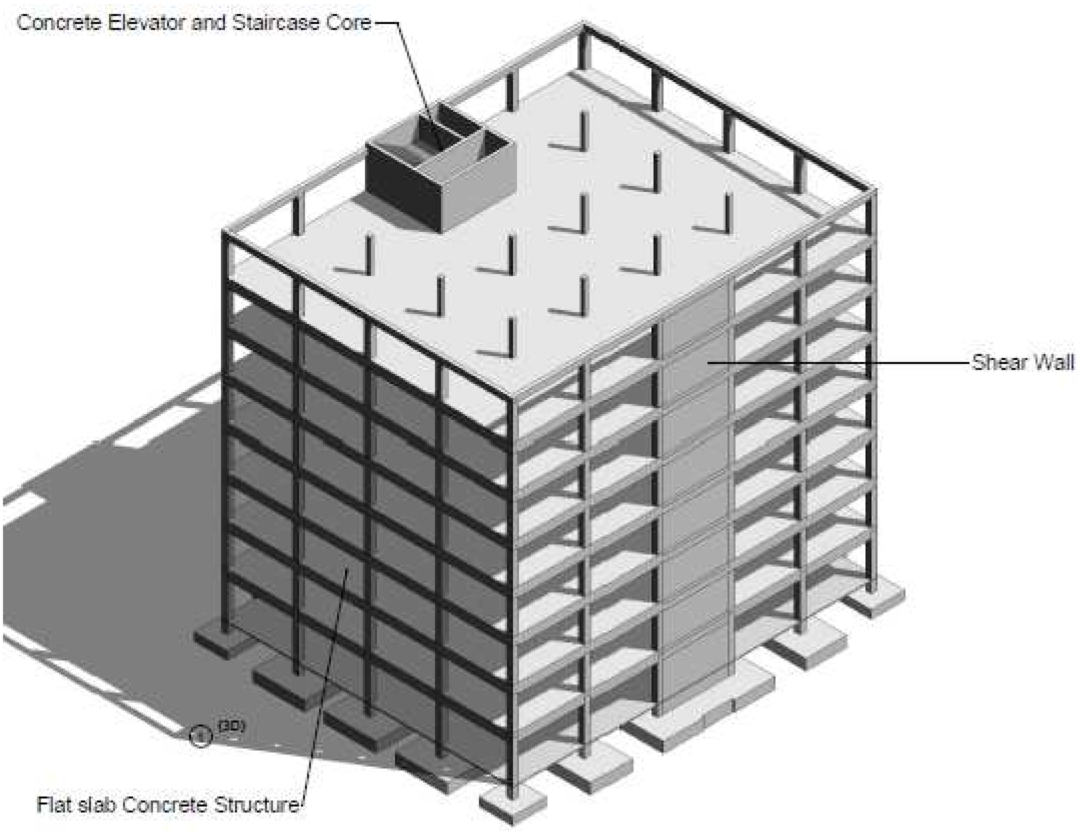


Figure 4.4: 3D Revit model of concrete frame

Lateral stability against wind loads is provided by the 250 mm thick reinforced concrete core walls and shear wall. A flat slab system with a ring beam is the system of choice for this particular design. Research by Drennan (2017) has shown that a post tensioned slab is a cheaper alternative for concrete slabs (especially in the case of long spanning slabs). However, normal reinforced concrete remains the most common building technique in South Africa. As such, and due to the 6×6 m^2 column grid, it was decided to simplify the design by selecting normal reinforced concrete. A requirement of the slab design was to refrain from the use of drops at columns, due to the commercial use of the building. A 300 mm thick 35 MPa concrete slab was thus required to accommodate punching shear within the slab. A power float finish was specified as it is a common finish for commercial buildings. A 35 MPa concrete was specified for the slab, whereas 30 MPa concrete was specified for the remaining concrete structure. The ring beam around the outer edge of the slab was specified to be 500 mm deep by 300 mm wide. The dimensions of the columns varied from floor 1 to 8. Similarly, the dimensions of the foundation footings varied based on a safe bearing pressure of 200 kPa and 30 MPa concrete. Table 4.3 provides a summary of the dimensions of the main concrete elements within the building. Upon a design review it was realized that a raft foundation may have been more appropriate given the large dimensions of the footings (resulting from the low safe bearing pressure chosen).

Table 4.3: Summary of Concrete Structure

Element	Location	Depth (m)	Width (m)	Length (m)	Quantity (No)
Footings (30MPa)	Inner	0.8	5.1	5.1	10
	Outer	0.7	3.2	4.1	10
	Corner	0.6	3.0	3.0	4
	Shear wall	0.8	4.0	8.0	1
	Core	0.8	10.0	10.0	1
Inner Columns	1-2	0.5	0.5	3.5	20
	3-5	0.4	0.4	3.5	20
	6-8	0.3	0.3	3.5	20
Outer Columns	G-8	0.5	0.5	3.5	16
Slab (35MPa)	Surface Bed	0.12	24	30	1
	Flat Slab: 1-8	0.3	24	30	7
Ring Beam	2-Roof	0.5	0.3	108	8
Walls	Core	0.25	33.8	3.5	8
	Shear	0.25	5.5	3	8

A combination of Prokon design software, Autodesk Robot, and calculations by the structural engineering firm were used to verify ULS and SLS requirements. Figure 4.5 provides a plan view and elevation of the concrete building. Detailed specification of reinforcing content was beyond the scope of this particular research as it would not have had a major influence on the cost or time of construction. Reference is made to the fire resistance of the building in Section 4.3.

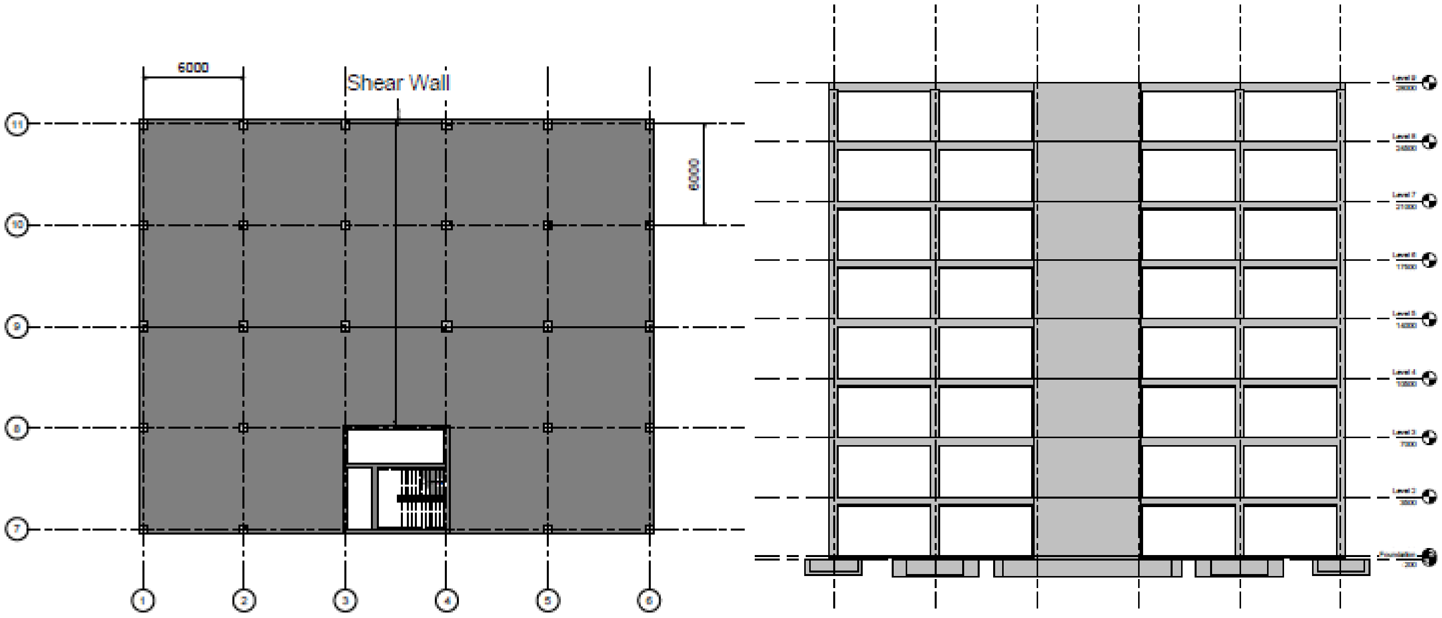


Figure 4.5: Concrete building plan and elevation views

4.2.2 Mass Timber Frame Building

Many different timber design systems currently exist, with more being developed as the demand for multi-storey timber buildings increases. Section 2.7 only made reference to a few well documented design systems. The system of choice depends on various factors such as; time of construction, cost of materials, architectural preferences, fire resistance, site location, and constructability. For this research a realistic timber building for South African conditions was envisaged. It takes into account the timber products that are currently manufactured in South Africa, as well as the skills and expertise of the carpenters/contractors.

The structural analysis and design of the building was performed by independent consulting engineering firm, A^2 Timber. It was decided to use European codes for the timber design instead of the South African design codes. This is largely ascribed to the structural engineer who performed the structural analysis and design being more familiar with Eurocode. SANS 10160 (which is compatible with the Eurocodes) was used for the loading code to ensure it remained consistent with the reinforced concrete frame design. Figure 4.6 is a 3D Revit model of the proposed mass timber structure.

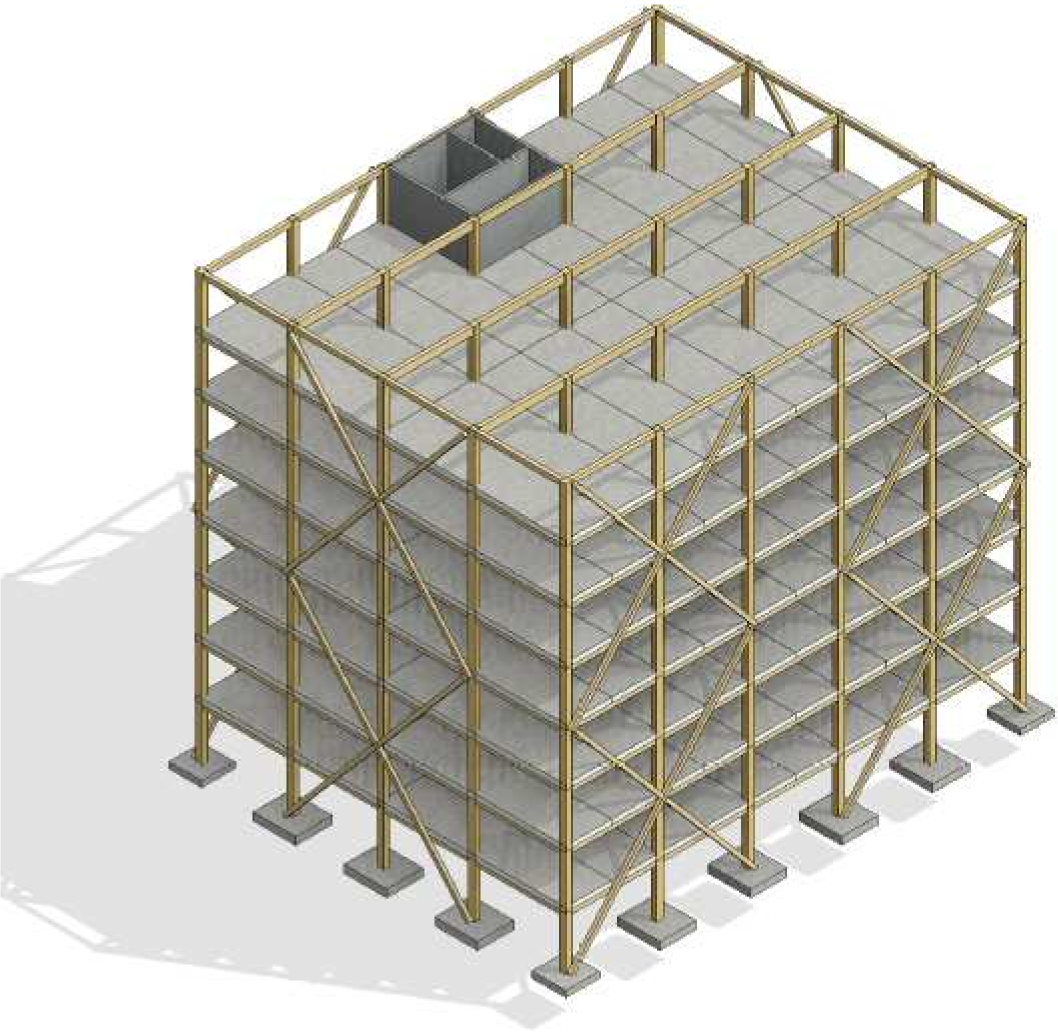


Figure 4.6: 3D Revit model of mass timber frame

A column-beam system with a CLT core and lateral glulam bracing is the system of choice for the timber building. One way spanning, 220 mm deep CLT floor panels span between large glulam beams as seen in Figure 4.7. Each 7 layer CLT floor panel (60-30-40-30-60) is 6 m long and 3 m wide, with a total estimated mass of 1.86 tons per panel. The CLT panels are simply supported between glulam beams (see Figure 4.7). A constructability review revealed that the CLT panels are too wide to fit into a standard 40ft shipping container which is approximately 12.03 m long, 2.35 m wide and 2.39 m high. This can be rectified by changing the CLT panels' widths to 2 m. Such a change will not impact the section capacity calculations or overall cost since the panels are one-way spanning.

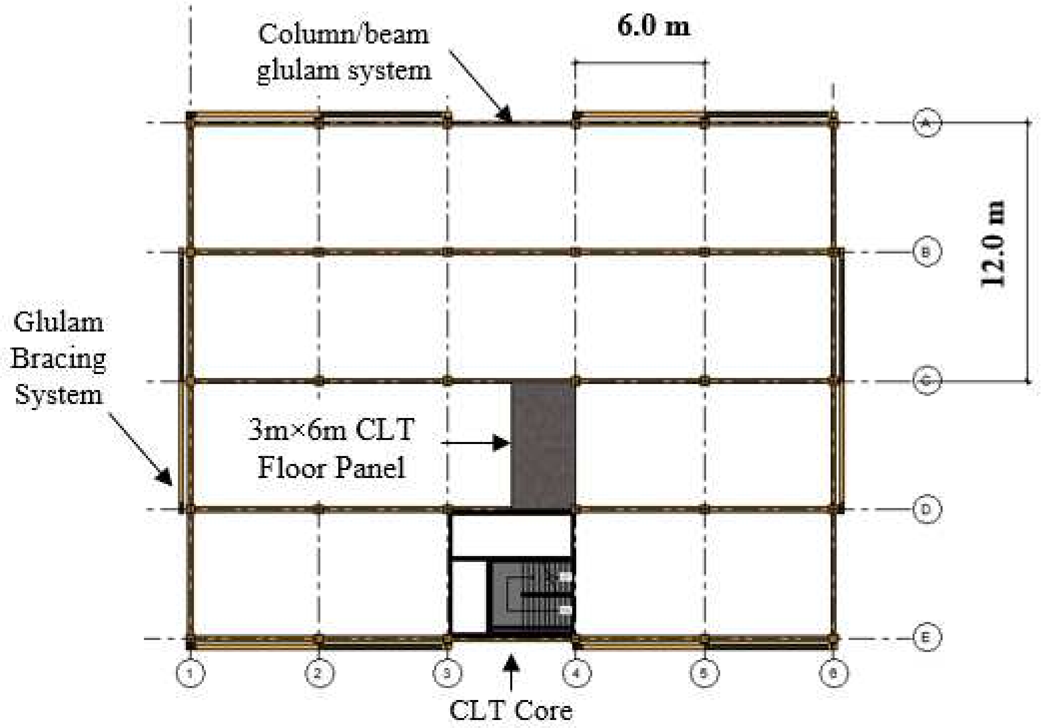


Figure 4.7: Plan view of the mass timber building

The structure of the proposed floor system is illustrated in Figure 4.8. A 50 mm screed layer protects the CLT from moisture damage and assists with vibration control. Additional sound insulation, separation membranes and sealing tapes are also recommended to ensure the floor system satisfies the necessary design requirements.

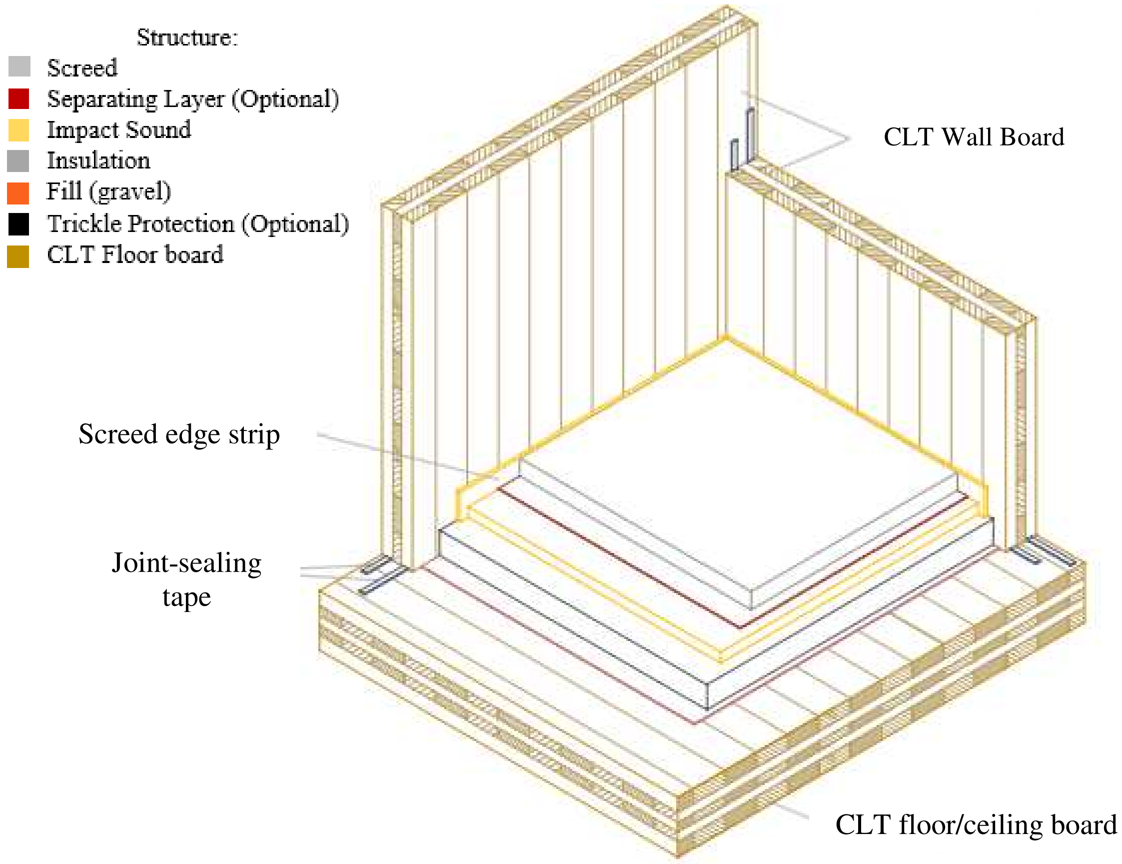


Figure 4.8: Proposed CLT floor system (Stora Enso, 2015)

Initially, all the glulam beams and columns were designed as GL24h timber (imported timber). However, in the subsequent chapters alternative South African timber species such as SA pine and Saligna (eucalyptus) are considered. Varying dimensions with different timber species were therefore scrutinised in an attempt to optimise the cost of the structure. These options are discussed further in Chapter 6. The design completed by A^2 Timber only considered the use of GL24h timber for the frame and C24 CLT for the core and floor. Potential alternative conceptual designs for South African timber species (S7 and S10 grade timber) was performed by the author through various calculations presented in Appendix E and Appendix H.

The design completed by A^2 Timber for GL24h timber is presented in Table 4.4. The internal beams are 520 mm deep and 240 mm wide, whereas the edge beams are 320 mm deep and 240 mm wide. The beams are supported on square 400 mm by 400 mm columns. 180 mm C24 CLT wall panels make up the core of the building and provide lateral stability. The lateral loads are also resisted by a glulam bracing system along the perimeter of the building as depicted in Figure 4.6. The dimensions of the glulam bracing beams are 260×240 mm. The elements satisfy the necessary ULS and SLS requirements (including vibrations).

Table 4.4: Summary of mass timber frame for GL24h

Element	Location	Depth (m)	Width (m)	Length (m)	Quantity (No)
Footings (30 MPa)	Inner	0.6	3.2	3.2	10
	Outer	0.5	2.4	2.8	10
	Corner	0.4	2.2	2.2	4
	Core	0.5	8	8	1
Columns (GL24h)	1-8	0.4	0.4	3.5	240
Internal Beams (GL24h)	1-8	0.52	0.24	6	120
Ring Beam (GL24h)	1-8	0.32	0.24	6	144
Bracing Beams (GL24h)	1-8	0.26	0.24	18.3	24
CLT Floors (220L75-2)	1-8	0.22	3	12	126
CLT Floors (220L75-2)	1-8	0.22	3	6	14
CLT core (180 C24)	1-8	28	0.18	32.1	1

4.2.2.1 Connection Design

The type of connections used to construct the timber frame is of high importance especially when considering fire resistance. Many different types of connections can be considered, but the cost varies significantly between different connection designs and manufacturers. Timber connection suppliers and designers were contacted to assist in the design of the connections. It was found that custom connections may be required to resist the high shear forces and bending moments experienced. An extensive analysis is required to finalise the connection design. A^2 Timber (European consulting engineer) assumed the beam-column and column-column connections to be fixed connections in the structural model as opposed to pinned connections. It is therefore vital that the connections behave as fixed connections. The main focus of the study is the cost of the connections, and not a detailed connection design. However, a connection design was attempted in Chapter 6 to obtain a rough estimate in cost.

The beam column connection experienced a maximum shear force of 136 kN and maximum bending moment of 150 kNm. Figure 4.9 shows a 3D render of a proposed connection to resist such forces. A steel plate and dowel system was recommended by the designers of A^2 Timber.

Leaving sections of the steel connection exposed presents a major risk from a fire point of view. The steel plate and dowel need to be covered by the timber elements as much as possible. Exposed sections require passive protection in the form of intumescent paint or cladding to prevent failure of the connection during fire.

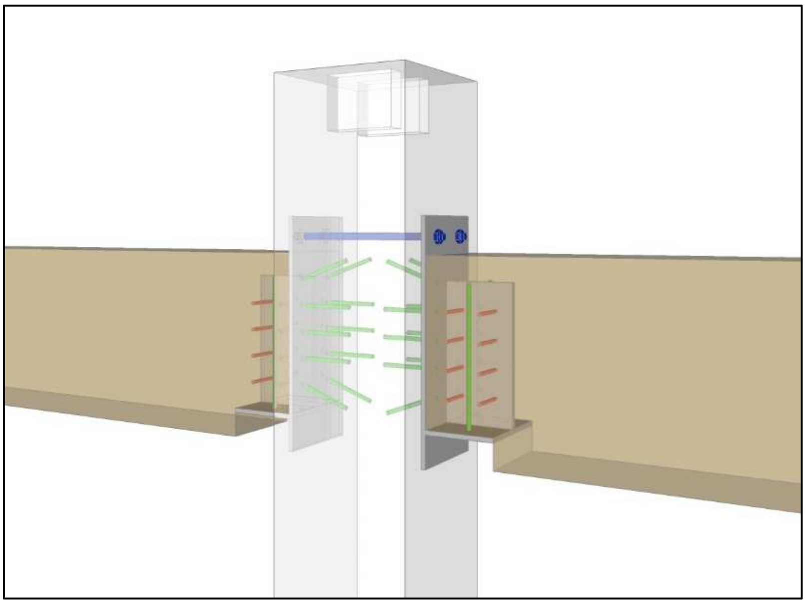


Figure 4.9: Potential Beam-Column connection used in timber frame

4.2.2.2 Treatment of Timber

An interview was conducted with the executive director of the South African Wood Preservatives Association (SAWPA) in order to clarify questions regarding the treatment of timber used in buildings in South Africa. The following section contains the 9 questions and answers from the interview:

1) In which building regulation does it specify that timber elements require treatment in buildings along the coast of South Africa? Please specify why this regulation exists.

   Response: "

   - Regulation A13(1)b specifies that "All timber used in the erection of a building shall be treated against termite and wood borer attack and fungal decay in accordance with the requirements of SANS 10005 and shall bear the certification mark of a body certified by the South African National Accreditation Systems."
   - In turn SANS 10005 in clause 12 qualifies where structural timber of the two main species used in permanent buildings shall be treated, e.g. all coniferous (softwood) species shall be treated in the coastal municipal areas and towns listed. The main reason for the introduction of these regulations since 1946 was to prevent and stop the spread of wood destroying insects i.e. *Hylotrupes bajulus* (European house borer/Italian beetle) *Cryptotermes brevis* (West Indian Dry-wood termites), and infestation and destruction of structural timbers by these insects."

2) What type of treatment is typically specified in order to satisfy this regulation? Please refer to the Hazard Classification where applicable.

Response:

"The treatment specified is dependent on the end-use and application of the timber in relation to the exposure class. For example:

- timber used in above ground dry interior applications (typically roof trusses and timber frame walls) are treated to H2 and LOSP or waterborne preservatives as listed in SANS 10005 are suitable
- timber used in above ground but exposed conditions (typically cladding, decking, exposed beams etc) are treated to H3 and in this case only copper based waterborne preservatives listed in SANS 10005 are suitable
- timber used in and below ground contact are treated to typically H4 but if used in heavy wet soils or fresh water then H5 is suitable. It must be noted that in the case of a permanent structure in which people live or gather all poles/posts used as foundation posts shall be treated to H5."

3) What would this treatment typically cost per square metre or cubic metre of timber element? If unable to give a reasonably accurate answer, please provide the name of an institution/organisation that could possibly be contacted.

Response:

"As an industry association we do not get involved in any pricing and costs of treated timber. It must also be noted that the cost of treatment will differ from processing plant to processing plant as it's not just the type and amount of chemical retention that determines the final price, but also cost of timber raw material, labour, time, transport, processing and operation costs, etc. We recommend that you contact processing plants to gather information on the typical costs per cubic metre."

4) Would this treatment yield successful results in the case of untreated spruce? If not, please specify in layman's terms as to why the treatment would be unsuccessful.

Response:

"No. Preservative treatment by pressure impregnation cannot be applied successfully to spruce. Spruce is prone to pit aspiration when seasoned below fibre saturation point (typically below 25-30% moisture). Pit aspiration renders the species impermeable, even in the normally treatable sapwood. Since most structural sawn or engineered spruce timber is seasoned to around 8-12%, the timber will be untreatable."

5) What other treatment in the case of untreated spruce yields more successful results?

Response:

"To provide for some means of protection against wood borer attack only (not fungal decay) in the proclaimed municipal coastal areas, the SANS 1288 standard provides for the treatment of spruce to H2 only (dry interior above ground) using light organic solvent type preservatives applied by double vacuum process in an autoclave. The standard specifically gives minimum process parameters with respect to time and vacuum limits during the process stages. It must however be noted that this process will not ensure the usual full sapwood penetration nor required retention for H2, but still only an envelope treatment, with perhaps a slightly deeper surface penetration because of the use of solvent based preservatives by double vacuum pressure to basically point of refusal. The use of an industrial application process is also to ensure all surfaces are covered during the application process."

6) What would this treatment typically cost per square metre or cubic metre? If unable to give a reasonably accurate answer, please provide the name of an institution/organisation that could possibly be contacted.
   Response:
   "See response to question 3, however the chemical cost should for all practical reasons be limited due to low retention and penetration achieved when applying the process to spruce"

7) What are the challenges regarding this treatment, especially in the case of large mass timber elements such as CLT that have been imported?
   Response:
   "The size of pressure vessels are limited to cater mostly for loose units of timber loaded onto bogeys in packs, and due to the size of CLT wall and floor panels the treatment will most likely not be doable after manufacture of the CLT panels."

8) If this challenge cannot be overcome, what other treatment is available which will still satisfy the necessary building regulations?
   Response:
   "There are presently no preservative treatment apart from the industrial impregnation processes specified in SANS 10005 that will be able to satisfy the building regulations and guarantee protection. In the case of spruce (due to it being impermeable), the application of suitable preservatives by hand by means of brush on or spray application is a possible alternative to the use of the double vacuum process however, should such a process be considered for case by case approval by the local authorities, strict adherence to at least the following minimum requirements must be ensured.
   - Ensure that all surfaces are coated – supervision
   - Must be applied before the spruce CLT panel and/or glulam beams are installed
   - That the exterior of the building (facade) shall consist of a system that ensure a closed and protected barrier environment that prevents direct exposure of the wood surfaces to moisture and possible insect infestation.

   It must be noted that the above is purely a way of finding a possible solution to give some form of protection to spruce against insect attack, but is in no way a definite guarantee to ensure long term prevention or protection especially due to the unknown factor of possible human error during application. Also see response to questions 5 and 9."

9) What do you believe must be done in order to overcome the issue regarding the treatment of large spruce elements such as CLT and BSH (glulam)? Should current regulations be reviewed, or should European suppliers treat the spruce within Europe beforehand?

   Response: "The preservative treatment of all the loose units prior to manufacture of CLT panels will be the best and most suitable means of ensuring proper preservative treatment. The CLT should however preferably be produced using permeable pine instead of spruce. Pine is permeable and will be able to take all the approved preservatives (solvent based or waterborne) to the required penetration and retention of the specified H class. Reviewing the regulations will not change the habits of *Hylotrupes bajulus* or *Cryptotermes brevis* from attacking and infesting softwood timber species."

4.3 Fire Design

The fire design of a building can be achieved through a rational design procedure or a prescriptive design procedure (Buchanan and Abu, 2016). The prescriptive design procedure is the more common of the two, due to the difficulty associated with a rational design procedure. The disadvantage of a prescriptive design is that it may be over-conservative and result in unnecessarily high costs. Traditionally, a rational design procedure is recommended to lower the overall cost of the building. Bearing this in mind, a rational design procedure was followed for the mass timber frame building, whereas a prescriptive procedure was followed for the reinforced concrete frame alternative. It is important to note that the rational fire design of the GL24h frame/C24 floor & core building was performed by A^2 Timber. The calculation procedure presented within this section is for the design verification by the author of South African timber species, namely S7 SA pine timber.

4.3.1 SANS 10400 Fire Rating Requirement

SANS 10400–T recommends a fire resistance rating of 60 minutes for 3 to 10 storey commercial buildings (SANS, 2011b). The concrete and timber elements specified in the building thus require a fire resistance rating of at least 60 minutes to satisfy SANS regulations. This is less than the 120 minute fire rating required for 3 to 10 storey residential buildings (SANS, 2011b).

4.3.2 Concrete Fire Design

Concrete is known to have excellent fire resistance resulting from its low thermal conductivity and non-combustible nature. Concrete structures seldom fail catastrophically and are often repaired after fires (Buchanan and Abu, 2016). It therefore remains one of the superior materials to use from a fire design perspective. Eurocode prescribes a minimum cover of 25 mm for concrete elements that fall within exposure class XC1. This can be specified in the concrete design and does not have an impact on cost of construction.

4.3.3 Timber Rational Fire Design

This section discusses the calculation procedure for the rational design of the timber beams and columns. It was assumed that glulam elements were made of S7 timber. This is different to the initial design by A^2 Timber, where the timber was initially assumed to be GL24h. As such, different cross-sectional dimensions are required as to those presented in Section 4.2.2. Eurocode 5 was used throughout the entire design procedure. Chapter 3 of the design manual titled *Design of Timber Structures* written by Crocetti and Martensson (2016), was used to assist with the ultimate limit state (ULS) and fire limit state (FLS) design process. Appendix E contains the detailed calculations by the author for the design of both the glulam beams and columns for ULS and FLS. The reduced cross section method was applied for both the glulam beams and columns. The nominal charring rate was assumed to be 0.7 mm/min for glulam beams and columns as per Eurocode 5. This equates to a reduction of 42 mm per exposed side for a 60 minute fire. A zero-thickness layer of 7 mm was also assumed as per Eurocode 5. The partial coefficients and combination factors were set to 1.0 for fire limit state in accordance with Eurocode 1. A simple Prokon frame analysis (Appendix E) was performed to determine design moments and shear forces in order to verify various hand calculations.

4.3.3.1 Glulam Beams at ULS

The line load acting on the beam (including the self-weight of the beam) at ULS was 44 kN/m. It was assumed that the 6 m glulam beam was fully fixed between columns resulting in a total ULS sagging and hogging moment of 150 kNm. The beam was initially sized by satisfying SLS deflection requirements. As such, the beam used for the design was 240 mm wide by 630 mm deep S7 beam (as opposed to the 540 mm by 240 mm deep GL24h beam). A partial material coefficient of 1.25 was applied for the use of glued-laminated timber, while a modification factor of 0.8 was applied for the load duration. A medium-term load duration was assumed which is typical for imposed floor loads. The 15.8 MPa characteristic bending strength of the S7 SA pine is effectively reduced by a factor of 0.64 (0.8/1.25). A design bending strength of 10.1 MPa was therefore used in resistance calculations. Given this information, a bending resistance of 161 kNm was calculated for the section which is greater than the design ULS sagging and hogging moments.

A design shear force of 136 kN was calculated, which was 7 kN greater than the 129 kN shear capacity of the S7 beam. The initial dimensions of 630×240 mm^2 were nevertheless accepted for the purpose of this investigation given the small difference between the shear capacity and design shear, as well as certain design assumptions which were made. For instance, assumptions regarding the timber density influence the floor load, which influences the design shear force. Furthermore, the type of connection used may significantly influence the location of shear failure. Shear failure can be prevented by moving the failure plane 315 mm away from the column centreline as shown in the connection used in Section 4.2.2.1. In such a case, designers may suggest physical testing to optimise the connection used.

4.3.3.2 Glulam Beams at FLS

The line load acting on the beam (including the self-weight of the beam) at FLS was 24.2 kN/m. This is a reduction in loading of approximately 45% when compared to ULS design. It shows the significant influence that the difference in partial coefficients and combination factors have between ULS design and FLS design. The maximum sagging and hogging design moments for the beam at FLS was calculated as 73 kNm. The adjusted dimensions for the beam from the 60 minute fire was 142 mm by 581 mm. The modification factors (glulam partial coefficient factor and load duration factor) are set to 1.0 during FLS design in accordance to Eurocode 1. This is a major contrast to the 0.64 material strength reduction factor during ULS. A FLS moment resistance of 126 kNm was calculated for the S7 beam which is greater than the calculated design moments. By following a similar methodology, a FLS design shear force of 68 kN was calculated while the shear resistance was 70 kN. The beam design therefore satisfies the necessary FLS requirements.

4.3.3.3 Glulam Columns at ULS

The ULS compression force in the ground floor columns was 2138 kN for a loading case where the floor load was the leading imposed load. An initial glulam column size of 400 mm by 400 mm was checked. The ULS compressive resistance of the column was calculated to be 2228 kN. The column therefore satisfied ULS requirements for both scenarios.

4.3.3.4 Glulam Columns at FLS

The cross section of the column was reduced by 49 mm on each side for a 60 minute fire. As such, the new FLS dimensions for the column was 302 mm by 302 mm. The FLS compression force in the ground floor columns was 1181 kN for a loading case where the floor load was the leading imposed load. The FLS compressive and bending moment resistance of the column was 1854 kN. The design therefore satisfied the necessary criteria for FLS.

4.3.3.5 CLT Floor and Core

Both the CLT floor system and CLT core were designed by A^2 Timber for a 60 minute fire using Stora Enso's Calculatis design software. Additional passive protection was specified for the interior and exterior of the core in order to achieve the required 120 minute fire rating in accordance with the 2021 International Building Code (Breneman, Timmers and Richardson, 2019).

4.3.4 Fire Protection Measures

The same active protection measures are specified for both the timber frame and concrete frame buildings. Section 2.6 makes reference to passive protection measures within a timber building to ensure that the minimum fire resistance ratings are achieved. Examples of passive protection materials include boards, sprays and intumescent coatings. Type X gypsum plasterboard is typically used to protect timber elements. Timber elements achieve a 60 minute fire rating by specifying 25 mm of Type X gypsum plasterboard. However, this is the prescriptive design approach, with no consideration of FLS. The S7 beams and columns of the timber frame building do not require passive protection according to the rational design performed in Section 4.3.3. However, structural fire engineers would recommend placing passive protection over the steel connections as connection performance within fires is still a topic of ongoing research. The timber has great aesthetic value when exposed and is often a desired finish by many architects. The 2021 International Building Code (IBC) will require for all mass timber in Type IV-A buildings to be completely covered by non-combustible protection (Breneman, Timmers and Richardson, 2019). The occupants of the building will therefore be oblivious to the material used for the structural frame. Similarly, the majority of Type IV-B buildings will also require non-combustible protection with only a limited number of exposed mass timber elements. However, allowance has been made for mass timber to be left exposed for Type IV-C buildings, which is positive from an architectural perspective. The mass timber building in this study has been designed as a Type IV-C building in order to take advantage of the aesthetic value of mass timber

4.4 Foundation Size Comparison

The total mass of each structural frame has a direct influence on foundation sizes. Table 4.5 contains a summary of the mass of each structural alternative. An average density of 2500 kg/m^3 of reinforced concrete was used for the concrete frame. Alternatively, an average density of 420 kg/m^3 and 470 kg/m^3 was used for the GL24h timber products and CLT respectively.

Table 4.5: Mass comparison excluding footings

Element	Timber (kg)	Concrete (kg)	Difference (kg)	Reduction %
Columns	48 584	389 375	340 791	88
Beams	87 440	306 000	218 560	71
Floors	1 261 700	3 985 200	2 723 501	68
Core	74 617	591 500	516 883	87
Shear Wall/ Bracing Elements	82 500	11 573	70 927	86
Connections*	11 000	-	-	-
Total	1 494 914	5 354 575	3 859 661	72
*Connection mass was initially estimated by the structural engineer				

The use of a mass timber as opposed to conventional reinforced concrete for the structural frame resulted in a 72% reduction in mass from the concrete frame for this particular comparison. In other words, the concrete frame building is approximately 3.6 times heavier than the mass timber frame option. The reduction in mass of the building frame resulted in significantly smaller foundation footings for the timber frame building. The total volume of reinforced concrete required for the mass timber frame building's foundations was approximately 135 m^3. This is significantly less than the 427 m^3 of reinforced concrete required for the footings of the reinforced concrete frame building. The use of mass timber as opposed to conventional reinforced concrete for the structural frame resulted in a 68% reduction in foundation size from the concrete building for this particular comparison.

4.5 Chapter 4 Conclusion

The chapter discussed and presented the designs for the multi-storey mass timber and reinforced concrete frame building which was designed by independent consulting engineering firms. Following this, a rational fire design was performed for the mass timber frame building through a simple Prokon frame analysis and various hand calculations. Finally, the chapter concluded with a comparison of the total mass of each structural frame and the respective foundation sizes of each building. The comparison showed that the concrete frame building is approximately 3.6 times heavier than the mass timber frame option. In the subsequent chapters the construction schedule for each building is presented followed by a development cost comparison and sensitivity analysis.

Chapter 5

5 Construction Schedule

A focus group workshop with industry professionals was conducted to determine the construction schedule of both the multi-storey mass timber and reinforced concrete frame buildings. Chapter 5 presents and discusses these construction schedules, and further highlights various assumptions that were made throughout the workshop. The industry professionals in the focus group mentioned a number of limitations/concerns which exist within the multi-storey timber building industry. The chapter thus concludes by discussing these limitations and concerns.

5.1 Focus Group Participants

A total of 5 industry professionals participated in the focus group workshop. Each professional currently practices in a different area of expertise and made valuable contributions throughout the workshop process. Table 5.1 provides information regarding the profession, qualification, experience and company name for each participant.

Table 5.1: Focus group participants

Profession	Qualification	Experience	Company	Position
Project Manager	BEng (Civil)	38 years	Capital Expenditure Projects (Pty) Ltd	Managing Director
Project Manager	BSc (Building Management)	30 years	Mitchell Du Plessis Projects (Pty) Ltd	Managing Director
Contractor	BSc (Building)	21 years	Isipani Construction (Pty) Ltd	Contracts Director
Carpenter Glulam Manufacturer	Master Degree in Carpentry	23 years	Holzbau Carpentry Hess CC	Owner
Carpenter CLT Manufacturer	Bachelor of Architecture Studies (B.A.S)	12 years	XLAM South Africa (Pty) Ltd	Director

Each focus group participant was provided with the 3D conceptual models of the buildings as well as additional information regarding multi-storey mass timber construction a week before the workshop commenced. The participants were required to complete individual construction schedules for both the timber and concrete frame building. On the day of the workshop a number of assumptions which may have been unclear were firstly discussed and clarified. Following this, the construction schedule and Gantt charts of each participant was presented and discussed. Finally, the participants of the workshop collectively developed a construction schedule for each of the two construction alternatives.

5.1.1 General Assumptions

Various assumptions were made for and during the interview. The general assumptions were as follows:

- The building is located in the Sandton CBD and is a wall-to-wall development. The full building footprint occupies the site.
- Part of the sidewalk and a number of parking bays will be taken over for construction purposes. Additional wayleaves may also be required for temporary storage of equipment and material. These additional costs apply for both building alternatives.
- A single fixed crane will be required for both the concrete and timber building. The crane will be fully occupied for both buildings. A fixed crane is preferred to a mobile crane in an attempt to minimise costs.
- The construction schedule for both buildings incorporates finishes. The finishes can be divided into the following 4 categories: first fixed services (above the ceiling); internal drywall partitions; ceilings; and final services. The finishes may differ for each alternative, but this is discussed within each section.
- A 5 day work week, from Monday to Friday, was applied.

5.1.2 Reinforced Concrete Frame Assumptions

The specific assumptions for the reinforced concrete frame building were as follows:

- Concrete for the slabs and beams is to be pumped, whereas the verticals (columns, shear walls and core) will be cast with buckets.
- A power float finish will be applied to the reinforced concrete slab.

5.1.3 Mass Timber Frame Assumptions

The specific assumptions for the timber frame build were as follows:

- A deliver and build construction technique will be applied. As such, excessive amounts of timber elements are not stored on-site. The timber elements are cut and shaped off-site.
- It is assumed that the industry is an established multi-storey timber building industry. Artisans are thus familiar with the construction technique and manufacturers are capable of supplying material regularly and on-time. The design and approval stages within the project will differ and are discussed in Section 5.5.
- It is assumed that the construction schedule remains unaffected whether the timber components are imported or locally manufactured. This is again discussed in later sections.
- Internal finishes are all installed on-site, despite the fact that services can be pre-installed in the factory for CLT elements. This is further discussed and analysed in Chapter 7.

5.2 Reinforced Concrete Frame Schedule

A detailed construction schedule is presented in Appendix F for both buildings. The following two sections highlight the main stages of construction for each building alternative. It was assumed that construction starts on the 6th of January 2020. Figure 5.1 and Figure 5.2 show timelines of the main tasks scheduled for construction of the concrete and timber structures, respectively. A total of 31 days is allocated to construct the reinforced concrete bases, stub columns and surface bed. Once the ground level is reached, a 15 day per floor turnaround time is deemed realistic. Three floors will be back propped at a time to allow for the concrete to reach sufficient strength. This means that internal finishes are held back for three floors down before access is allowed. Additionally, a total of 20 days per floor is allocated for fit-out (installation of internal finishes). As such, fit-out for the ground floor only starts once the 3rd floor slab achieves its required strength (15 working days). Fit-out of the 5th floor thus starts once the final floor (floor 8) is poured. The ring beam for the roof requires 15 days to reach its required strength. Hence, concrete work is finished on the 25st of September 2020, while internal finishes for all floors are completed on the 20th of October 2020 – approximately 4 weeks later. Overall, the total time required to finish the building frame and internal finishes is 207 working days (42 weeks or 10 months).

5.3 Mass Timber Frame Schedule

The time to construct the foundations and building substructure was assumed to be the same for both buildings as seen in Figures 5.1 and 5.2. The mass timber frame is constructed significantly faster than the reinforced concrete frame. A 5 day per floor turnaround time is deemed realistic for the timber building as opposed to the 15 days allocated for concrete. This is in line with the turnaround times calculated for the two case studies presented in Section 2.7. The Mjostarnet had an average turnaround time of 4.8 days per floor, while the Brock Commons building was constructed at a rate of 2.5 days per floor (Pilon *et al.*, 2016b; Abrahamsen, 2018). A total of 40 working days is required to construct the entire timber frame. A 20 day fit-out time per floor is also allocated for the mass timber building. The focus group saw this as a conservative estimate as CLT panels allow for the installation of services off-site. This could reduce the fit-out time significantly. The fit-out time includes:

- build-up of flooring system
- installation of MEP services
- internal drywall partitions
- installation of gypsum dropped ceiling and insulation
- painting and fire proofing

It was assumed that multiple floors can be fit-out simultaneously by different fit-out teams. In other words, start of fit-out of floor two is independent of fit-out of floor one. Analysis of the Gantt chart for the mass timber frame structure showed that at least 4 fit-out teams are required to avoid delays when working with a 20 day fit-out time per floor. Analysis showed that a 15 day fit-out time per floor require 3 teams, while a 10 day fit-out time per floor only requires 2 teams. This is discussed in Chapter 7.

The entire timber structure, including internal finishes, is constructed in 104 working days (approximately 21 weeks or 5 months). This is 5 months earlier than the reinforced concrete frame and translates in to 50% reduction in construction schedule. The focus group noted that the true benefit of mass timber construction comes from early access for follow-on trades (fit-out). This is highlighted in Figures 5.1 and 5.2, where a total fit-out time of 136 days are required for the reinforced concrete frame building, whereas only 55 days are required for the mass timber frame building.

5.4 Lead-in Time

Research has shown that the lead-in times for flat slab concrete structures to be approximately 4 weeks (The Concrete Centre, 2006). This is due to the fact that the primary materials required for the construction of reinforced concrete structures are readily available. The contractor should have sufficient time to gather the necessary materials to commence work on the foundation and substructure if construction is planned to start a month after the purchasing of the land. As such, no delays can be expected due to the required 4 week lead-in time. Construction of the foundations and substructure starts on the 6th of January 2020 and ends on the 5th of March 2020. This gives the contractor a further 2 months before construction starts on the main structural frame. The contractor therefore has a 2 to 3 month lead-in time for mass timber products to be manufactured and delivered. The focus group estimated that a realistic lead-in time of 2 months is required for both the reinforced concrete and mass timber frame buildings. No additional delays are therefore expected as a result of the assumed 2 month lead-in time.

The possibility of a longer lead-in time for the mass timber frame building was discussed during the focus group workshop. Some professionals argued that a much longer lead-in time of 3 to 5 months could be expected for the mass timber frame building. This is due to the fact that a very detailed design process is required with very low tolerances on the manufactured elements. The recommended lead-in time for steel structures in South Africa is approximately 6 weeks, 2 weeks more than the flat slab concrete structures (Drennan, 2017). This validates the possibility of a potentially longer lead-in time for the mass timber frame building. Given this information, different scenarios need to be investigated for the lead-in time of the mass timber frame building. As such, the effect of incorporating delays into the mass timber frame construction schedule is investigated in Chapter 7. It should also be noted that the 3 to 5 month lead-in time may also be reduced if Building Information Modelling (BIM) is adopted by all major stakeholders throughout the project delivery process.

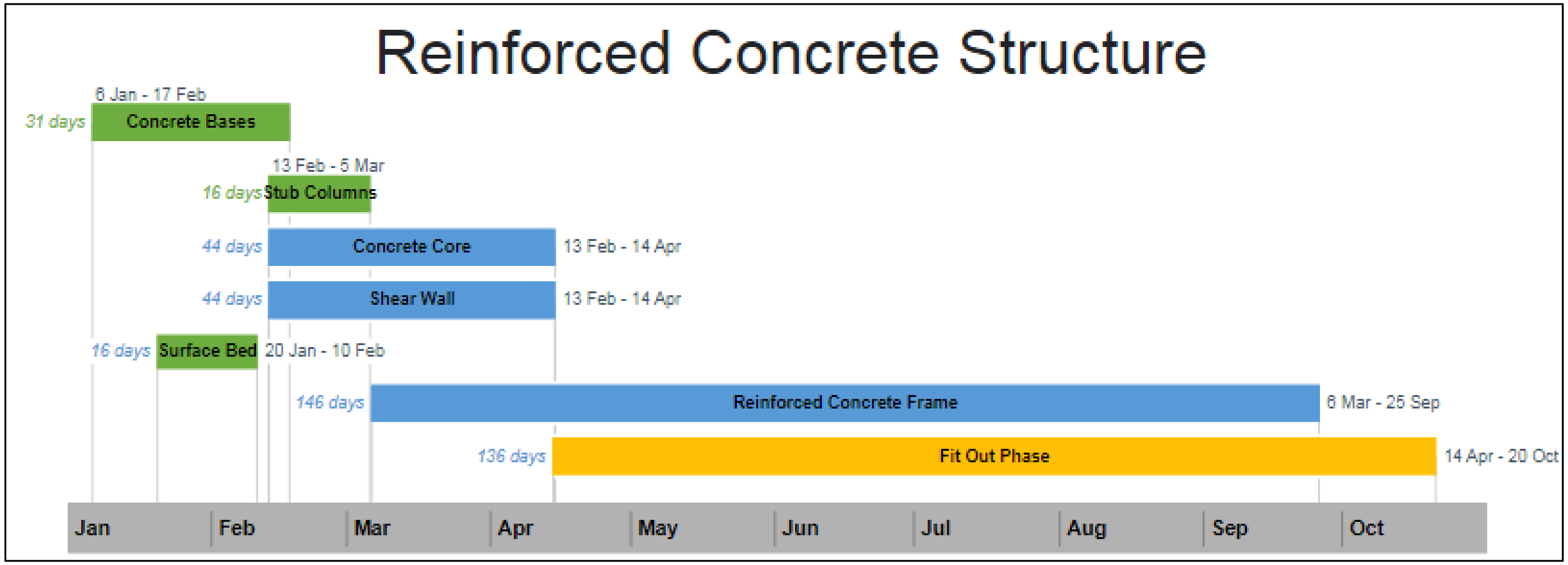


Figure 5.1: Timeline of concrete structure

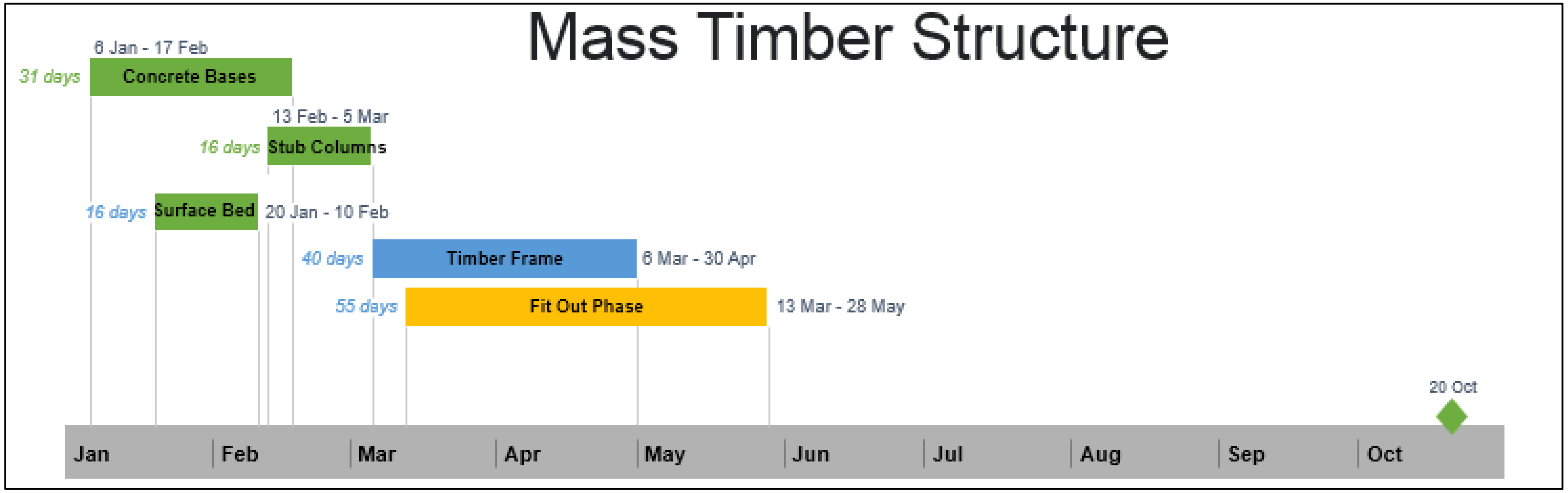


Figure 5.2: Timeline of mass timber structure

5.5 Current Limitations

The industry professionals in the focus group mentioned a number of limitations/concerns ranging from design codes and building regulations to manufacturing processes and on-site labour. The following section highlights a number of these limitations and concerns.

5.5.1 South African Design Codes

The South African timber design codes, specifically SANS 10163, does not provide the necessary guidelines required for the design of cross laminated timber structures and are thus in need of review. . Furthermore, the mechanical properties of various composites such as cross laminated timber (CLT), laminated veneer lumber (LVL), parallel strand lumber (PSL), and glued-laminated timber (glulam) need to be determined for different classes of South African timber to assist future designers of mass timber structures.

5.5.2 Importing Timber

Importing timber could have a major effect on the construction schedule. Clearing the products through the ports remains a challenge which directly increases the risk of the project. Furthermore, the cost of the imported timber products is heavily dependent on the exchange rate. As such, Chapters 6 and 7 investigate the effect that importing timber may have on the overall construction cost.

5.5.3 Building Regulations

South African building regulations require that timber buildings within specified coastal zones be treated. This treatment is to prevent damage from borers and other insect as discussed in Section 4.2.2.2. Most imported timber is untreated, which presents a challenge if the mass timber building is located within the coastal zone. Furthermore, the treatment commonly applied to SA pine is not successful for spruce. This was a concern for the professionals in the focus group. This concern led to an interview being conducted with the executive director of SAWPA as described in Section 4.2.2.2. The main finding of the interview was the suggestion that imported CLT (and other mass timber products) should be produced using permeable species such as pine instead of spruce. Otherwise all the loose units (timber planks) will have to undergo preservative treatment prior to manufacture of CLT panels.

5.5.4 Manufacturing Processes

Popular South African timber species do not achieve the same mechanical performance as popular European species. An example of this is a comparison between SA pine and European spruce. According to SANS 10163-1, S5 SA pine has a mean and 5th percentile E-modulus of 7800 MPa and 4630 MPa, respectively (see Table 5.2). C24 European spruce has a much greater mean and 5th percentile E-modulus of 11 000 MPa and 7400 MPa, respectively. The design implication of this is that higher strength structural timber (S7, S10) is required in South Africa, which is not readily available, or the S5 members need to be enlarged to impractical dimensions. It was noted that hybrid timber laminates can be manufactured for the beams and columns to account for the lack of S7 and S10 timber. An example hereof is placing S7/S10 in high stress areas of the cross section and S5 in the lower stress areas of the beams. The superior structural performance and larger cross-sectional dimensions that can be manufactured from European timber are two of the main reasons why designers would choose to import timber, as opposed to supporting South African suppliers/manufacturers. Table 5.2 summarises the main mechanical properties of S5, S7, S10 and C24 timber. In Chapter 6 different options are investigated for the procurement of timber elements. This investigation considered the required cross-sectional dimension for each timber grade and calculated a cost per running metre of beam/columns. Through this, the most cost-effective solution was determined.

Table 5.2: Mechanical properties comparison (SANS, 2012; Crocetti and Martensson, 2016)

Description	S5 (MPa)	S7 (MPa)	S10 (MPa)	C24 (MPa)
Mean E modulus	7800	9 600	12 000	11 000
5th Percentile E modulus	4630	5 700	7 120	7 400
Bending Strength	11.5	15.8	23.3	24
Compression Strength (parallel to grain)	18	22.8	26.2	21
Shear Parallel to Grain	1.6	2.0	2.9	4.0

5.5.5 Reduction of On-site Labour

A suggested team of approximately 6 skilled carpenters and 2 to 3 unskilled assistants would be required to place and fix the main timber members. This is a significant decrease in on-site labour as opposed to reinforced concrete construction. This may be concerning from a National Development Plan (NDP) point of view, which promotes increasing on-site labour for employment creation. However, although on-site unskilled labour decreases, a significant increase in labour can be expected off-site. This includes, but is not limited to, the plantations, sawmills and manufacturing plants. In other words, mass timber construction would result in a migration of unskilled on-site labour to skilled off-site labour. This topic requires further research to quantify the effect on off-site and on-site labour migration.

5.6 Chapter 5 Conclusion

The aim of Chapter 5 was to determine accurate construction schedules for both the mass timber and reinforced concrete frame buildings. A focus group comprising of experienced industry professionals was assembled to ensure that the construction schedules are realistic for South Africa. The focus group workshop identified that the construction of the reinforced concrete frame building and mass timber frame building will take 42 weeks and 21 weeks, respectively. Chapter 6 investigates the effect of the 5 month reduction in construction schedule on the overall profitability of the mass timber frame building.

Chapter 6

6 Development Cost

Chapter 6 presents a comparative study of the construction costs for the two buildings. The three main cost components of the total construction cost are initially presented and discussed. A percentage of the total construction cost is allocated towards preliminary and general (P&G) costs. Notably, the differences in construction schedule between the two buildings has a significant effect on the P&G costs. As such, a method has been devised to quantify this effect and is explored in Section 6.1.5. Following this, an attempt was made in determining the total capital investment required for each project. This is required in order to consider major potential savings in the form of an earlier return on investment and reduced interest expense. These savings are as a result of the 5 month reduction in construction schedule identified in Chapter 5. The expected cash outflow for each construction project is presented in Section 6.4. The chapter concludes by calculating an internal rate of return for each development and commenting on the financial viability of the projects.

Various stakeholders assisted in the costing of the two buildings. Two professional quantity surveyors were involved throughout the costing process. Various manufacturers were contacted to assist in the costing of the mass timber frame building due to a lack of established multi-storey mass timber projects in South Africa. These manufacturers included CLT manufacturers, glulam manufacturers, steel connection suppliers, custom steel part manufacturers, and international suppliers.

6.1 Total Construction Cost

The total construction cost has been divided into three cost components namely; foundation and substructure cost, structural frame cost, and non-structural costs. Appendix G contains the complete Bill of Quantities for each building. Costs presented within tables are to the nearest rand whereas the final costs that are reported on have been rounded up to the nearest thousand.

6.1.1 Foundation and Substructure Cost

The relative size of the foundation footings for the two buildings differed as a result of the significant difference in mass of each structure. The mass timber frame building was approximately 3.6 times lighter than the reinforced concrete frame building as discussed in Section 4.4. This translated into a saving of R 1 070 000 (68%) in the foundation and substructure cost as seen in Table 6.1.

Table 6.1: Substructure and foundation cost comparison

Cost Item	Concrete Frame (R)	Timber Frame (R)	% Saving
Substructure Excavation	207 844	68 139	67%
Foundations	1 370 172	440 574	68%
Total	1 578 016	508 714	68%

6.1.2 Structural Frame Cost

The structural frame cost accounts for the largest difference in cost between the two building alternatives. The following section describes the different options for a number of the cost items. In some cases an analysis was required to determine the most cost-effective solution. Timber industry professionals from Universal Plywoods (Pty) Ltd, XLAM South Africa (Pty) Ltd, Holzbau Carpentry Hess CC, and Rothoblaas South Africa (Pty) Ltd provided valuable input throughout the structural frame cost analysis.

6.1.2.1 Procurement of Timber

Different options were investigated for the procurement of mass timber elements as shown in Table 6.2 and Table 6.3. The first three columns with timber alternatives consider manufacturing the glulam elements locally using different timber species and grades. The final column presents the estimated cost of importing the timber elements from Europe, which is dependent on the rand-euro exchange rate. The dimensions of the timber elements vary according to the grade and species of timber specified in the design. Appendix H presents the calculations which were performed to determine equivalent cross-sectional dimensions based on similar bending resistances (approximately 161 kNm) for the different grades and species. In terms of bending resistance, a 240 mm by 630 mm S7 glulam beam is approximately equivalent to a 240 mm by 520 mm S10 and GL24h glulam beam. An aspect which demands consideration is the availability of a specific timber grade for a given timber species. S5 and S7 SA pine is generally available from South African sawmills, whereas S10 SA pine is difficult to obtain. Manufacturers therefore resort to using Saligna (eucalyptus) – a more expensive hardwood species – to manufacture S10 glulam beams. Table 6.2 presents the cost per running metre of beam for the different options. Discussion with manufacturers indicated that it costs approximately R 12 000/m^3 of S7 SA pine to manufacture glulam or CLT (Holzbau Carpentry Hess, 2020; XLAM South Africa 2020). The lack of S10 SA pine availability presents a challenge in determining a realistic cost per metre cube of glulam manufactured. A 20% premium has been added to the S7 price for comparison purposes based on discussions with Holzbau Carpentry Hess. S10 SA pine is however not considered in the final Bill of Quantities due to a lack of availability and uncertainty surrounding the cost per cubic metre.

Table 6.2: Cost per metre comparison for beams

Description	S7 SA Pine	S10 SA Pine	S10 Saligna	GL24h Spruce
Dimension (mm)	630×240	520×240	520×240	520×240
Cost/m^3	R 12 000	R 14 400[a]	R17 000	R 15 863[b]
Cost per m	R 1 815	R 1 797	R 2 122	R 1980 excl. treatment
Transportation cost of beams included in price estimate.				
[a] Assumed a 20% premium on the cost of S7 SA pine.				
[b] R17: €1 Euro exchange rate. Includes customs and import taxes, transportation and commission.				

Given the above information and the assumptions that were made, S7 SA pine and S10 SA pine are the two most cost-effective solutions for the glulam beams in the mass timber frame building. S10 SA pine beams could potentially work out to be the most cost-effective solution given the R14 400 per cubic metre assumption. Saligna beams remain one of the most expensive options with a 17% increase in cost per running metre when compared to S7 SA pine.

The cost per cubic metre of glulam imported from Europe (also known as BSH) was approximately €630 for untreated spruce. Timber import industry professionals from Universal Plywoods (Pty) Ltd indicated that transportation of the timber from Europe works out at roughly R 38 000 per 40ft container. It was further estimated that a total of 48 m^3 of spruce can be loaded into a 40ft shipping container. As such, the total transportation cost excluding customs and import tax amounts to R 785 per cubic metre of GL24h spruce. General rule of thumb indicates an additional 15% increase in cost for import tax and customs. A further 20% was added for commission of the sale of the timber. At an exchange rate of R17:€1, the total price per cubic metre of the untreated spruce equated to R 15 863. Analysis of the rand-euro exchange rate showed that any rate below R12.6: €1 could make importation of untreated spruce the most cost-effective solution. Timber elements within buildings found in coastal zones require treatment due to current building regulations in South Africa as discussed in the interview conducted in Section 4.2.2.2. The mass timber structure is assumed to be located within the Sandton CBD which falls outside the coastal zone. As such, it does not require additional treatment. However, the timber will definitely require treatment if the building was located within one of South Africa’s coastal cities which will increase the overall cost of the mass timber element.

A similar comparison was made for the glulam columns in Table 6.3. The compressive resistances between the timber grades and investigated species do not vary as much as the bending and shear resistances. As such, column dimensions are relatively similar for the different grades. S7 SA pine remains one of the most cost-effective solutions for this particular project, given the assumptions that were made. The cost per metre of S10 SA pine columns is more expensive than that of S7 given the R14 400 per cubic metre assumption. The cost analysis showed that Saligna is not a viable option if the cost per cubic metre remains at R 17 000 (Table 6.3).

Table 6.3: Cost per metre comparison for columns

Description	S7 SA Pine	S10 SA Pine	S10 Saligna	GL24h Spruce
Dimensions (mm)	394×394	368×368	368×368	380×380
Cost/m^3	R 12 000	R 14 400[a]	R 17 000	R 15 863[b]
Cost per m	R 1 863	R 1 950	R 2 302	R 2 291 excl. treatment
Transportation cost of columns included in price estimate.				
[a] Assumed a 20% premium on the cost of S7 SA pine.				
[b] R17: €1 Euro exchange rate. Includes customs and import taxes, transportation and commission.				

Interviews with manufacturing professionals indicated that current manufacturing limitations within South Africa prevent the large-scale production of large cross-sectional beams/columns typically required in multi-storey mass timber structures. Initial discussions showed that maximum production sizes in South Africa are in the range of 144 mm by 800 mm. Dimensions of the mass timber building considered in this research are in excess of this, but can be reduced by optimising the overall design. Unfortunately, limitations within manufacturing may prevent designers from designing freely in the future. Moreover, the current conceptual design contains approximately 1600 m^3 of mass timber which will need to be manufactured over a 70 day construction period. This translates into approximately 23 m^3 of mass timber that will need to be manufactured on a daily basis for this particular multi-storey mass timber building in order to avoid potential delays. The production of such high volumes of mass timber may prove to be a massive challenge for local manufacturers due to most manufacturers only having a single production line. As a result of this, importation of timber becomes a more viable option despite the additional cost associated with it. Investment into the upgrading/upscaling of machinery within the manufacturing sector will inevitably alleviate the challenge regarding manufacturing. A fictitious situation was thus assumed where large mass timber products can be manufactured within SA.

Table 6.4 summarises the results for the investigation of different CLT procurement options. Upon investigation it was discovered that the mechanical performance of S7 SA pine CLT requires testing to determine how its mechanical properties compares to that of C24 spruce CLT. It was assumed that the mechanical properties were approximately equivalent in order to perform the cost analysis. The price of 220 mm thick untreated C24 spruce is approximately € 110 per square metre depending on the European supplier. An additional R 175 per square metre was added for transportation based on the R38 000 per 48 m^3 shipping container. Finally, 15% and 20% were added, respectively, for customs/import taxes and commission. The price for producing CLT from S7 SA pine equates to approximately R 12 000 per cubic metre which is equivalent to R 2 640 per square metre for a 220 mm thick panel. From Table 6.4 it is evident that the S7 SA pine CLT is a more cost-effective alternative to importing CLT from Europe, given the above assumptions. Consideration needs to be made regarding the number of CLT manufacturers in South Africa and the risk associated to this. Currently only one CLT manufactures exists in South Africa which may increase the overall risk of the project.

Table 6.4: CLT comparison

Description	S7 SA pine	C24 spruce
Panel Dimension [a]	220mm×3000mm×6000mm	220mm×3000mm×6000mm
Cost/m^2	R 2 640[a]	R 2 822[b]
Cost per panel	R 47 520	R 50 798 excl. treatment
[a] Transportation of CLT included in price estimate.		
[b] R17: €1 Euro exchange rate. Inc. customs and import taxes, transportation, and commission.		

6.1.2.2 Steel Connection Cost

Rothoblaas South Africa (Pty) Ltd assisted in the costing of the steel connections, membranes and soundproofing. The total cost of the steel connections proved difficult to determine due to a number of reasons. Firstly, there are no existing South African multi-storey mass timber projects of this size to use as a reference for costing purposes. Effectively, local connections suppliers found it challenging to provide costs without entering into a detailed connection design process. Thus, a European supplier was contacted regarding the steel connection cost. A general rule of thumb which the European supplier works by is the following:

- $Connection\ Cost_{Glulam} \approx €\,80 - €\,100\ per\ m^3\ of\ glulam$
- $Connection\ Cost_{CLT\ Flooring} \approx €\,6\ per\ m^2\ of\ CLT\ flooring$

The above equations provide a rough estimate of the steel connection cost, the acoustic profile and taping for air tightness within the mass timber frame building for European conditions. Table 6.5 presents the total connection cost after applying the above equations.

Table 6.5: Estimation of steel connection cost incl. acoustics profile and taping

Description	**Amount**
Total Glulam Volume	356 m^3
Rate per m^3	€ 100 per m^3
Cost of Glulam connections & extras	€ 35 609
Total CLT Surface Area	5757 m^2
Rate per m^2	€ 6 per m^2
Cost of CLT connections & extras	€ 34 544
Total	€ 70 153

An exchange rate of R17:€1 results in a total connection cost of R 1 192 601. When adding a further 15% for customs and import tax, as well as 20% for commission of the sale, the total connection, soundproofing, membrane and taping cost equates to R 1 610 005, which accounts for 6.9% of the total structural cost. This proved to be a useful initial estimate for the total connection, soundproofing, membrane and taping cost. This cost can only be considered reliable if the European markets were identical to that of the South African markets. As such, the method can only be used for comparative purposes, indicating that a more detailed design process was indeed required.

A connection design was thus attempted for the main elements. A preliminary connection design was completed by collaborating with Rothoblaas designers and using Rothoblaas' MyProject design software. The connections and additional items required in the mass timber frame building are listed in the Bill of Quantities in Appendix G. The total cost of the steel connections is R 1 512 659, while soundproofing, membranes and taping costs are an additional R 502 522. The total connection, soundproofing, membrane, and taping cost equates to R 2 015 212, which is R 405 207 more than the estimate shown in Table 6.5. This cost accounts for 8.7% of the total structural cost, which is 1.7% more than the initial 6.9% estimate. A total connection, soundproofing, membrane and taping cost of 9% to the total structural cost can be regarded as a realistic estimate given the lack of previous studies conducted within this field. More research is therefore required for the connection cost of multi-storey mass timber building in South Africa to establish realistic estimates for quantity surveyors.

6.1.2.3 Fire Protection Cost

Fire protection is provided in the form of Type X gypsum plasterboard. The fire protection makes up 0.7% of the total structural cost. This cost does not include sprinkler systems and other active protection system that may be common to both building alternatives. The CLT panels, beams and columns have been designed for a 60 minute fire rating. As such, no additional passive fire protection was allocated towards the beams, columns and CLT floor system. An additional 15 mm of Type X gypsum plasterboard was added to the interior and exterior of the CLT core to achieve a 120 minute fire rating.

6.1.2.4 Structural Frame Cost Comparison

Table 6.6 provides a summary of the overall structural cost of the mass timber frame building. Note that the structural frame cost excludes the foundation and substructure cost as this was discussed in Section 6.1.1. Labour includes the cost of pre-cutting, installation and fixing of the mass timber elements. The total structural frame cost of the mass timber building is R 22 776 000. The timber elements constitute approximately 82% of the total structural frame cost. The mass timber frame cost item can be subdivided into 4 categories namely; floors, beams & columns, core & stairs, and bracing. Floors account for approximately 68% of the mass timber frame cost item, while beams & columns, core & stairs and bracing account for 19%, 12%, and 2%, respectively. Evidently, sufficient time needs to be allocated towards optimising the mass timber floor system as it carries a significant cost.

Table 6.6: Mass timber frame cost

Cost Item	Amount (R)	%
Concrete, Formwork, Reinforcing (includes labour)	863 297	3.8
Timber Frame (S7 SA pine)	18 683 636	82.0
Steel Connections	1 512 659	6.6
Membranes	22 316	0.1
Soundproofing	480 236	2.1
Fire Protection	150 511	0.7
Labour	1 063 362	4.7
Total	R 22 776 018	100

The total cost of the structural frame of the reinforced concrete building as per the proposed Bill of Quantities in Appendix G is R 10 262 000. Table 6.7 shows that the concrete cost makes up approximately 36% of the structural frame cost while formwork and reinforcing contribute 34% and 31%, respectively. The cost of labour for the concrete, formwork, and reinforcing is included within each respective cost item for the concrete frame building as per standard industry practice.

Table 6.7: Reinforced concrete frame cost

Cost Item	Amount (R)	%
Concrete	3 674 117	36
Formwork	3 452 791	34
Reinforcing	3 135 317	31
Total	R 10 262 224	100

A cost comparison between the two building alternatives reflects that the structural cost of the mass timber frame building is R 12 514 000 more than the reinforced concrete frame building. This translates to an increase of 122% in the structural cost of the reinforced concrete frame building. The structural frame of the mass timber building is effectively 2.2 times more expensive than that of the reinforced concrete frame building.

Lateral stability is provided in the form of a reinforced concrete core and shear wall in the concrete frame, whereas a glulam bracing system and CLT core provides the main lateral stability for the timber frame alternative. A comparison of the total cost of the two lateral stability systems shows that the timber system costs R 2 716 000, while the concrete system cost R 2 340 000. This is a R 376 000 increase in the cost of the concrete building lateral stability system and translates into a 16% increase. The latter serves as evidence of the potential savings for a mass timber frame building when a concrete core is incorporated, as seen with the Brock Commons building in Chapter 2. Such a change may possibly extend the construction schedule leading to indirect additional costs. Multi-storey mass timber hybrid buildings can potentially lead to the optimisation of the mass timber building as well as potential savings. Research is however required to quantify the potential cost of a mass timber hybrid building for South Africa.

6.1.3 Non-structural Cost

The third cost component of the total construction cost comprises the cost of the non-structural items. Research has shown that the frame cost accounts for 8%–18% of the total construction cost, depending on the structural material used (The Concrete Centre, 2008; Barrett Byrd Associates, 2016). This highlights the significant contribution that non-structural costs carry in the total building cost. Table 6.8 provides a summary of the main non-structural costs which are common to both buildings. The rates have been obtained from a quantity surveyor that has extensive experience in the costing of multi-storey commercial buildings in South Africa. Mechanical, Electrical and Plumbing (MEP) services make up 46% of the non-structural cost while the aluminium glass facade accounts for a further 23%. The total non-structural cost for both buildings is R 45 157 000.

Table 6.8: Non-structural cost

Cost Item	Unit	Quantity	Rate	Amount (R)
Roof	m^2	720	570	410 400
Facade	m^2	3024	3500	10 584 000
Internal Divisions	m^2	5472	404	2 210 688
Floor Finishes	m^2	5472	315	1 723 680
Internal Wall Finishes	m^2	5472	270	1 477 440
Ceilings	m^2	5472	220	1 203 840
Fittings	m^2	5472	255	1 395 360
Electrical Installation	m^2	5472	2 141	11 715 552
Plumbing Installation	m^2	5472	126	689 472
Fire Services	m^2	5472	68	372 096
Air-conditioning	m^2	5472	1 450	7 934 400
Lift	no	1	1 000 000	1 000 000
External Work & Parking	m^2	5472	720	3 939 840
Provision for Sustainability	no	1	500 000	500 000
Total				45 156 768

6.1.4 Total Construction Cost

The total construction cost excluding preliminary and general costs, contractor contingencies and contract escalations is summarised in Table 6.9 and Figure 6.1. The total construction cost for the mass timber frame and reinforced concrete frame building is R 68 442 000 and R 56 997 000, respectively. The R 11 445 000 difference in total construction cost translates into a 20% increase in construction cost of the concrete frame building. The structural frame of the concrete structure constitutes 18% of the total construction cost, which is in line with 18% stated by Barrett Byrd Associates (2016). This gives an indication that the total construction cost is similar to that of other projects and validates the overall reliability of the costing procedure. The structural frame cost for the mass timber frame building accounts for 33% of the total construction cost, which is significantly more than that of the reinforced concrete frame building. The low substructure and foundation cost are ascribed to the favourable ground conditions assumption made during the design process. Section 6.1.5 investigates the effect of a difference in P&G costs on the total construction cost.

Table 6.9: Total construction cost excluding P&G costs

Cost Item	Timber Frame (R)	%	Concrete Frame (R)	%
Substructure & Foundation	508 714	1	1 578 016	3
Structural Frame	22 776 018	33	10 262 224	18
Non-structural components	45 156 768	66	45 156 768	79
Total	68 441 500	100	56 997 008	100

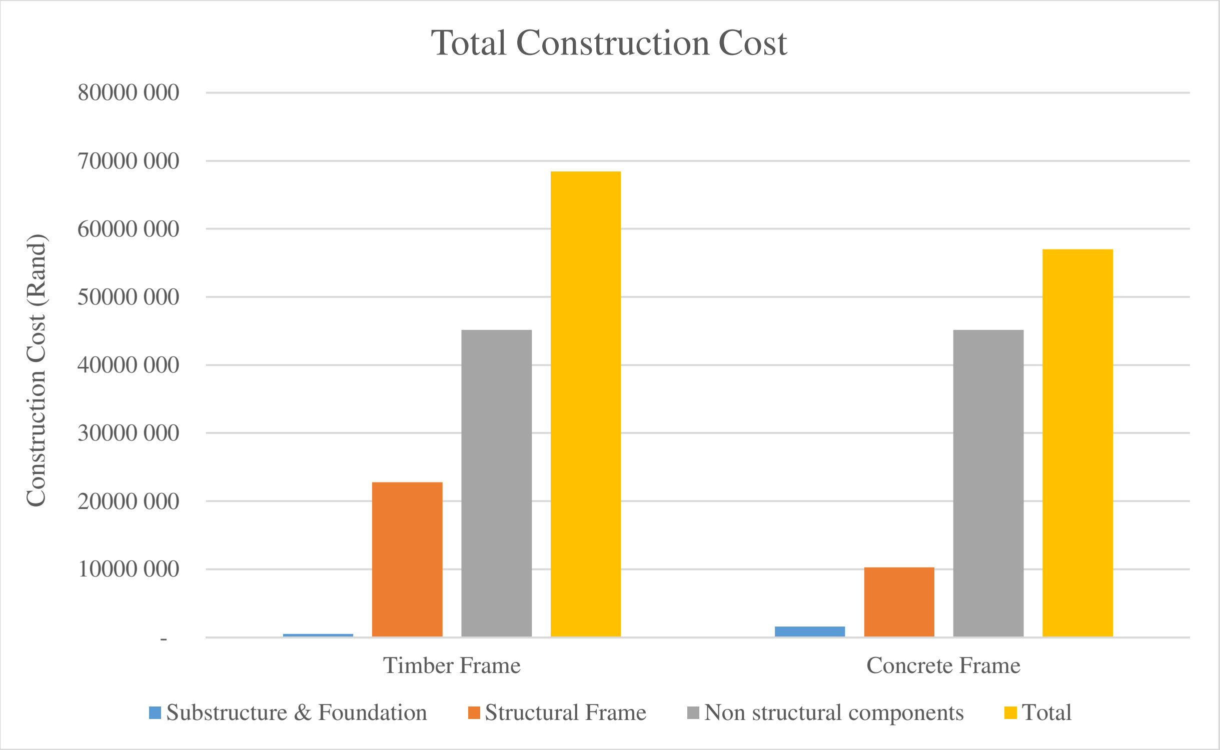


Figure 6.1: Total construction cost excluding P&G costs

6.1.5 Preliminary and General Cost

Preliminary and general costs cover a wide variety of cost items. P&G costs can be divided into three subsections:

1. Fixed Costs: Costs that remain the same regardless of the value or time of the project.
2. Value Costs: Costs that are dependent on the value of the project.
3. Time Costs: Costs that vary with the total time of construction.

A number of P&G cost items fall within more than one of these subsections. Insurance, for instance, varies according to the value of the construction, as well as the time for which it has to be insured. Insurance; site security/protection of works; equipment, sheds and offices; managing and supervision of works are a few of the main cost items within P&G costs. Studies have shown preliminary and general cost range between 10–15% of the total construction cost for office buildings (Davison, 2012). Following an interview with an experienced commercial property developer from Abland (Pty) Ltd, an initial estimate of 10% was assumed for the P&G costs for both the mass timber and reinforced concrete frame building (Abland, 2020).

The construction schedules for the two buildings differ by 5 months, indicating that the time value cost component of the total P&G cost should also differ. Analysis of the P&G costs from previous projects provided by quantity surveyors established that time costs make up a significant component of the total P&G cost. The time costs accounted for 65% to 90% of the total P&G cost for a number of similar projects which were analysed. A method was devised in an attempt to quantify the difference that a reduction in construction schedule may have on the overall P&G cost. This was achieved by using the reinforced concrete frame construction schedule as the base case. In other words, an assumption was made that the mass timber frame construction schedule was originally the same as the reinforced concrete frame construction schedule, namely 10 months. As a result of this, the P&G cost for the mass timber frame building was initially calculated for a 10 month period. The question which now stands is the following: "What if the mass timber frame construction schedule was in fact 5 months?" This can be answered by calculating a monthly time cost over the 10 month period (assumed construction schedule), and then applying it over 5 months (actual construction schedule). The following step by step procedure shows the methodology to determine a Monthly Time Cost for the time component of the P&G cost, by utilising the concrete frame building's construction schedule as the base case:

1. Total P&G cost was taken as 10% for both projects
2. P&G cost was divided into two components: Fixed/Value Costs (35%) and Time Costs (65%)
3. Total Time Cost was divided by the assumed construction time to determine a Monthly Time Cost
4. Monthly Time Cost was multiplied by actual construction time of the mass timber frame to determine the Actual Time Cost

Table 6.10: Calculation of P&G costs

Description	Amount
Assumed Construction Time: 10 months	
Assumed P&G Cost @ 10%	R 6 844 150.00
Fixed/Value P&G Costs (@ 35% of P&G)	R 2 395 452.50
Time P&G Costs (@ 65% of P&G)	R 4 448 697.50
Monthly Time P&G Cost (Time P&G Costs ÷ Assumed Construction Time)	R 444 869.75
Actual Construction Time: 5 months	
Actual Time Cost (Monthly Time Cost × Actual Construction Time)	R 2 224 348.75
Fixed/Value Cost (remains unchanged)	R 2 395 452.50
Actual P&G Cost	R 4 619 801.25

From the calculation procedure in Table 6.10, the total P&G cost for the mass timber frame building is R4 619 800 as a result of a 5 month shorter construction schedule. This is equivalent to 7% of the total mass timber frame construction cost. The total P&G cost has therefore in effect been reduced from 10% to 7% through the calculation procedure in Table 6.10. The total P&G cost for the concrete frame building remained unchanged at R 5 699 700 (10% of the total concrete frame construction cost). R1 079 900 (19%) was saved in P&G costs due to a 5 month reduction in construction schedule of the timber frame building. Chapter 7 investigates the effect of increasing the percentage time cost of the P&G cost. Table 6.11 contains the total construction cost including the P&G cost, contractor contingencies and contract escalations. The 3 month pre-contract escalation accounts for potential escalations in costs in the 3 month time period between the feasibility study and the start of construction. The contract escalation further accounts for potential escalations during the construction period. A total construction cost of R 75 638 000 and R 65 311 000 was calculated for the mass timber frame and reinforced concrete frame building, respectively. The mass timber frame building is R 10 327 000 more expensive than the concrete frame building with regards to total construction cost.

Table 6.11: Total Construction cost including P&G cost

Cost Item	Mass Timber Frame (R)	Concrete Frame (R)
Total Construction Cost	68 441 500	56 997 008
Preliminary and General Cost	4 619 801	5 699 701
Contingencies (2.5%)	1 826 533	1 567 418
Pre-contract Escalation (1.5%)	280 829	240 990
Contract Escalation (1.5%)	469 804	806 314
Total	R 75 638 467	R 65 311 431

6.2 Total Capital Investment

The developer of the commercial building incurs a number of additional costs. These costs contribute to the total capital investment required for the development. Abland (Pty) Ltd, a well-established property development firm, assisted in identifying and quantifying the different capital cost items. The land cost is the price of undeveloped land within the Sandton CBD. Furthermore, the development is assumed to be Green certified Prime&A- grade offices. This gives an indication of the promotional cost required. Table 6.12 provides a summary of the capital cost items. It is assumed that these costs/percentages remain constant for both the reinforced concrete and mass timber frame building. The land is assumed to be fully serviced and subdivided, thus no allowances have been made for costs associated to the servicing and subdivision of the land.

Table 6.12: Total capital investment

Cost Item	Value
Land Cost @ R 3500/m^2	R 19 152 000
Professional Fees	14.5% of construction cost
Marketing	R 2 800 000
Interest During Construction	8% per annum and based on applied S-Curves
Bank Raising Fee	1% of development loan
Legal Costs	R 50 000
Plan Approvals	R 109 000
Development Fee	2.5% of construction cost
Fire Engineer	0.25% of construction cost
Wet Services Engineer	0.25% of construction cost
Environmental Consultant	0.25% of construction cost
Geotechnical Engineer	0.25% of construction cost
Traffic Engineer	0.25% of construction cost
Green Star Consultant	R 500 000
Landscape Architect	R 200 000
Safety Consultant	R 150 000
Sundry Items	R 50 000

The interest incurred during construction was calculated through multiple iterations in a financial model due to its dependency on the construction ‘S-curves’. The interest incurred during construction is discussed in the ensuing sections. Overall, the total capital investment required for the mass timber frame building is R 115 691 000. This is R 10 573 000 more than the R 105 118 000 total capital investment required for the reinforced concrete frame building which translates into a 10% increase.

6.3 Earlier Return on Investment

One major advantage of an accelerated construction schedule is the potential of earning an earlier return on the investment. Tenants can occupy the office 5 months earlier for the mass timber frame building as opposed to the reinforced concrete frame building. This earlier return on investment needs to be incorporated for a fair comparison between the two developments. The current monthly rental fee for green certified office spaces in the Sandton CBD is approximately R 150 per m^2 whereas Cape Town CBD is closer to R 165 per square metre (Abland, 2020). On-grade parking bays hold a further opportunity to earn an income from the development. Table 6.13 indicates that the total monthly income for the development is R 929 300 based on the Sandton CBD rental fee. This results in a R 4 646 500 income over the 5 months whilst the reinforced concrete frame building is still under construction. The effect of an earlier return on investment is presented in Section 6.5 and quantified by calculating the internal rate of return of each development.

Table 6.13: Monthly return on investment

Income Description	Rate	Area/No of Bays	Monthly Income (R)
Gross Rentable Area	R 150/m^2	5427	820 800
On Grade Parking	R500/bay	217	108 500
Monthly Net Rental			R 929 300

6.4 Interest during construction

Developments are typically funded through equity provided by the developer/private investors and a development loan obtained from an accredited credit provider. The credit provider typically funds 70% of the capital value of the development for such a project (Abland, 2020). The remaining 30% is funded through equity, which includes equity in respect of the land value. Table 6.13 presents the calculation procedure for the capital value, development loan and equity required.

Table 6.14: Capital value, development cost and equity

Description	Mass Timber Frame (R)	Concrete Frame (R)
Total Annual Rental Income	R 11 151 600	R 11 151 600
Capital Value @ 9.5% pa. capitalization rate	R 117 385 263	R 117 385 263
Development Cost	R 115 691 352	R 105 117 753
Development Loan @ 70% of Capital Value	R 82 169 684	R 82 169 684
Equity in respect of land value	R 19 152 000	R 19 152 000
Additional Equity required	R 14 369 668	R 3 796 069

Money is drawn from the development loan once equity is exhausted. It is assumed interest is charged on the money drawn from the development loan at a rate of 8% per annum for this particular project. Due to a difference in construction schedules, it can be expected that equity will be utilised at different rates. Proportions for monthly expenditure were applied based on the experience from the developer and are shown in Appendix I. This allowed for monthly expenditure to be determined and an 'S-curve' for both buildings to be developed. The rate at which equity was utilised and money drawn from the development loan was therefore determined.

Figure 6.2 shows the expected cash outflow (excluding interest expense and land cost) for both the mass timber and reinforced concrete buildings. From Figure 6.2 it is clear that the R 14 370 000 equity is completely exhausted within 2 months of construction for the timber frame building. Similarly, within 2 months the R 3 796 000 equity for the concrete frame building is also exhausted. Interest is effectively charged for 4 months for the timber frame building and 9 months for the concrete frame building. The total interest payable by the developer over the 5 month construction period is R 1 486 000 for the timber frame building. Alternatively, R 2 706 000 is payable by the developer for interest incurred over the 10 months of construction for the concrete frame building. The 5 month shorter construction schedule results in savings of R 1 220 000 in interest for the timber frame building. Appendix I exhibits the detailed procedure for the calculation of the monthly interest expense over the construction period.

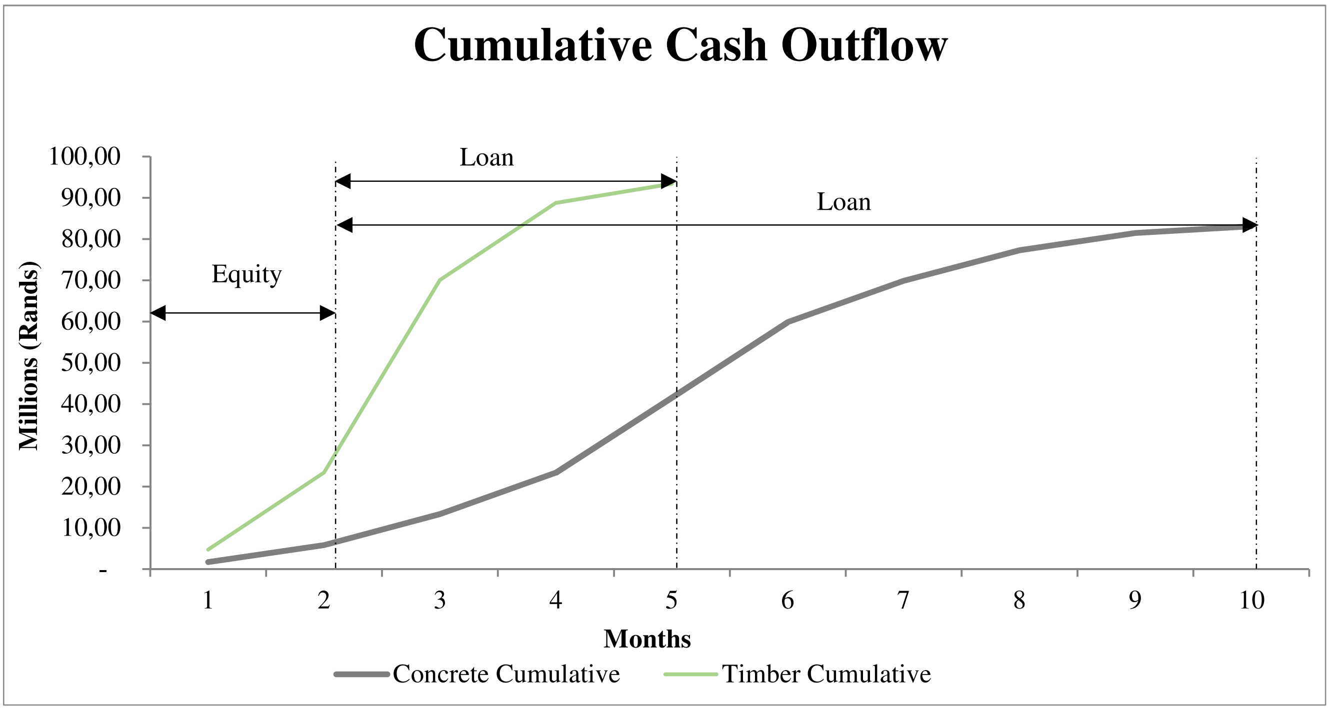


Figure 6.2: Cumulative cash outflow during construction

6.5 Internal Rate of Return

The feasibility of the two structural alternatives can be assessed through the calculation and evaluation of the internal rate of return (IRR) and minimum acceptable rate of return (MARR) of each development. Internal rate of return is a metric used to gauge the potential profitability of a development (Blank and Tarquin, 2014). Internal rate of return can be defined as the discount rate required to set the net present value of all project cash inflows and outflows equal to zero. It therefore quantifies the effect that an earlier occupancy by tenants of the multi-storey mass timber building may have (Abland, 2020).

The MARR of a particular project is dependent on a number of factors with some of the main factors being the cost of capital, associated risk, and IRR of other investment opportunities (Hayes, 2020). If the IRR is greater than the MARR then the development is financially justified (Blank and Tarquin, 2014). When evaluating two different developments, the development with the greatest IRR is the more profitable development from an investor's perspective.

The MARR, or hurdle rate, can be assumed to be 15% for the commercial developments in this study (Abland, 2020). Appendix J contains the amortization schedule required to calculate the 5 year IRR of the mass timber and reinforced concrete buildings. The mass timber building achieved a 5 year IRR of 20.9% while the reinforced concrete building achieved a 5 year IRR of 25.7%, 4.8% higher than the IRR of the mass timber frame building. Figure 6.3 presents the cash inflow and outflow over time for the 5 year IRR calculation of the mass timber frame development. The 67 months represented in the timeline includes the 2 month pre-construction period, the 5 month construction period, and the 60 month rental period. The timeline illustrates how all of the equity is utilised within the first 3 months. This is followed by the 'sale' of the development 5 years after construction is completed.

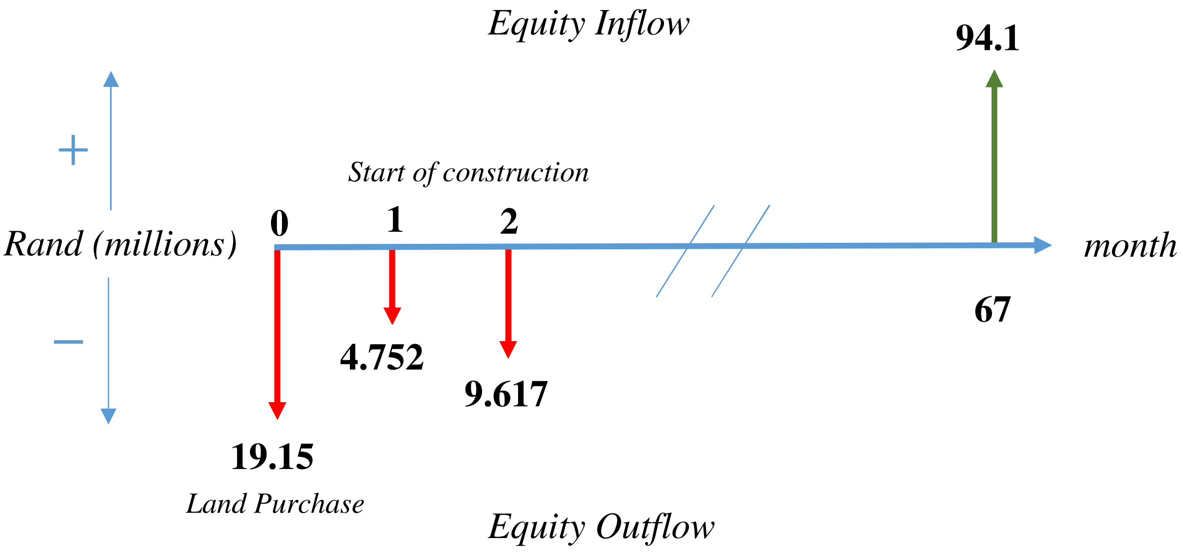


Figure 6.3: Mass timber building: Internal rate of return timeline

From the 4.8% higher 5 year IRR for the reinforced concrete frame development, it is clear that the concrete alternative remains more profitable than the timber alternative despite the 5 month shorter construction schedule. Notably, the 5 year IRR of both developments is above the 15% MARR, indicating that they are both financially justified. This is a positive result for both developments particularly the multi-storey mass timber building in the context of South Africa. It indicates that a multi-storey mass timber building can be financially viable in South Africa if a number of factors are addressed throughout the entire value chain of the mass timber products. However, it is evident from this particular comparison – given the assumptions that were made – that mass timber frame commercial buildings will struggle to achieve higher internal rate of returns than conventional reinforced concrete frame commercial buildings. Research by Drennan (2017) showed that more cost-effective concrete frame solutions exist than that of a conventional reinforced concrete flat slab system for commercial buildings. One such example is a post tensioned flat slab structure, which proved to be 1.4% cheaper than that of a reinforced concrete flab slab structure. In light of this, mass timber advocates will also argue that alternative mass timber systems exist which are more cost-effective than the system implemented within this particular study.

6.6 Chapter 6 Conclusion

The aim of Chapter 6 was the determination of the total capital investment required for each development. Before this could be achieved different options were investigated for the procurement of timber elements. Analysis showed that S7 SA pine was the most cost-effective solution, given the assumptions that were made. The completion of the Bill of Quantities for each building allowed for the determination of the total capital investment required for each development. The total capital investment required for the mass timber frame development was 10% more than that of the reinforced concrete frame development (R115 691 000 versus R105 118 000). A 5 year internal rate of return (IRR) of 20.9% and 25.7% was calculated for the mass timber frame and reinforced concrete frame developments, respectively.

Before any major conclusions are finally drawn, a sensitivity analysis is required. A number of variables exist within each development which influences the IRR. The effect of these variables is investigated in Chapter 7.

Chapter 7

7 Sensitivity Analysis

Chapter 7 explores the effect of certain variables on the overall construction cost comparison between the two buildings through a sensitivity analysis. The investigation is limited to the variables identified to potentially have the greatest effect on the overall construction cost of the mass timber frame building. The variables that have been identified include; overall fit-out time for finishes, lead-in time before construction commences, rental rate, cost per cubic metre of SA pine, cost of imported timber, and preliminary and general (P&G) cost.

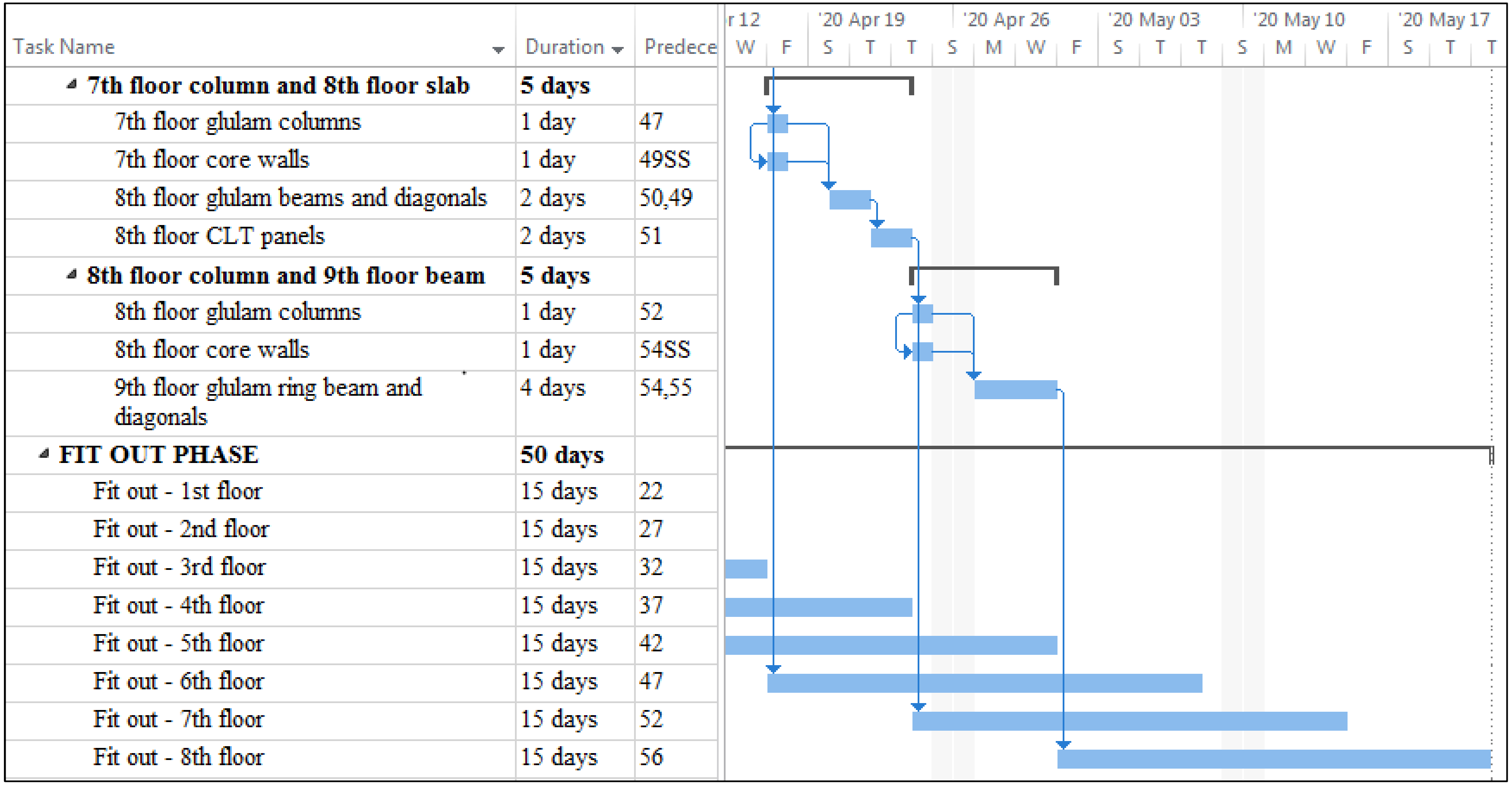
The sensitivity of these variables is presented and discussed in the ensuing sections. The analysis allows for the evaluation of certain assumptions which were made during the focus group workshop and the development of the financial model. The focus of this chapter is the multi-storey mass timber frame building. As such, the results of the concrete frame building remain unchanged throughout the analysis.

7.1 Fit-out Time

In Chapter 5, a 4-week fit-out period per floor (20 days) was allowed for both the mass timber and reinforced concrete frame buildings. This was regarded as a conservative assumption as mass timber elements allow for the pre-installation of services off-site. As such, a reduced fit-out time is likely for the mass timber frame building. Two scenarios were investigated namely; a 2 week fit-out period per floor, and 3 week fit-out period per floor. A new total construction period was determined by adjusting the existing construction schedule for the two scenarios.

7.1.1 3-Week Fit-Out Time

The final fit-out of each floor is dependent on the completion of the structural frame of that floor. To this end, the fit-out task lags behind the erection of the structural elements as shown in Figure 7.1. The change in fit-out time from 20 to 15 days per floor resulted in a total reduction of 5 working days in the overall construction schedule. This was less than what was initially expected. The reason for this is due to the fit-out task's dependency on the completion of the structural frame. Furthermore, the fit-out of consecutive floors is independent of one another due to the possibility of multiple fit-out teams (IE HVAC team, electrical team, tiling team, fire proofing team etc.). The one week reduction in construction schedule has no major cost savings associated with it. The expected completion of the timber frame has moved from the 28th of May to the 21st of May. Realistically tenants will only occupy the building at the start of the following month.



Task Name	Duration	Predece
7th floor column and 8th floor slab	**5 days**	
7th floor glulam columns	1 day	47
7th floor core walls	1 day	49SS
8th floor glulam beams and diagonals	2 days	50,49
8th floor CLT panels	2 days	51
8th floor column and 9th floor beam	**5 days**	
8th floor glulam columns	1 day	52
8th floor core walls	1 day	54SS
9th floor glulam ring beam and diagonals	4 days	54,55
FIT OUT PHASE	**50 days**	
Fit out - 1st floor	15 days	22
Fit out - 2nd floor	15 days	27
Fit out - 3rd floor	15 days	32
Fit out - 4th floor	15 days	37
Fit out - 5th floor	15 days	42
Fit out - 6th floor	15 days	47
Fit out - 7th floor	15 days	52
Fit out - 8th floor	15 days	56

Figure 7.1: 3 week fit-out adjustment

7.1.2 2-Week Fit-Out Time

A 2-week fit-out period reduces the original construction schedule by 10 working days. This small reduction in construction schedule is due to the same reason as for the 3-week fit-out time. Similarly, the minor change in construction schedule does not result in major cost savings. However, if the 10 work day reduction in construction schedule allows for the building to be occupied at the start of a month, then the developer may in effect benefit greatly. Although the difference is small, it depends on the completion date of the building. If, for instance, the building was to be completed on the 5th of June, then a 5 or 10 day reduction in construction schedule may result in tenants occupying the building for the month of June. This will result in an additional R 929 300 for the month of June in the form of rent.

An analysis was performed to investigate the effect of changing the construction schedule by one month intervals on the overall profitability of the project. Table 7.1 shows how the P&G cost, interest incurred during construction, IRR and initial yield fluctuate as a result of the change in construction schedule. Analysis of the financial model shows that a one month reduction in construction schedule typically results in a 0.5% to 0.6% increase in the 5 year IRR of the timber frame building as seen for the 3 month and 4 month construction schedules. Alternatively, a one month increase in overall construction schedule results in a decrease of 0.5% in the 5 year IRR.

Table 7.1: Development sensitivity for different construction schedules

Description	3 Months	4 Months	5 Month	6 Month	7 Months	8 Month
P&G cost (R)	3 730 062	4 174 932	4 619 801	5 064 671	5 509 541	5 954 411
Interest incurred (R)	998 586	1 240 005	1 486 188	1 693 472	1 904 448	2 171 210
IRR	22.02%	21.43%	20.88%	18.23%	17.67%	17.18%
Initial Yield	9.8%	9.7%	9.6%	9.6%	9.5%	9.4%
Development Value (R)	168 521 726	168 521 726	168 521 726	156 764 397	156 764 397	156 764 397

Following standard industry practice, a 7.5% per annum increase in the rental rate is accounted for. This has a major effect on the overall 5 year IRR of the project because the development value is based on the annual earnings from the development (Section 6.4). In other words, if the rental rate increases, so does the overall value of the development. The 2.7% decrease in IRR from a 5 to 6 month construction schedule is a direct result of this 7.5% increase. The asset value decreased by R 11 757 000 from the 5 month case to the 6 month case due to the one month delay in the 7.5% escalation in rental rate. In order to gain a greater understanding of this change it may be necessary to study the amortization schedule presented in Appendix J.

7.2 Lead-In Period

During the focus group workshop, a 2 month lead-in period was allowed for both buildings. In Chapter 5, an analysis of the construction schedules shows that a 2 month lead-in period will not result in any delays on-site. Some argued that a 3 to 5 month lead-in period may be required for the mass timber frame building due to the detailed design, the very low tolerances and precise scheduling requirements. It was stated that a more accurate estimate for the lead-in period for the mass timber frame building may be between 3 to 5 months. In an attempt to quantify this effect, three scenarios were investigated namely; a 1 month, 2 month, and 3 month delay in the commencement of construction of the mass timber frame building. This gave an indication that a potential delay due to extended lead-in periods may have on the internal rate of return on the project. It was assumed that no additional direct costs are incurred during the lead-in month. In other words, the additional lead-in months only delayed the official start date of the construction. The effect of a delay in construction commencement date is summarised in Table 7.2.

Table 7.2: Effects of Lead-in period adjustment on 5 year IRR

Description	Original	1 Month Delay	2 Month Delay	3 Month Delay
5 year IRR	20.88%	18.80%	18.79%	18.78%

Initially a 1 month delay results in a 2.08% decrease in the 5 year IRR. This is due to a R 11 757 000 change in asset value from month 68 to month 67 due to an escalation in the rental contract. It can be seen from Table 7.2 that an additional 2 month or 3 month delay does not have a significant effect on the 5 year IRR. The reason for this is due to the assumption that no costs are incurred during these months. In essence, the only factor brought into consideration is the value lost due to the time value of money.

7.3 Rental Rate

The current monthly income received from the commercial development is R 929 300 per month. 88% of this income is the rental income for the 5472 m^2 of office floor space. R150/m^2 was deemed as an accurate estimate for office space in the Sandton CBD area. This rate fluctuates according to the rental market and differs throughout South Africa. In Section 2.1.2.3 a brief investigation was undertaken to determine the desirability of green certified Prime&A – grade offices in South Africa. The Rode's report showed that the vacancy rate in the 4th quarter of 2018 for Green certified Prime&A – grade offices in South Africa was 5.9% lower than non-green certified offices despite demanding a premium of 13.6% (SAPOA, 2018). The buildings considered within this dissertation did not undergo a green rating process, but evidence exists throughout literature of the reduced carbon footprint associated with timber construction as discussed in Section 2.2.2.1. Studies have also shown the positive effect of exposed timber on the well-being of the residents in timber structures (Section 2.2.2.2).

A potential premium on the mass timber frame building may therefore be justifiable especially when considering the potential desirability of tenants to work in such a mass timber frame building. The effect of adjusting the rental rate on the 5 year IRR and initial yield is summarised in Table 7.3 and Figure 7.2. The rental rate for the reinforced concrete frame building remained constant at R150/m^2 for the entire analysis. The percentage increase can therefore be seen as a premium that tenants are willing to pay for the mass timber frame building.

Table 7.3: Rental rate analysis for the mass timber frame building

Increase	Rental Rate (R/m^2)	5 Year IRR (%)	Initial Yield (%)
0%	150	20.9	9.6
5%	158	23.9	10.1
7.8%	161	25.7	10.3
10%	165	27.3	10.5
13.6%	170	30.0	10.8
15%	173	31.1	10.9

Analysis of the results shows the significant effect of the rental rate on the 5 year IRR of the development. A 7.8% increase in rental rate results in a 5 year IRR of 25.7%. This is equivalent to the 25.7% IRR recorded for the reinforced concrete frame building. A 5 year IRR of 30.0% was achieved when increasing the original rental rate by 13.6% (the recorded premium for green certified office spaces). This is 4.3% higher than the 5 year IRR of the reinforced concrete frame building. Furthermore, a 15% premium would result in a 5 year IRR of 31.1% for the mass timber frame building.

The initial first year yield of the development changed marginally throughout the rental rate analysis as seen in Figure 7.2. This can be ascribed to the method in which yield is calculated. First year yield is calculated by taking the first year annual rental income divided by the total development cost. The potential positive effect of an earlier return on investment is not realised through a yield calculation. This serves as evidence that the internal rate of return (IRR) remains the ideal financial indicator for the comparison of the two building systems as it incorporates the time value of money.

The analysis of the rental rate yielded positive results for the mass timber frame building. It shows that the mass timber frame building can be more profitable than the reinforced concrete frame building if a rental premium of at least 7.8% is achieved.

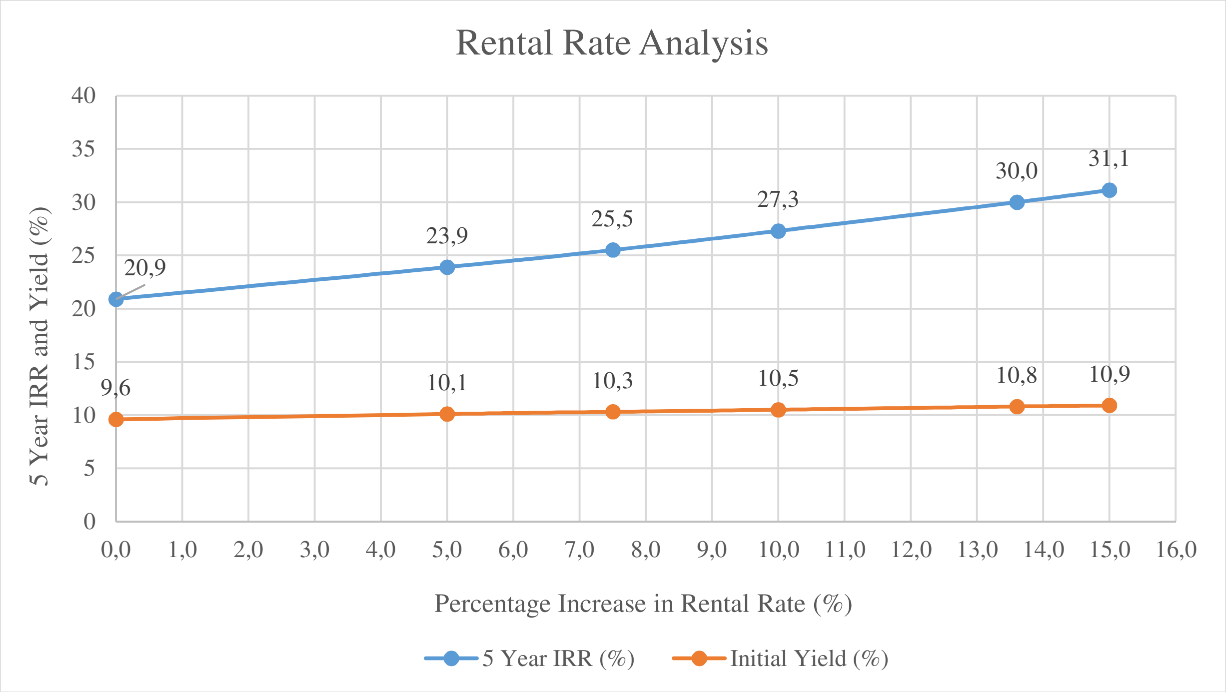


Figure 7.2: Rental rate analysis for the mass timber frame building

7.4 Cost of SA Pine

The large difference in the structural frame cost between the two buildings can be partly attributed to the high cost per cubic metre of S7 SA pine. Discussion with manufacturers indicated that it costs approximately R 12 000 per cubic metre of S7 SA pine to manufacture glulam or CLT (Holzbau Carpentry Hess, 2020; XLAM South Africa 2020). It remains difficult to determine how prices may differ in an established multi-storey mass timber market. To this end, fictional market prices of S7 SA pine were investigated. The results are summarised in Table 7.4.

Table 7.4: Analysis of S7 SA pine cost

Change	SA Pine Cost (R/m^3)	Structural Cost (R)	Difference (R)	IRR (%)
+15%	R13 800	26 074 029	933 606	18.9%
+10%	R13 200	25 140 423	933 606	19.5%
+5%	R12 600	24 206 817	933 606	20.2%
0%	R12 000	23 284 732	933 606	20.9%
-5%	R11 400	22 339 606	933 606	21.6%
-10%	R10 800	21 406 000	933 606	22.3%
-15%	R10 200	20 472 394	933 606	23.1%

Table 7.4 shows that a 5% decrease in the cost of SA pine results in a R 933 600 (4%) reduction in the overall structural cost of the development. This translates into an increase of approximately 0.7% in the 5 year IRR. Similarly, a 5% increase in the cost of SA pine results in a 0.7% decrease in the 5 year IRR. Furthermore, a 15% reduction in the cost of SA pine results in a 23.1% 5 year IRR for the multi-storey

mass timber frame development. This is still 2.6% less than the 25.7% 5 year IRR achieved for the reinforced concrete frame development. From this analysis it is clear that fluctuation in the cost of the SA pine has a substantial effect on the 5 year IRR of the development, although it is not as sensitive as fluctuation in the rental rate. An increase of 5% in the rental rate increases the 5 year IRR between 3.0 to 3.8%, which is significantly more than the 0.7% increase recorded for an decrease of 5% in the cost of S7 SA pine. Results showed that the price of S7 SA pine needs to be reduced by at least 33% for the mass timber frame development to earn a higher 5 year IRR than the reinforced concrete frame development.

7.5 Importation of Timber

Section 2.1.1 eludes to the fact that the importation of structural timber will have to be considered for the immediate future in order to sustain a potential multi-storey mass timber building market. As such, an analysis of the potential structural cost and 5 year IRR of the development is required if all of the mass timber is imported. Table 7.5 contains the results for the analysis. The results of the analysis are based on the cost of untreated spruce as calculated in Section 6.1.2.1.

Table 7.5: Analysis of importing timber

Exchange Rate	Spruce Glulam Cost (R/m^3)*	Structural Cost (R)	5 Year IRR (%)
R19:€1	17 602	32 520 480	15.2
R18:€1	16 733	31 387 958	15.8
R17:€1	15 863	30 255 437	16.4
R16:€1	14 994	29 122 915	17.0
R15:€1	14 124	27 990 393	17.7
*The cost does not include treatment of the spruce.			

At a R17:€1 exchange rate, the total structural cost increases from R 23 285 000 for the original S7 SA pine option to R 30 255 000 for imported spruce. This amounts to a 30% increase in the total structural cost of the building. Additionally, it results in a 4.5% decrease in the 5 year IRR from 20.9% to 16.4%. When comparing this to the reinforced concrete frame alternative, it becomes clear that the concrete frame structure performs overwhelmingly better from a financial point of view. In Section 6.5 a 25.7% IRR is calculated for the reinforced concrete frame alternative. This is 9.3% higher than the 16.4% calculated for the imported mass timber frame. A 15% increase in the rental rate improves the 5 year IRR of the imported mass timber frame development from 16.4% to 24.2%. This is still 1.5% below the 5 year IRR of the reinforced concrete frame building, proving that it is unlikely that the option of importing timber will be more profitable than the reinforced concrete frame building. However, a

16.4% 5 year IRR still makes the development financially viable as it is above the 15% hurdle rate. With this being said, the analysis clearly shows that more profitable options exist.

From the analysis it can be concluded that a R1 increase in the rand to euro exchange rate results in a decrease of approximately 0.6% in the 5 year IRR of the imported mass timber development. A similar change occurs if the rand strengthens against the euro. A R1 decrease in the rand to euro exchange rate results in a 0.6% increase in the IRR. Notably, the 5 year IRR's of the importation option is significantly less than that of producing the mass timber elements locally. What should be taken into consideration is the assumption which was made regarding the locally produced mass timber elements. Investigation into the production of mass timber elements in South Africa raised concerns regarding the manufacturing capabilities of local suppliers as discussed in Section 6.1.2.1. As such, a fictional situation was assumed where South African suppliers can manufacture the large cross-sectional dimensions required for the mass timber frame building in this research. Without this assumption, the timber will most likely have to be imported for the mass timber building considered in this study, unless current manufacturing capabilities improve.

7.6 P&G Cost

In Section 6.1.5 a method was introduced of calculating a preliminary and general (P&G) cost if the overall construction schedule is reduced. In order to calculate the 'new' P&G cost an assumption was required regarding the split between time costs, value costs and fixed costs. It was initially assumed that time costs accounts for 65% of the total preliminary cost whereas fixed and value costs make up the remaining 35%. The effect of changing the split between time costs and fixed/value costs is investigated in Table 7.6.

Table 7.6: Analysis of P&G cost

Split	P&G Cost (R)	Difference (R)	5 Year IRR (%)
65:35	4 619 801	-	20.90
70:30	4 448 698	171 103	20.99
80:20	4 106 490	342 208	21.24
90:10	3 764 283	342 207	21.49

A 10% increase in the percentage cost which the time cost accounts for results in an increase of 0.25% in the 5 year IRR. It is unlikely that the time cost makes up more than 90% of the total P&G cost. The maximum increase in the 5 year IRR as a result of the initial 65:35 split assumption is approximately 0.6%. This shows that an error in the initial 65:35 assumption does not have such a significant influence on the final result.

7.7 Chapter 7 Conclusion

Chapter 7 investigated the effect of certain variables on the overall cost and profitability of the mass timber frame development. The variables that are most likely to change were investigated.

From the analysis it can be concluded that the rental rate and cost of the SA pine are the two variables with the greatest effect on the overall profitability of the development. The analysis showed that a rental premium of 7.8% or higher for the mass timber frame building will yield higher internal rates of return as opposed to that of the reinforced concrete frame alternative. Results also showed that the price of S7 SA pine needs to be reduced by at least 33% for the mass timber frame development to earn a higher 5 year IRR than the reinforced concrete frame development.

The option of importing the mass timber from Europe was also investigated. The investigation showed that importing the mass timber will decrease the 5 year IRR of the development by approximately 4.5%, thus making the reinforced concrete frame building significantly more profitable.

Analysis of the construction schedules shows that a one month increase in construction schedule generally results in a 0.5-0.6% decrease in 5 year IRR. However, escalation within the rental rate from one month to the next may cause an IRR spike of up to 2.7%. This is due to the value of the development (or ‘selling price’ of the development) being directly dependant on the potential annual income of the development.

The analysis yields both positive and negative results for the mass timber frame building. It showed that mass timber can be more profitable than conventional reinforced concrete construction given certain scenarios. However, this may not occur if a number of aspects within the timber industry are not addressed.

Chapter 8

8 Conclusion and Recommendations

Mass timber construction has become increasingly popular in the past decade, with several high-rise timber structures being developed (Salvadori, 2017). This growth in market share of multi-storey mass timber buildings has yet to be seen in South Africa. Recent studies conducted within South Africa have yielded positive results regarding the mechanical performance and fire performance of mass timber products made from South African timber species (Crafford and Wessels, 2016; van der Westhuyzen, Walls and de Koker, 2020). Due to these positive results, questions arose within the AEC and property industry as to the development cost associated with multi-storey mass timber buildings. Moreover, property developers were particularly interested as to how the development cost would compare to a typical building system in South Africa – such as flat slab reinforced concrete frame structures.

Concerns were raised regarding the sustainability of such a potential multi-storey mass timber building market. In other words, could South Africa supply enough high-grade raw timber to sustain a multi-storey mass timber building market, or would the mass timber elements need to be imported? The research undertaken in this dissertation therefore aimed to address these topics. Furthermore, the aspiration to acquire additional knowledge and skills regarding the development, implementation and use of Building Information Modelling (BIM) for a project was of significance. As such, the research project served as a case study for the implementation of BIM within a project team. Through this small case study an assessment was made regarding the potential benefits of BIM as well as the current limitations thereof. For the sake of clarity, each research outcome is addressed separately in the following sections.

8.1 Economics Surrounding the Timber Industry in South Africa

Investigation of existing literature showed that South Africa could potentially supply enough high-grade timber for a future multi-storey mass timber building market. Initial calculations showed that approximately 720 to 1220 similar 8 storey mass timber buildings could potentially be constructed from the 6.2 million m^3 of future roundwood production. This would however only occur in 24 to 30 years' time, once new plantations become available. Until then, South Africa will have to consider the importation of mass timber products in order to sustain a rapid growth in multi-storey mass timber building construction. This is further emphasised by current manufacturing limitations in South Africa.

Interviews with manufacturing professionals indicated that current manufacturing limitations within South Africa prevent the large-scale production of large cross-sectional beams/columns required for this particular multi-storey mass timber structure. As a result of this, importation of timber becomes a more viable option despite the additional associated cost. Investment into the upgrading of equipment within the manufacturing sector will inevitably alleviate the challenge regarding manufacturing.

8.2 Design Concepts and Construction Schedule Comparison

In Chapter 2 different concepts and designs for multi-storey mass timber buildings were investigated. This led to the development and design of an 8 storey commercial mass timber frame building for South Africa, as well as a replica reinforced concrete frame building. The mass timber frame building comprised of a glulam column-beam system with a CLT core, CLT floor and lateral glulam bracing.

Following the development of the conceptual designs, a focus group workshop was conducted in an attempt to determine accurate construction schedules for each building alternative. It was confirmed that the reinforced concrete frame building will take 207 working days (42 weeks or 10 months) to complete, whereas the mass timber frame building will take 104 working days (approximately 21 weeks or 5 months). This is a reduction of 103 working days (21 weeks or 5 months). During the workshop it was identified that the true benefit of mass timber construction lies in the early release of follow-on trades. Fit-out of floors starts immediately once the mass timber structural frame is locally complete, whereas a 3 week delay applies with the reinforced concrete frame alternative.

8.3 Development Cost Comparison

A number of industry professionals assisted in the development of a Bill of Quantities for the two commercial developments. Once complete, an analysis was performed comparing the different cost items of the buildings.

A 68% saving was achieved in the foundation and substructure cost of the mass timber frame development which is due to the mass timber frame being 3.6 times lighter than that of the reinforced concrete frame. On the other hand, the structural frame of the mass timber building was approximately 2.2 times more expensive than that of the reinforced concrete frame. This can mainly be ascribed to the high cost of the mass timber as compared to that of the reinforced concrete.

A saving of 19% was achieved in the P&G cost due to the 5 month reduction in construction schedule of the mass timber frame building. The total capital investment required for the mass timber frame and reinforced concrete frame developments was R 115 691 000 and R 105 118 000, respectively. This translates into a 10% increase in cost between the two investments.

The 5 month reduction in construction schedule resulted in savings of R 1 220 000 (45%) in interest incurred during construction for the mass timber frame building. Internal rate of return (IRR) was identified as the primary financial indicator to compare the profitably of the developments as it considers the earlier return of investment achieved for the mass timber frame building. A 5 year IRR of 20.9% and 25.7% was calculated for the mass timber frame and reinforced concrete frame developments, respectively. The reinforced concrete frame building achieved a 4.8% higher 5 year IRR for the base case analysis. Notably, the 5 year IRR of both developments is above the 15% MARR, indicating that they are both financially justified. This is a positive result for both developments, particularly the multi-storey mass timber building in the context of South Africa. It indicates that a multi-storey mass timber building can be financially viable in South Africa provided a number of factors are addressed throughout the entire value chain of the mass timber products.

8.4 Sensitivity Analysis

A number of assumptions regarding certain variables were made throughout the development of the construction schedule and costing procedure. A sensitivity analysis therefore proved useful in determining the effect that these variables had on the profitability of the mass timber frame development.

The construction schedule, rental rate, cost of SA pine, cost of importing the mass timber, and the adjustment of the P&G cost were considered for the analysis. One of the main findings of the analysis was that the mass timber frame building proved to generate a higher 5 year IRR than that of the reinforced concrete frame once the mass timber building achieved a rental premium of 7.8% or more. Research has shown that tenants are willing to pay up to a 13.6% rental premium for green certified buildings in South Africa (SAPOA, 2018). A premium of 13.6% in the rental rate resulted in a 5 year IRR of 30.0%, 4.3% higher than that of the reinforced concrete frame building.

Investigation of the cost of SA pine revealed that a 5% reduction in the cost of SA pine results in a 4% saving in the overall structural cost of the development. This increases the 5 year IRR of the development by 0.7%. On the contrary, a 0.7% decrease in the 5 year IRR was observed for a 5% increase in the cost of SA pine.

Analyses showed that the importation of the mass timber elements remains an expensive option. The imported mass timber frame building achieved a significantly lower 5 year IRR of 16.4% at a R17:€1 exchange rate. A rental premium of 15% managed to improve the 5 year IRR to 24.2%, but this is still 1.5% lower than the 5 year IRR of the reinforced concrete frame building.

8.5 Benefits and Limitations of Building Information Modelling

The project was used as a case study for the implementation of Building Information Modelling (BIM) in order to acquire additional knowledge and skills regarding the development, implementation and use of BIM. In addition to this, observations were made regarding the potential benefits and limitations of BIM throughout the design and project delivery process. A number of the benefits associated with BIM were realised with the main benefits being 3D visualisation and clash detection. However, shortcomings were observed in the all-round implementation of BIM by industry stakeholders. Furthermore, the case study indicated that education regarding BIM in South Africa requires improvement for an improved implementation of BIM within industry.

8.6 Final Remarks

The findings within this dissertation have shown that there is great potential in the multi-storey mass timber building domain in South Africa. The sensitivity analysis showed that the mass timber frame building achieved the same 5 year IRR than the reinforced concrete building once a 7.8% rental premium was added. However, the research has clearly shown that great strides are still required in the forestry sector, mass timber manufacturing sector, as well as the AEC sector before multi-storey commercial mass timber buildings may prove to be more profitable than conventional multi-storey reinforced concrete buildings. Two of the most notable changes include improvement in the sourcing of high-grade structural timber (S7, S10) and investment into equipment that can enable the large-scale production of large beams/columns, typically required in multi-storey mass timber structures. Development and investment of capital and resources is required throughout the entire value chain of mass timber production in order to establish a sustainable multi-storey mass timber market. The future success of mass timber construction in South Africa is thus dependent on the collaboration and teamwork of industry stakeholders and research institutions throughout the public and private domain.

8.7 Recommendations

A number of recommendations can be made as a result of the findings from the research. The recommendations are as follows:

Timber Industry:

- Sustainable large volumes of high-grade structural timber (S7 and S10 SA pine) are required for a growth in the multi-storey mass timber building market. South African plantations and sawmills therefore need to increase their production/sourcing of high-grade timber (S7, S10).

- Current South African manufacturers of mass timber products need to consider investing in larger machinery in order to supply the required dimensions for multi-storey mass timber construction. A lack of investment in this sector may result in the importation of mass timber products being the only viable option in the future.

- Significantly more research is required in the field of multi-storey mass timber buildings. Specifically, in the mechanical performance, fire performance, and seismic performance of mass timber elements produced from South African timber species. Moreover, additional research is required in the connections required in mass timber buildings.

Building Information Modelling:

- Up-to-date, easily accessible South African BIM product libraries are required for easy implementation of BIM. Mass timber suppliers need to contribute to these product libraries to improve efficiency within the design delivery process.

- It was found in this particular study (which is admittedly only a small sample) that the main challenge regarding BIM was education. Education of BIM throughout South Africa in all industries requires improvement in order to assist industry stakeholders with understanding the concept of BIM and to assist in the implementation thereof.

Architecture and Engineering Sector:

- South Africa requires more architects and structural engineers who are familiar with the design of multi-storey mass timber buildings. A review of the South African timber design codes is required to incorporate the design of CLT structures. Furthermore, the mechanical properties of South African CLT, glulam, LVL, and PSL products need to be added.

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10 Appendix A - Processing Chain of Timber Products

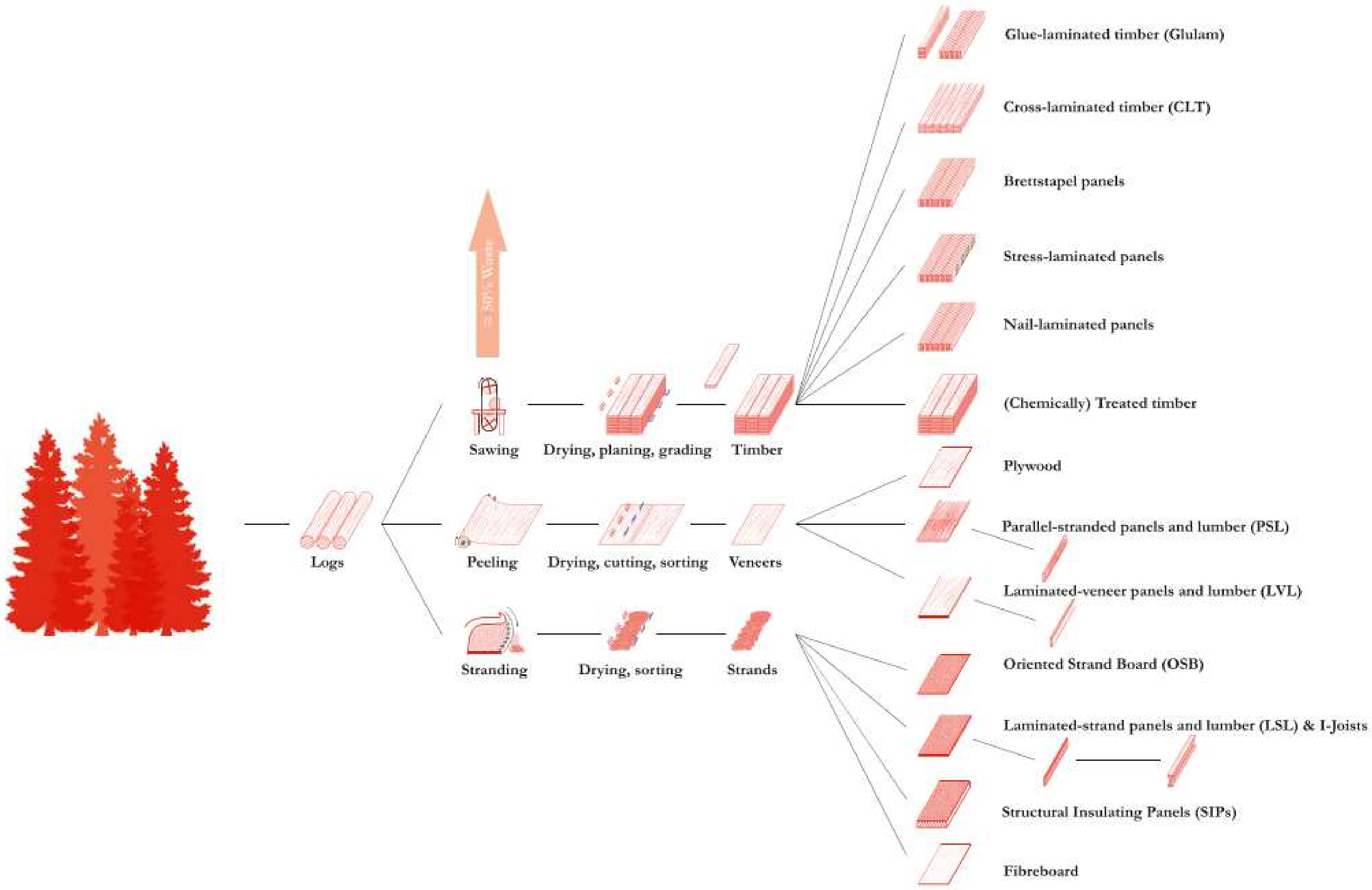
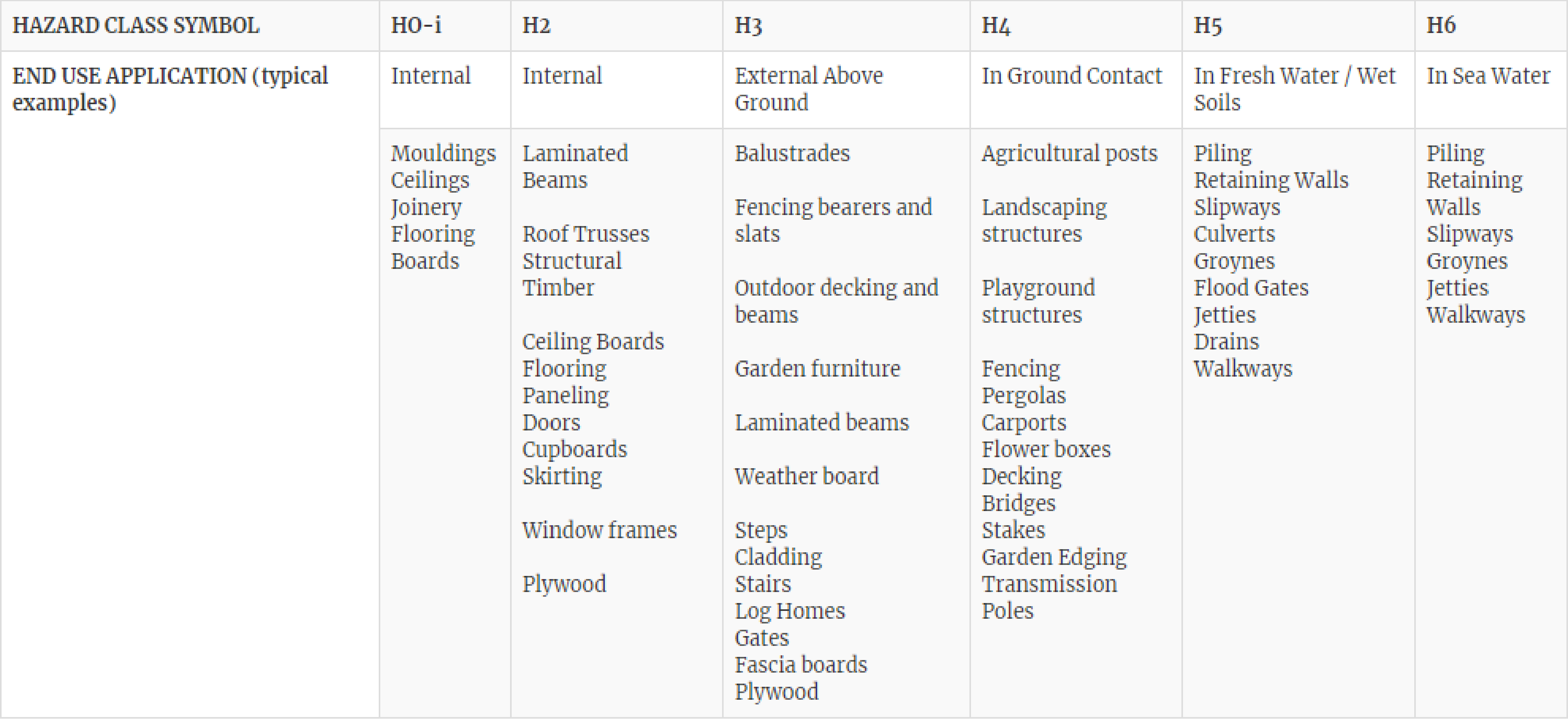


Figure 10.1: Processing chain for timber products (Ramage *et al.*, 2017)

11 Appendix B - Hazard Classification System

Table 11.1: South African Hazard Classification Categories (SAWPA, 2019b)



HAZARD CLASS SYMBOL	H0-i	H2	H3	H4	H5	H6
END USE APPLICATION (typical examples)	Internal	Internal	External Above Ground	In Ground Contact	In Fresh Water / Wet Soils	In Sea Water
	Mouldings Ceilings Joinery Flooring Boards	Laminated Beams Roof Trusses Structural Timber Ceiling Boards Flooring Paneling Doors Cupboards Skirting Window frames Plywood	Balustrades Fencing bearers and slats Outdoor decking and beams Garden furniture Laminated beams Weather board Steps Cladding Stairs Log Homes Gates Fascia boards Plywood	Agricultural posts Landscaping structures Playground structures Fencing Pergolas Carports Flower boxes Decking Bridges Stakes Garden Edging Transmission Poles	Piling Retaining Walls Slipways Culverts Groynes Flood Gates Jetties Drains Walkways	Piling Retaining Walls Slipways Groynes Jetties Walkways

12 Appendix C - Brock Commons Tallwood House

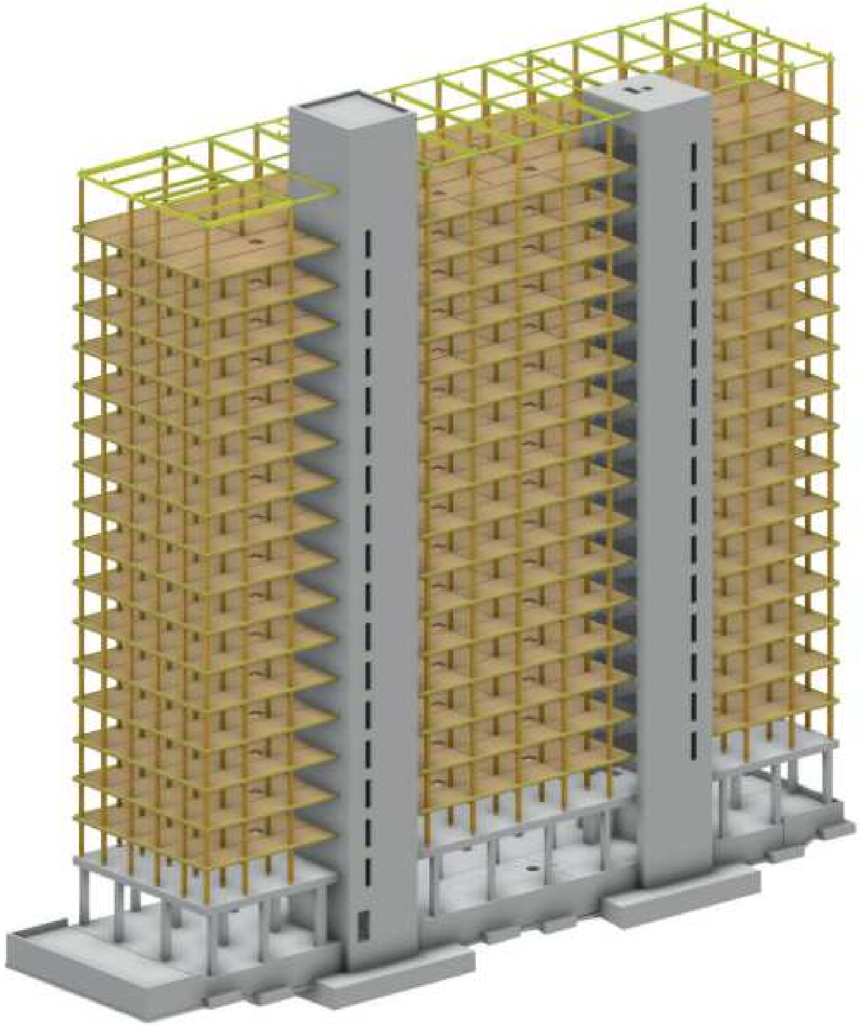
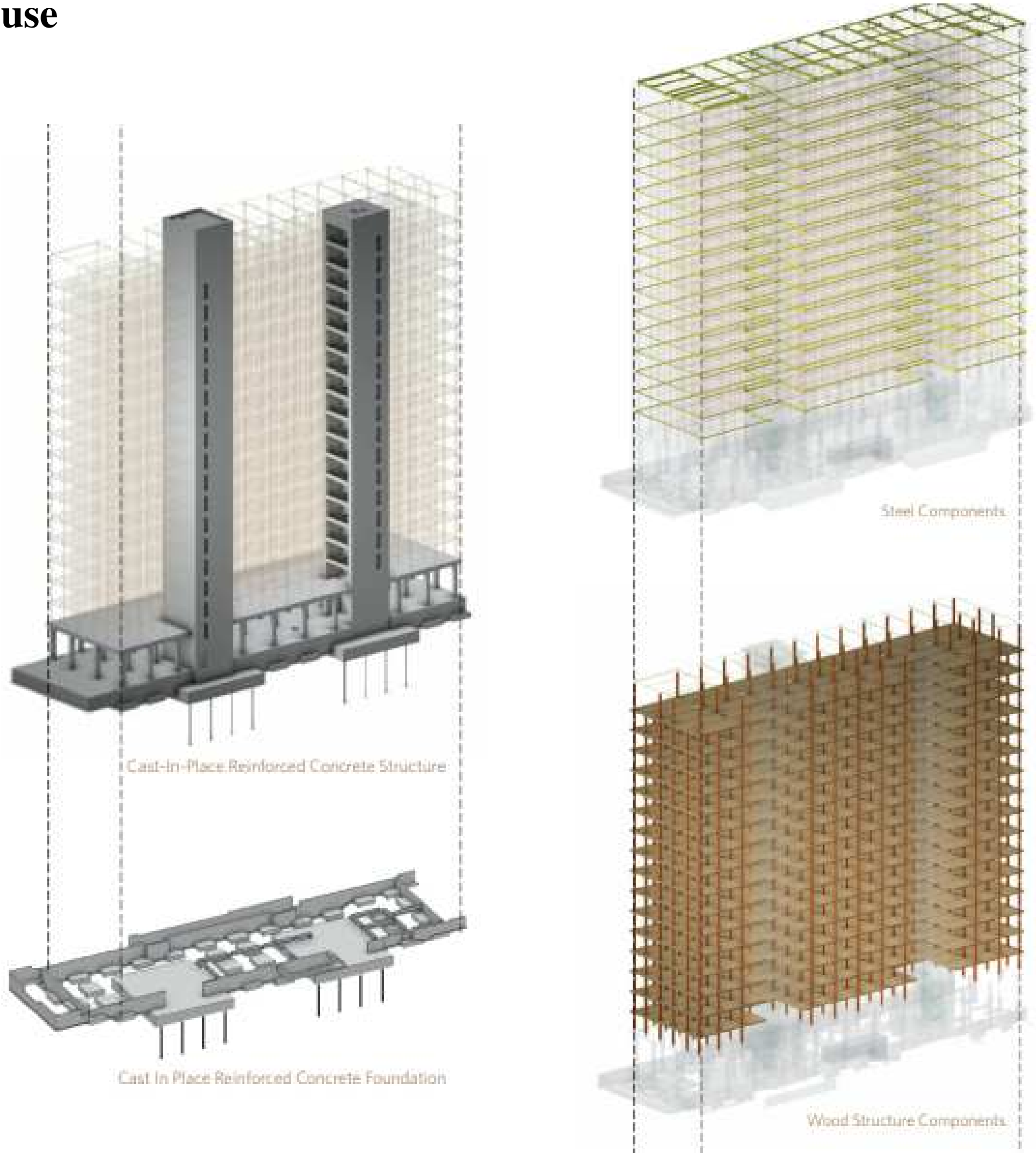


Figure 11.1: 3D Render of BCTH (Pilon et al., 2016b)



13 Appendix D - Mjostarnet

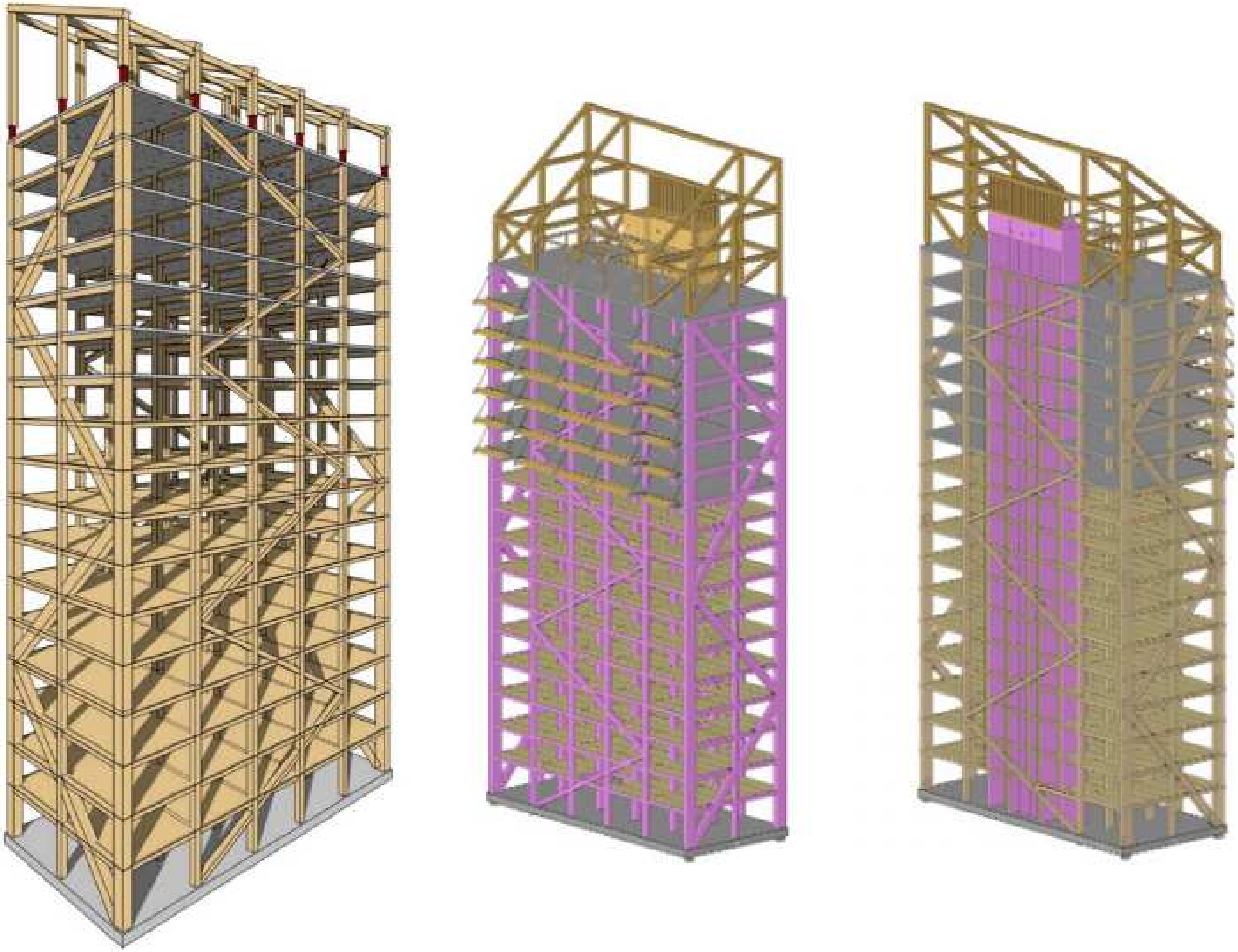


Figure 13.1: 3D Render of Mjostarnet (Abrahamsen, 2018)

Appendix E: Design of Timber Elements for S7 Grade

Properties

$f_y := 350\ \text{MPa}$

$E_{mean} := 9.6\ \text{GPa}$ Stiffness value for deformation calculations

$E_{0.05} := 5.7\ \text{GPa}$ Stiffness value for capacity analysis

$G := 77 \cdot 10^3\ \text{MPa}$

$l := 6000\ \text{mm}$ Span of CLT flooring system

$\rho_{screed} := 23\ \frac{\text{kN}}{\text{m}^3}$ $t_{screed} := 50\ \text{mm}$ Screed Properties

$\rho_{CLT} := 470\ \frac{\text{kg}}{\text{m}^3} \cdot 9.81\ \frac{\text{m}}{\text{s}^2} = 4.6107\ \frac{\text{kN}}{\text{m}^3}$ $t_{CLT} := 220\ \text{mm}$ CLT Properties

Loading Calculations:

$G_{k\_slab} := \rho_{screed} \cdot t_{screed} + \rho_{CLT} \cdot t_{CLT}$ 220L75-2 CLT dead weight plus screed

$G_{k\_slab} = 2.1644\ \text{kPa}$

$G_{k\_ceiling\_services} := 0.3\ \text{kPa}$

$G_{k\_tiles} := 0.22\ \text{kPa}$ dead load of vinyl tiles

$G_k := G_{k\_slab} + G_{k\_ceiling\_services} + G_{k\_tiles} = 2.6844\ \text{kPa}$

$Q_k := 2.5\ \text{kPa}$ As per SANS 10160-2

$h_{beam} := 630\ \text{mm}$ $b_{beam} := 240\ \text{mm}$ $\rho_{beam} := 420\ \frac{\text{kg}}{\text{m}^3} \cdot 9.81\ \frac{\text{m}}{\text{s}^2} = 4.1202\ \frac{\text{kN}}{\text{m}^3}$

Ultimate limit state: Imposed Load Leading

$w_{ULS\_slab} := 1.2 \cdot G_k + 1.6 \cdot Q_k = 7.2212\ \frac{\text{kN}}{\text{m}^2}$

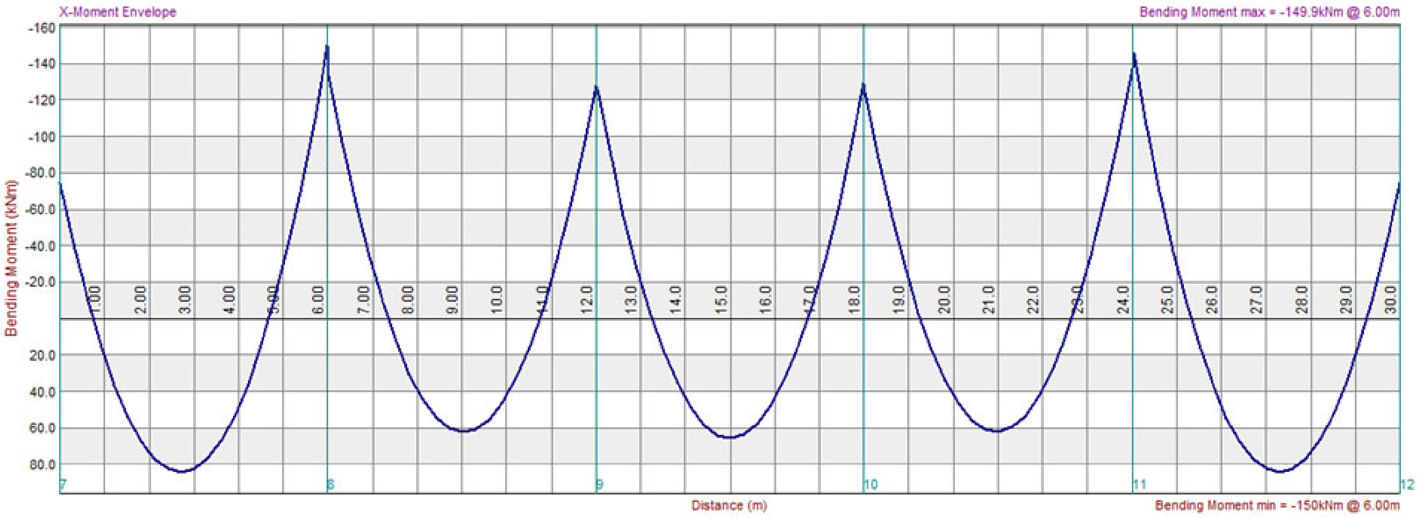
$R_{ULS\_slab} := \left(\frac{w_{ULS\_slab} \cdot l}{2}\right) \cdot 2 = 43.3273\ \frac{\text{kN}}{\text{m}}$ Loading on beam from slab

$R_{beam} := \rho_{beam} \cdot h_{beam} \cdot b_{beam} = 0.623\ \frac{\text{kN}}{\text{m}}$ Dead weight of beam

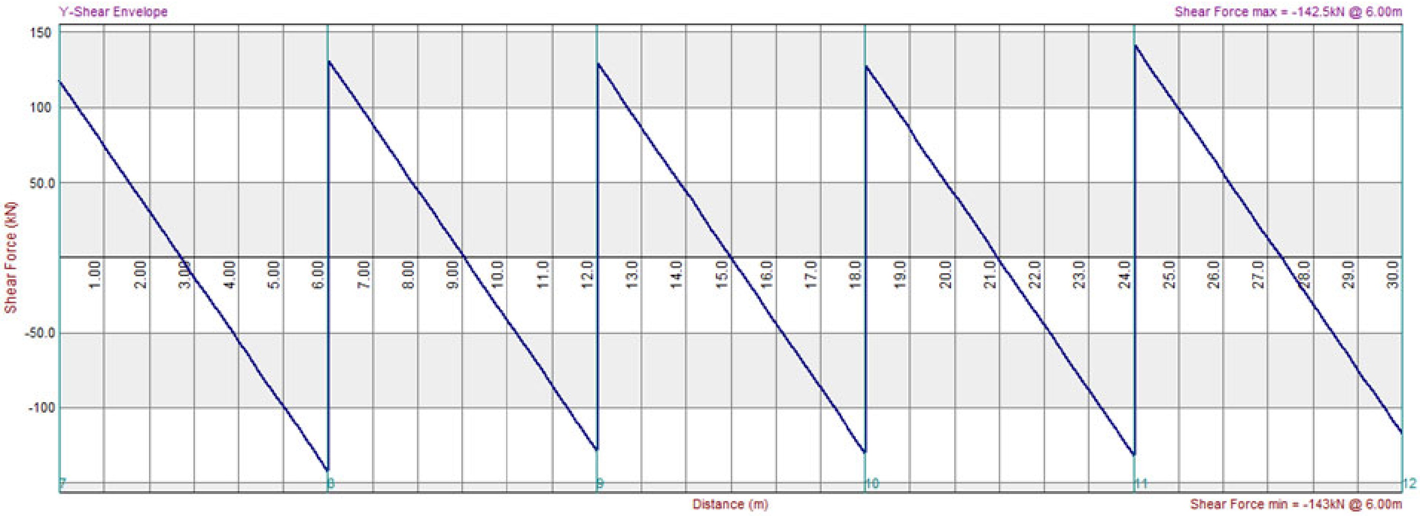
$w_{ULS} := 1.2 \cdot R_{beam} + R_{ULS\_slab} = 44.0749\ \frac{\text{kN}}{\text{m}}$ Factored Line load on beam

Assumption:

The beam-column connections are assumed to be fixed connections



$M_{ULS\_spanning} := 150\ \text{kN m}$ $\qquad$ $M_{ULS\_hogging} := 150\ \text{kN m}$



$V_{D\_ULS} := 143\ \text{kN}$

However, this is at the center on the column. Shear failure would occur at the column face.

The column face is a distance of 200mm, 175mm and 150mm from the column centerline

At 150mm away $\quad V_{D\_ULS} := 136\ \text{kN}$

At 175mm away $\quad V_{D\_ULS} := 135\ \text{kN}$

At 200mm away $\quad V_{D\_ULS} := 134\ \text{kN}$

Serviceability Limit State

$$w_{SLS\_slab} := 1.1 \cdot G_k + 1.0 \cdot Q_k = 5.4528\ \frac{\text{kN}}{\text{m}^2}$$

$$R_{SLS\_slab} := \left(\frac{w_{SLS\_slab} \cdot l}{2} \right) \cdot 2 = 32.7167\ \frac{\text{kN}}{\text{m}}$$

$$w_{SLS} := 1.1 \cdot R_{beam} + 1.0 \cdot R_{SLS\_slab} = 33.402\ \frac{\text{kN}}{\text{m}}$$

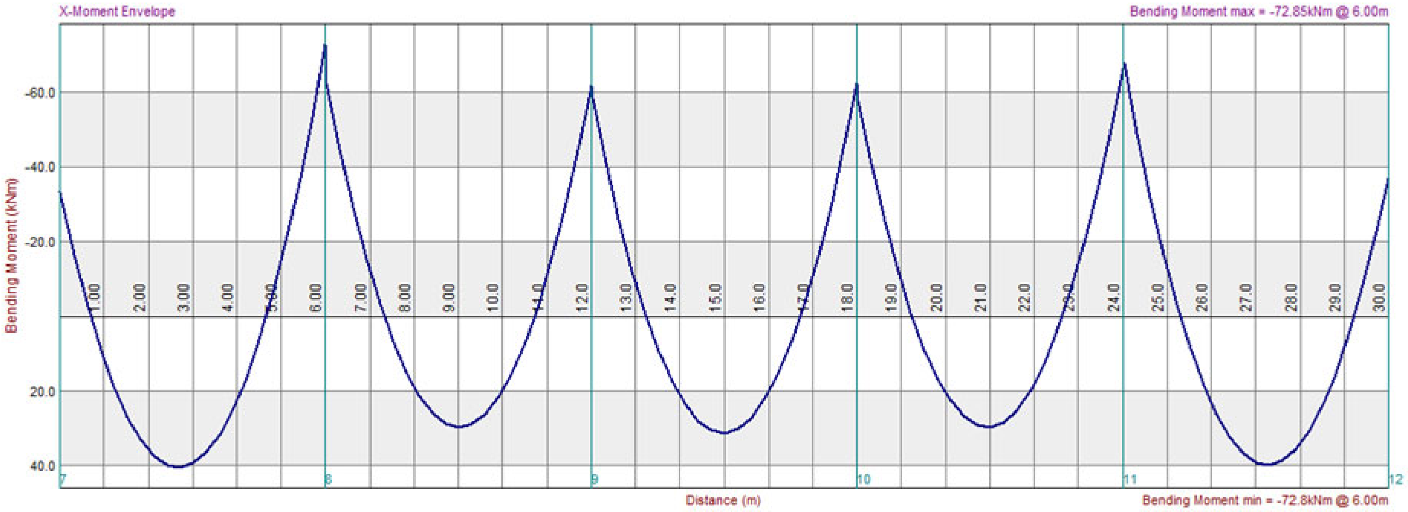
Design Moment for Fire Loading

$w_{fire\_slab} := 1.0 \cdot G_k + 0.5 \cdot Q_k = 3.9344 \ \frac{kN}{m^2}$

Partial factors in accordance with Eurocode.

$R_{fire\_slab} := \left(\frac{w_{fire\_slab} \cdot l}{2} \right) \cdot 2 = 23.6061 \ \frac{kN}{m}$

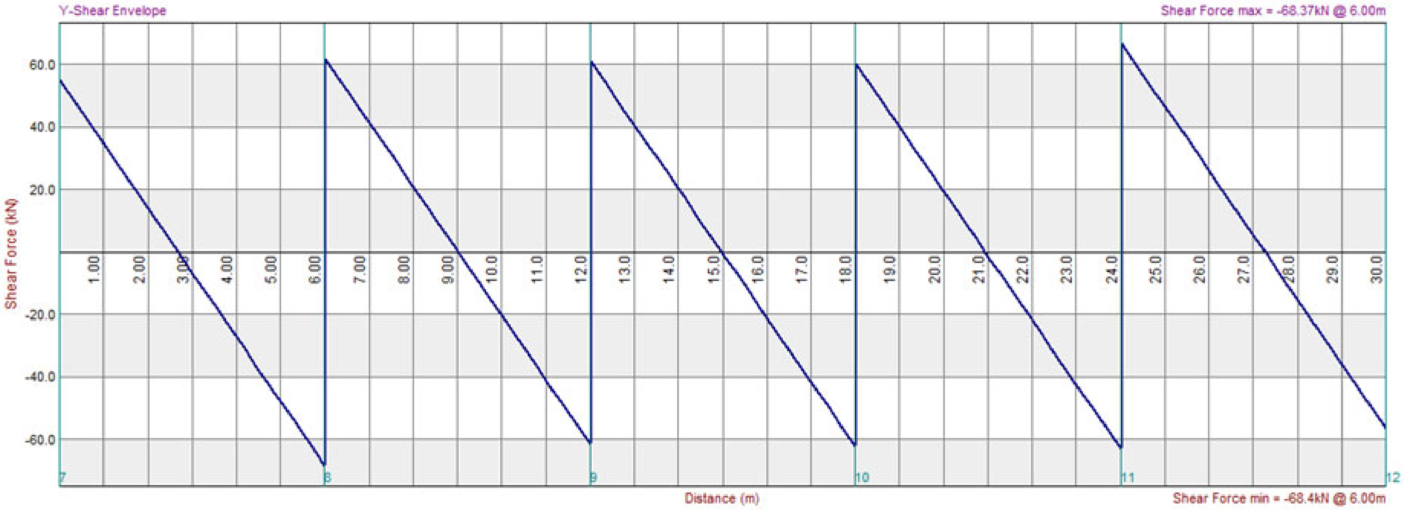
$w_{fire} := 1.0 \cdot R_{beam} + 1.0 \cdot R_{fire\_slab} = 24.2291 \ \frac{kN}{m}$



$M_{fire\_spanning} := 73 \ kN \ m$

Max Design Moment at fire

$M_{fire\_hogging} := 73 \ kN \ m$



$V_{D\_fire} := 68 \ kN$

1.Design Strength in ULS

$f_{d\_comp} := \frac{\left(k_{mod} \cdot f_{k\_comp}\right)}{\gamma_M}$ Service Class 1 is for elements in indoor environment

$\gamma_M := 1.25$ ULS partial coefficient from Table 3.1, Glued laminated timber

$k_{mod} := 0.8$ Strength modification factor from Table 3.2, medium term load

$f_{k\_comp} := 22.8\ \text{MPa}$ From SANS 10163-1 Table N.1

$f_{d\_comp} = 14.592\ \text{MPa}$ Design compression parallel to grain

2.Final Modulus of Elasticity

$E_{meanfinal} := \frac{E_{mean}}{1 + \psi_2 \cdot k_{def}}$

$E_{mean} = 9.6\ \text{GPa}$ Stiffness values for deformation calculations

$\psi_2 := 0.3$ Offcie areas from Table 2.2

$k_{def} := 0.6$ Factor accounting for moisture from Table 9.1

$E_{meanfinal} = 8.1356\ \text{GPa}$

SLS Deflection Check:

$b_{beam} = 240\ \text{mm}$ $h_{beam} = 630\ \text{mm}$

$I_{beam} := \frac{1}{12} \cdot b_{beam} \cdot h_{beam}^{3} = 5.0009 \cdot 10^{9}\ \text{mm}^{4}$

$\Delta := 0.0065 \cdot \frac{w_{SLS} \cdot l^{4}}{E_{meanfinal} \cdot I_{beam}} = 6.9159\ \text{mm}$ Deflection for 4 span continous beam (SAISC Red Book)

$\frac{l}{500} = 12\ \text{mm}$ Rigid floor Eurocode 0 $\frac{l}{500} > \Delta$ SLS deflection requirements satisfied

3.1 Bending Resistance at ambient

$f_{m\_k} := 15.8\ \text{MPa}$ From SANS 10163-1 Table N.1

$l_{ef} := 0.9 \cdot l = 5.4\ \text{m}$ Effective length as a ratio of the span

$f_{m\_d} := \frac{\left(k_{mod} \cdot f_{m\_k}\right)}{\gamma_M} = 10.112\ \text{MPa}$ Design bending strength

$y := \frac{h_{beam}}{2} = 315\ \text{mm}$ Assume slab provides suffcient lateral support

$W := \frac{I_{beam}}{y} = 1.5876 \cdot 10^{7}\ \text{mm}^{3}$ Section modulus about the strong axis

$\sigma_{m\_crit} := \frac{0.78 \cdot b_{beam}^{2}}{h_{beam} \cdot l_{ef}} \cdot E_{0.05} = 75.2762\ \text{MPa}$

$\lambda_{relm} := \sqrt{\dfrac{f_{m\_k}}{\sigma_{m\_crit}}} = 0.4581$ $\lambda_{relm} < 0.75$ Therefore $k_{crit} := 1$

$M_{Rd} := f_{m\_d} \cdot W \cdot k_{crit} = 160.5381\ \text{kN m}$ $M_{ULS\_spanning} = 150\ \text{kN m}$ $M_{Rd} > M_{ULS\_spanning}$

$M_{Rd} > M_{ULS\_hogging}$

3.2 Bending Resistance after 60 min standard fire

$\beta_n := 0.7\ \dfrac{\text{mm}}{\text{min}}$ Glulam Charring Rate

$t := 60\ \text{min}$ SANS 10144-2 for offices between 3 to 10 storeys

$c := \beta_n \cdot t = 42\ \text{mm}$ $z := 7\ \text{mm}$ Zero Thickness layer

$h_f := h_{beam} - c - z = 581\ \text{mm}$

Burning from 3 sides (Bottom,Left Side, Right Side)

$b_f := b_{beam} - 2 \cdot c - 2 \cdot z = 142\ \text{mm}$

$y_{fire} := \dfrac{h_f}{2} = 290.5\ \text{mm}$ Assume slab provides sufficient lateral support

$I_{fire} := \dfrac{1}{12} \cdot b_f \cdot h_f^{\,3} = 2.3208 \cdot 10^{9}\ \text{mm}^{4}$

$W_{fire} := \dfrac{I_{fire}}{y_{fire}} = 7.9889 \cdot 10^{6}\ \text{mm}^{3}$ Section modulus about the strong axis

$\sigma_{m\_crit\_fire} := \dfrac{0.78 \cdot b_f^{\,2}}{h_f \cdot l_{ef}} \cdot E_{0.05} = 28.5743\ \text{MPa}$

$\lambda_{relm\_fire} := \sqrt{\dfrac{f_{m\_k}}{\sigma_{m\_crit\_fire}}} = 0.7436$ $\lambda_{relm} < 0.75$ Therefore $k_{crit} := 1$

$M_{Rd\_fire} := f_{m\_k} \cdot W_{fire} \cdot k_{crit} = 126.2253\ \text{kN m}$ $M_{fire\_spanning} = 73\ \text{kN m}$ $M_{Rd\_fire} > M_{fire\_spanning}$

$M_{fire\_hogging} = 73\ \text{kN m}$ $M_{Rd\_fire} > M_{fire\_hogging}$

4.1 Shear Resistance at ambient

$f_{v\_k} := 2.0\ \text{MPa}$ From SANS 10163-1 Table N.1

$f_{v\_d} := \dfrac{f_{v\_k}}{\gamma_M} \cdot k_{mod} = 1.28\ \text{MPa}$ ULS Design shear strength

$A := b_{beam} \cdot h_{beam} = 1.512 \cdot 10^{5}\ \text{mm}^{2}$ Shear capacity at ULS

$V_{Rd} := A \cdot \dfrac{f_{v\_d}}{1.5} = 129.024\ \text{kN}$ $V_{D\_ULS} = 134\ \text{kN}$ Not Okay(discussed in Section 4.3.3)

4.2 Shear resistance after 60 min standard fire

$V_{Rd\_fire} := h_f \cdot b_f \cdot \dfrac{f_{v\_d}}{1.5} = 70.4017\ \text{kN}$ $V_{D\_fire} = 68\ \text{kN}$ $V_{Rd\_fire} > V_{D\_fire}$ Okay

5 Compression in Ground floor column at Ambient

$E_{0.05} = 5.7\ \text{GPa}$ $f_{k\_comp} = 22.8\ \text{MPa}$ $f_{d\_comp} = 14.592\ \text{MPa}$ $l_e := 3.5\ \text{m}$ Column Height

$h_{col} := 400\ \text{mm}$ $b_{col} := 400\ \text{mm}$ $I_{col} := \frac{1}{12} \cdot h_{col} \cdot b_{col}^{\ 3}$ $A_{col} := h_{col} \cdot b_{col}$

$\rho_{column} := 420\ \frac{\text{kg}}{\text{m}^3} \cdot 9.81\ \frac{\text{m}}{\text{s}^2} = 4.1202\ \frac{\text{kN}}{\text{m}^3}$ $l := 6\ \text{m}$

$R_{column} := \rho_{column} \cdot h_{col} \cdot b_{col} \cdot l_e = 2.3073\ \text{kN}$ Weight of a single column

$N_{ULS\_ground\_floor} := \frac{w_{ULS} \cdot l}{2} \cdot 2 \cdot 8 + 1.2 \cdot R_{column} \cdot 8 = 2137.7463\ \text{kN}$

5.1 Capacity of Ground Floor Column at ambient

$i := \sqrt{\frac{I_{col}}{A_{col}}}$

$\lambda := \frac{l_e}{i} = 30.3109$ Slenderness Ratio

$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{k\_comp}}{E_{0.05}}} = 0.6102$

$\beta_c := 0.1$ Initial out of straightness parameter

$k := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^{\ 2}\right) = 0.7017$

$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^{\ 2}}} = 0.9541$ for $\lambda_{rel} > 0.3$ Instability Factors

$N_{Rd} := f_{d\_comp} \cdot A_{col} \cdot k_c = 2227.5439\ \text{kN}$ $N_{Rd} > N_{ULS\_ground\_floor}$ Okay at ambient for ground floor

$N_{ULS\_ground\_floor} = 2137.7463\ \text{kN}$

5.2 Compression in ground floor column after 60min standard fire

$N_{fire\_ground\_floor} := \frac{w_{fire} \cdot l}{2} \cdot 2 \cdot 8 + 1.0 \cdot R_{column} \cdot 8 = 1181.4552\ \text{kN}$

$\beta_n := 0.7\ \frac{\text{mm}}{\text{min}}$ Glulam Charring Rate $t = 60\ \text{min}$ Fire rating as per SANS 10400-T

$c := \beta_n \cdot t = 42\ \text{mm}$ $z = 7\ \text{mm}$ Zero Strength Thickness Layer

$h_f := h_{col} - 2 \cdot c - 2 \cdot z = 302\ \text{mm}$

Burning from 4 sides

$b_f := b_{col} - 2 \cdot c - 2 \cdot z = 302\ \text{mm}$

$I_f := \frac{1}{12} \cdot h_f \cdot b_f^{\ 3}$ $A_f := h_f \cdot b_f$

$i_f := \sqrt{\frac{I_f}{A_f}}$

$\lambda_f := \frac{l_e}{i_f} = 40.1469$

$\lambda_{f\_rel} := \frac{\lambda_f}{\pi} \cdot \sqrt{\frac{f_{k\_comp}}{E_{0.05}}} = 0.8082$ $\lambda_{rel} > 0.3$ Slenderness Ratio at FLS

$k_f := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{f\_rel} - 0.3\right) + \lambda_{f\_rel}^{\ 2}\right) = 0.852$

$k_{f\_c} := \frac{1}{k_f + \sqrt{k_f^{\ 2} - \lambda_{f\_rel}^{\ 2}}} = 0.8915$ Instability Factors

$\beta_c := 0.1$ Initial out of straightness parameter

$f_{comp\_fire} := f_{k\_comp} = 22.8\ \text{MPa}$

$N_{Rd\_fire} := f_{comp\_fire} \cdot A_f \cdot k_{f\_c} = 1853.8566\ \text{kN}$ $N_{Rd\_fire} > N_{fire\_ground\_floor}$ Okay

$N_{fire\_ground\_floor} = 1181.4552\ \text{kN}$

5.3 Capacity of Third Floor Column at ambient

$N_{ULS\_third\_floor} := \frac{w_{ULS} \cdot l}{2} \cdot 2 \cdot 6 + 1.2 \cdot R_{column} \cdot 6 = 1603.3097\ \text{kN}$

$b_{col} := 350\ \text{mm}$ $h_{col} := 350\ \text{mm}$

$I_{col} := \frac{1}{12} \cdot h_{col} \cdot b_{col}^{\ 3}$ $A_{col} := h_{col} \cdot b_{col}$

$\text{i} := \sqrt{\frac{I_{col}}{A_{col}}}$

$\lambda := \frac{l_e}{\text{i}} = 34.641$ Slenderness Ratio

$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{k\_comp}}{E_{0.05}}} = 0.6974$

$\beta_c := 0.1$ Initial out of straightness parameter

$k := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^{\ 2}\right) = 0.763$

$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^{\ 2}}} = 0.9322$ for $\lambda_{rel} > 0.3$ Instability Factors

$N_{Rd} := f_{d\_comp} \cdot A_{col} \cdot k_c = 1666.3773\ \text{kN}$ $N_{Rd} > N_{ULS\_third\_floor}$ Okay at ambient for 3rd floor

$N_{ULS\_third\_floor} = 1603.3097\ \text{kN}$

5.4 Compression in ground floor column after 60min standard fire

$$N_{fire\_third\_floor} := \frac{w_{fire} \cdot l}{2} \cdot 2 \cdot 6 + 1.0 \cdot R_{column} \cdot 6 = 886.0914\ \text{kN}$$

$\beta_n := 0.7\ \frac{\text{mm}}{\text{min}}$ Glulam Charring Rate $t = 60\ \text{min}$ Fire rating as per SANS 10100-T

$c := \beta_n \cdot t = 42\ \text{mm}$ $z = 7\ \text{mm}$ Zero Strength Thickness Layer

$h_f := h_{col} - 2 \cdot c - 2 \cdot z = 252\ \text{mm}$

Burning from 4 sides

$b_f := b_{col} - 2 \cdot c - 2 \cdot z = 252\ \text{mm}$

$I_f := \frac{1}{12} \cdot h_f \cdot b_f^{\ 3}$ $A_f := h_f \cdot b_f$

$$i_f := \sqrt{\frac{I_f}{A_f}}$$

$$\lambda_f := \frac{l_e}{i_f} = 48.1125$$

$$\lambda_{f\_rel} := \frac{\lambda_f}{\pi} \cdot \sqrt{\frac{f_{k\_comp}}{E_{0.05}}} = 0.9686$$ $\lambda_{rel} > 0.3$

Slenderness Ratio at FLS

$$k_f := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{f\_rel} - 0.3\right) + \lambda_{f\_rel}^{\ 2}\right) = 1.0025$$

$$k_{f\_c} := \frac{1}{k_f + \sqrt{k_f^{\ 2} - \lambda_{f\_rel}^{\ 2}}} = 0.793$$

Instability Factors

$\beta_c := 0.1$ Initial out of straightness parameter

$f_{comp\_fire} := f_{k\_comp} = 22.8\ \text{MPa}$

$N_{Rd\_fire} := f_{comp\_fire} \cdot A_f \cdot k_{f\_c} = 1148.1255\ \text{kN}$ $N_{Rd\_fire} > N_{fire\_third\_floor}$ Okay

$N_{fire\_third\_floor} = 886.0914\ \text{kN}$

5.5 Capacity of Sixth Floor Column at ambient

$$N_{ULS\_sixth\_floor} := \frac{w_{ULS} \cdot l}{2} \cdot 2 \cdot 3 + 1.2 \cdot R_{column} \cdot 3 = 801.6548\ \text{kN}$$

$b_{col} := 300\ \text{mm}$ $h_{col} := 300\ \text{mm}$

$I_{col} := \frac{1}{12} \cdot h_{col} \cdot b_{col}^{\ 3}$ $A_{col} := h_{col} \cdot b_{col}$

$i := \sqrt{\frac{I_{col}}{A_{col}}}$

$\lambda := \frac{l_e}{i} = 40.4145$ Slenderness Ratio

$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{k\_comp}}{E_{0.05}}} = 0.8136$

$\beta_c := 0.1$ Initial out of straightness parameter

$k := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^{\;2}\right) = 0.8567$

$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^{\;2}}} = 0.889$ for $\lambda_{rel} > 0.3$ Instability Factors

$N_{Rd} := f_{d\_comp} \cdot A_{col} \cdot k_c = 1167.5495\ \mathrm{kN}$ $N_{Rd} > N_{ULS\_sixth\_floor}$ Okay at ambient for 6th floor

$N_{ULS\_sixth\_floor} = 801.6548\ \mathrm{kN}$

5.6 Compression in ground floor column after 60min standard fire

$N_{fire\_sixth\_floor} := \frac{w_{fire} \cdot l}{2} \cdot 2 \cdot 3 + 1.0 \cdot R_{column} \cdot 3 = 443.0457\ \mathrm{kN}$

$\beta_n := 0.7\ \frac{\mathrm{mm}}{\mathrm{min}}$ Glulam Charring Rate $t = 60\ \mathrm{min}$

$c := \beta_n \cdot t = 42\ \mathrm{mm}$ $z = 7\ \mathrm{mm}$ Zero Strength Thickness Layer

$h_f := h_{col} - 2 \cdot c - 2 \cdot z = 202\ \mathrm{mm}$

Burning from 4 sides

$b_f := b_{col} - 2 \cdot c - 2 \cdot z = 202\ \mathrm{mm}$

$I_f := \frac{1}{12} \cdot h_f \cdot b_f^{\;3}$ $A_f := h_f \cdot b_f$

$i_f := \sqrt{\frac{I_f}{A_f}}$

$\lambda_f := \frac{l_e}{i_f} = 60.0216$

$\lambda_{f\_rel} := \frac{\lambda_f}{\pi} \cdot \sqrt{\frac{f_{k\_comp}}{E_{0.05}}} = 1.2083$ $\lambda_{rel} > 0.3$

$k_f := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{f\_rel} - 0.3\right) + \lambda_{f\_rel}^{\;2}\right) = 1.2755$

$k_{f\_c} := \frac{1}{k_f + \sqrt{k_f^{\;2} - \lambda_{f\_rel}^{\;2}}} = 0.5939$ Instability Factors

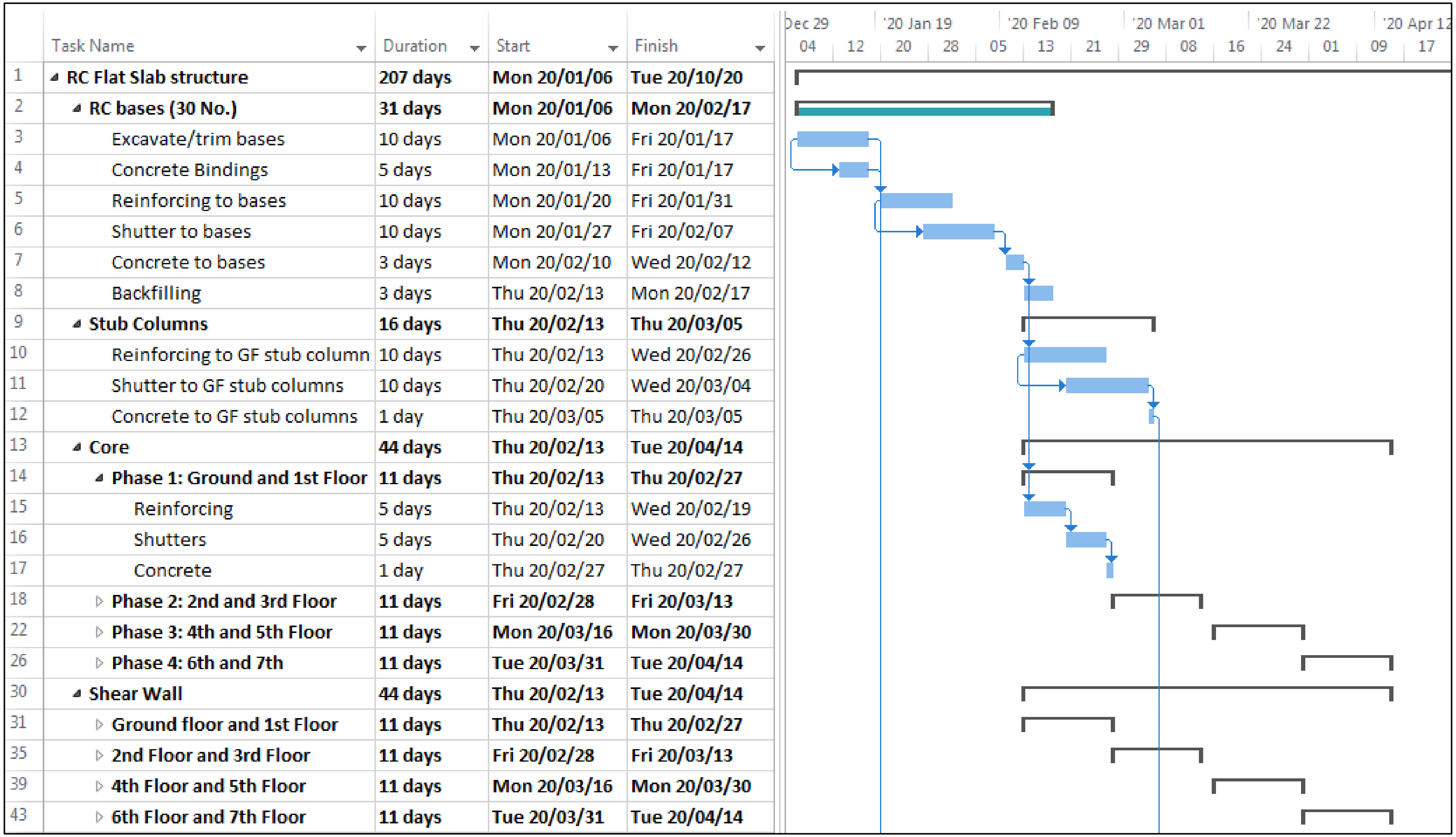
$\beta_c := 0.1$ Initial out of straightness parameter

$f_{comp\_fire} := f_{k\_comp} = 22.8$ MPa

$N_{Rd\_fire} := f_{comp\_fire} \cdot A_f \cdot k_{f\_c} = 552.5343$ kN $N_{Rd\_fire} > N_{fire\_sixth\_floor}$ Okay

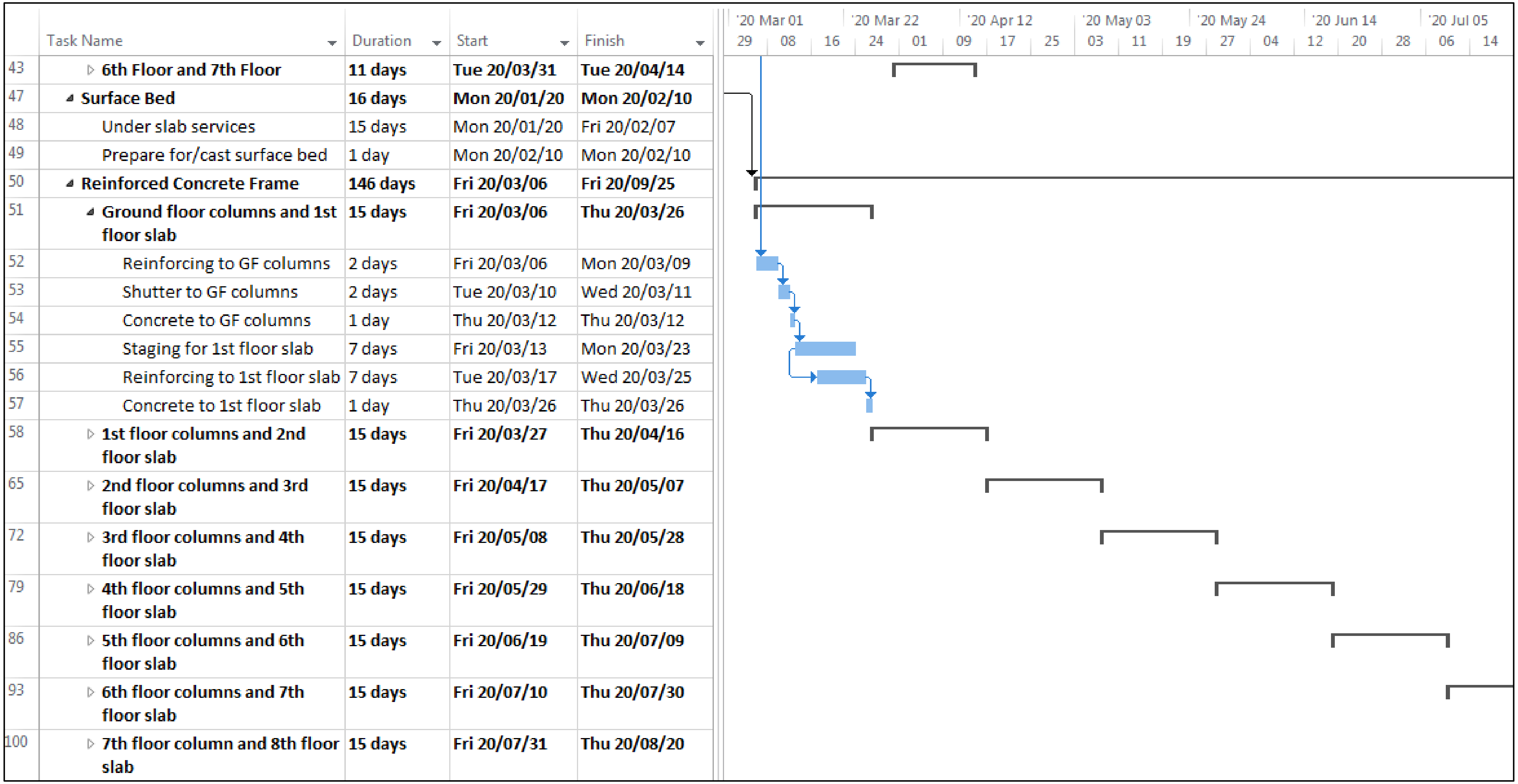
$N_{fire\_sixth\_floor} = 443.0457$ kN

15 Appendix F - Construction Schedule

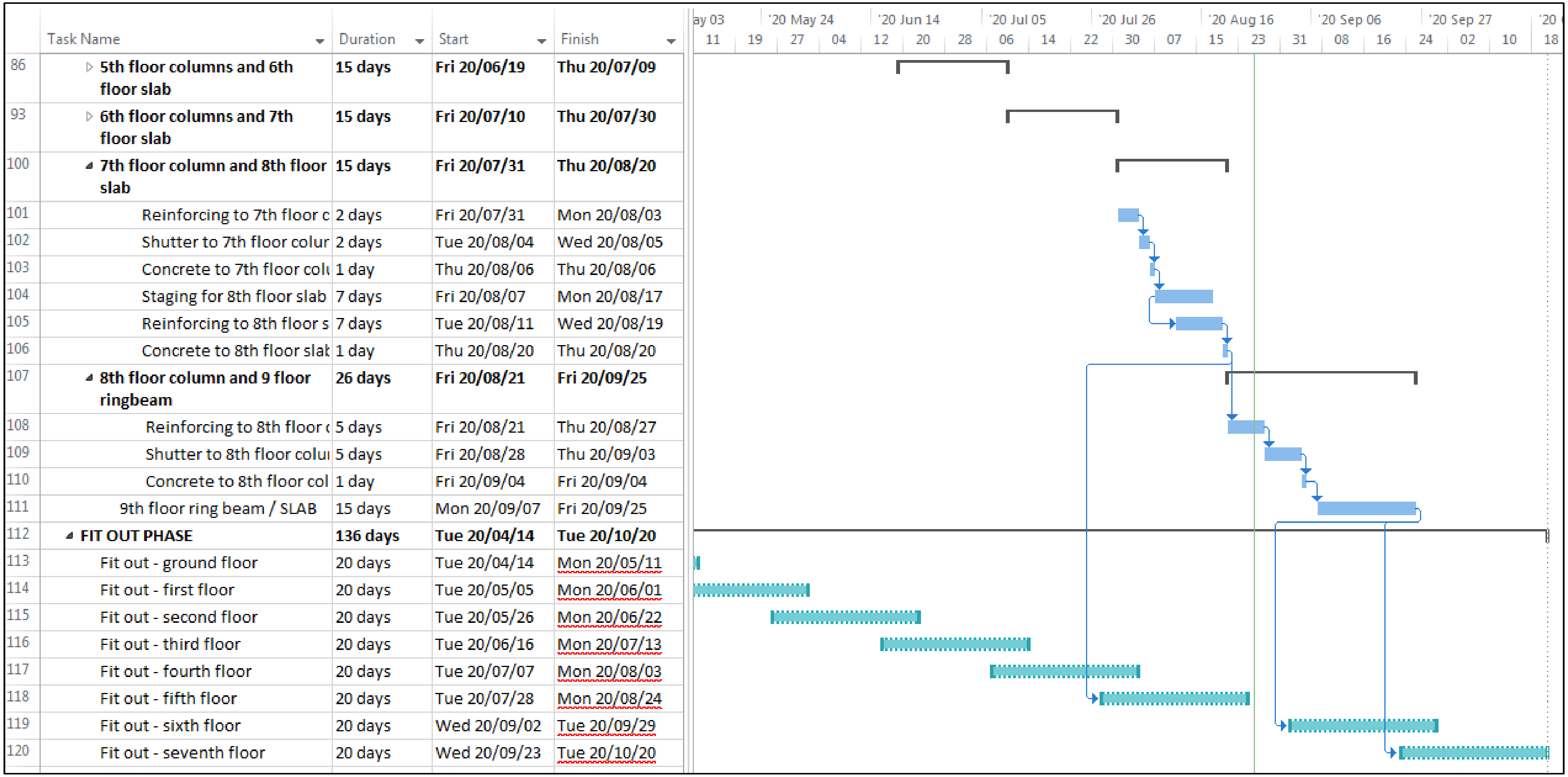


	Task Name	Duration	Start	Finish
1	**RC Flat Slab structure**	**207 days**	**Mon 20/01/06**	**Tue 20/10/20**
2	**RC bases (30 No.)**	**31 days**	**Mon 20/01/06**	**Mon 20/02/17**
3	Excavate/trim bases	10 days	Mon 20/01/06	Fri 20/01/17
4	Concrete Bindings	5 days	Mon 20/01/13	Fri 20/01/17
5	Reinforcing to bases	10 days	Mon 20/01/20	Fri 20/01/31
6	Shutter to bases	10 days	Mon 20/01/27	Fri 20/02/07
7	Concrete to bases	3 days	Mon 20/02/10	Wed 20/02/12
8	Backfilling	3 days	Thu 20/02/13	Mon 20/02/17
9	**Stub Columns**	**16 days**	**Thu 20/02/13**	**Thu 20/03/05**
10	Reinforcing to GF stub column	10 days	Thu 20/02/13	Wed 20/02/26
11	Shutter to GF stub columns	10 days	Thu 20/02/20	Wed 20/03/04
12	Concrete to GF stub columns	1 day	Thu 20/03/05	Thu 20/03/05
13	**Core**	**44 days**	**Thu 20/02/13**	**Tue 20/04/14**
14	**Phase 1: Ground and 1st Floor**	**11 days**	**Thu 20/02/13**	**Thu 20/02/27**
15	Reinforcing	5 days	Thu 20/02/13	Wed 20/02/19
16	Shutters	5 days	Thu 20/02/20	Wed 20/02/26
17	Concrete	1 day	Thu 20/02/27	Thu 20/02/27
18	**Phase 2: 2nd and 3rd Floor**	**11 days**	**Fri 20/02/28**	**Fri 20/03/13**
22	**Phase 3: 4th and 5th Floor**	**11 days**	**Mon 20/03/16**	**Mon 20/03/30**
26	**Phase 4: 6th and 7th**	**11 days**	**Tue 20/03/31**	**Tue 20/04/14**
30	**Shear Wall**	**44 days**	**Thu 20/02/13**	**Tue 20/04/14**
31	**Ground floor and 1st Floor**	**11 days**	**Thu 20/02/13**	**Thu 20/02/27**
35	**2nd Floor and 3rd Floor**	**11 days**	**Fri 20/02/28**	**Fri 20/03/13**
39	**4th Floor and 5th Floor**	**11 days**	**Mon 20/03/16**	**Mon 20/03/30**
43	**6th Floor and 7th Floor**	**11 days**	**Tue 20/03/31**	**Tue 20/04/14**

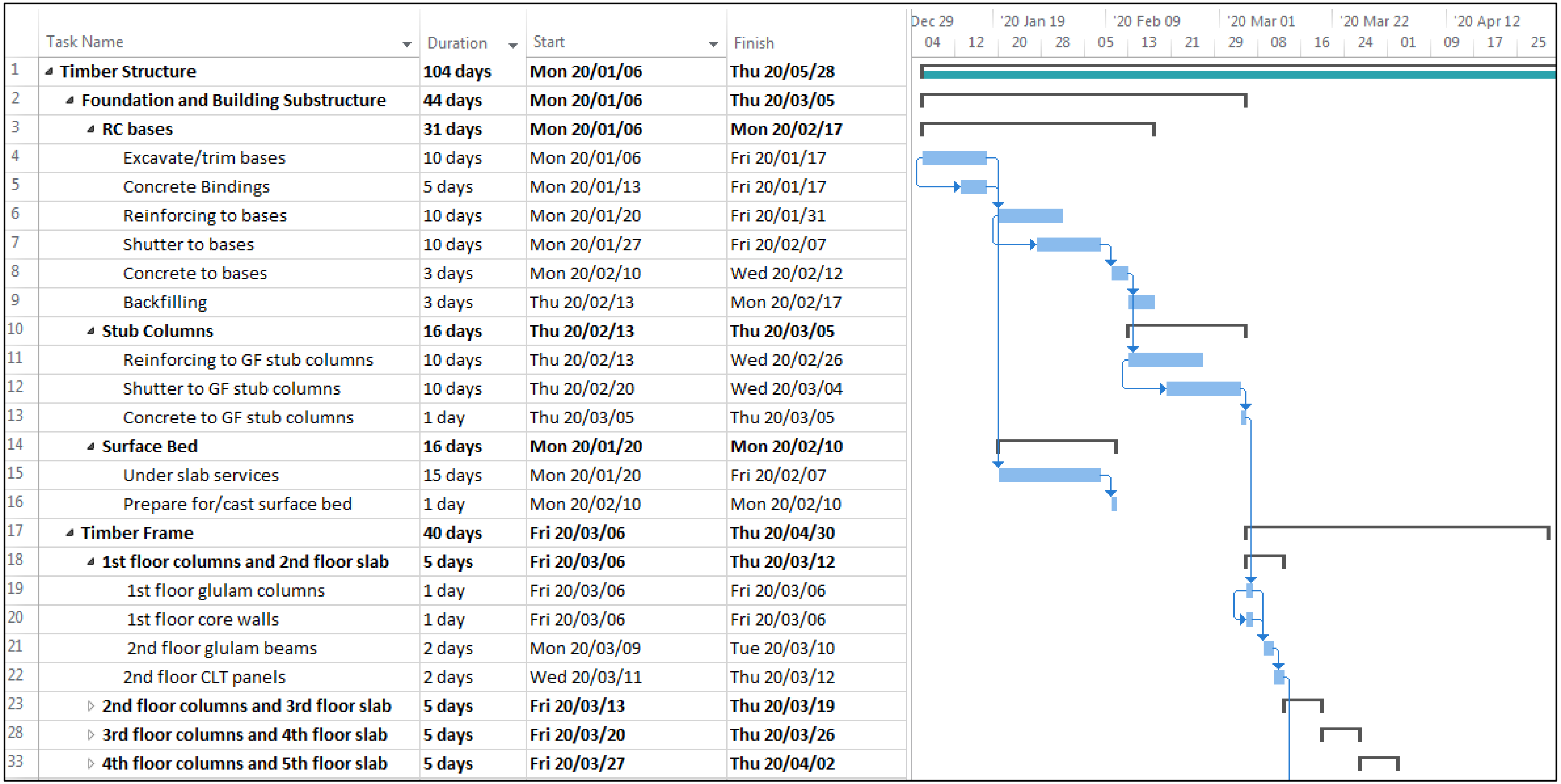
Figure 15.1: Reinforced concrete building construction schedule



	Task Name	Duration	Start	Finish
43	**6th Floor and 7th Floor**	**11 days**	**Tue 20/03/31**	**Tue 20/04/14**
47	**Surface Bed**	**16 days**	**Mon 20/01/20**	**Mon 20/02/10**
48	Under slab services	15 days	Mon 20/01/20	Fri 20/02/07
49	Prepare for/cast surface bed	1 day	Mon 20/02/10	Mon 20/02/10
50	**Reinforced Concrete Frame**	**146 days**	**Fri 20/03/06**	**Fri 20/09/25**
51	**Ground floor columns and 1st floor slab**	**15 days**	**Fri 20/03/06**	**Thu 20/03/26**
52	Reinforcing to GF columns	2 days	Fri 20/03/06	Mon 20/03/09
53	Shutter to GF columns	2 days	Tue 20/03/10	Wed 20/03/11
54	Concrete to GF columns	1 day	Thu 20/03/12	Thu 20/03/12
55	Staging for 1st floor slab	7 days	Fri 20/03/13	Mon 20/03/23
56	Reinforcing to 1st floor slab	7 days	Tue 20/03/17	Wed 20/03/25
57	Concrete to 1st floor slab	1 day	Thu 20/03/26	Thu 20/03/26
58	**1st floor columns and 2nd floor slab**	**15 days**	**Fri 20/03/27**	**Thu 20/04/16**
65	**2nd floor columns and 3rd floor slab**	**15 days**	**Fri 20/04/17**	**Thu 20/05/07**
72	**3rd floor columns and 4th floor slab**	**15 days**	**Fri 20/05/08**	**Thu 20/05/28**
79	**4th floor columns and 5th floor slab**	**15 days**	**Fri 20/05/29**	**Thu 20/06/18**
86	**5th floor columns and 6th floor slab**	**15 days**	**Fri 20/06/19**	**Thu 20/07/09**
93	**6th floor columns and 7th floor slab**	**15 days**	**Fri 20/07/10**	**Thu 20/07/30**
100	**7th floor column and 8th floor slab**	**15 days**	**Fri 20/07/31**	**Thu 20/08/20**

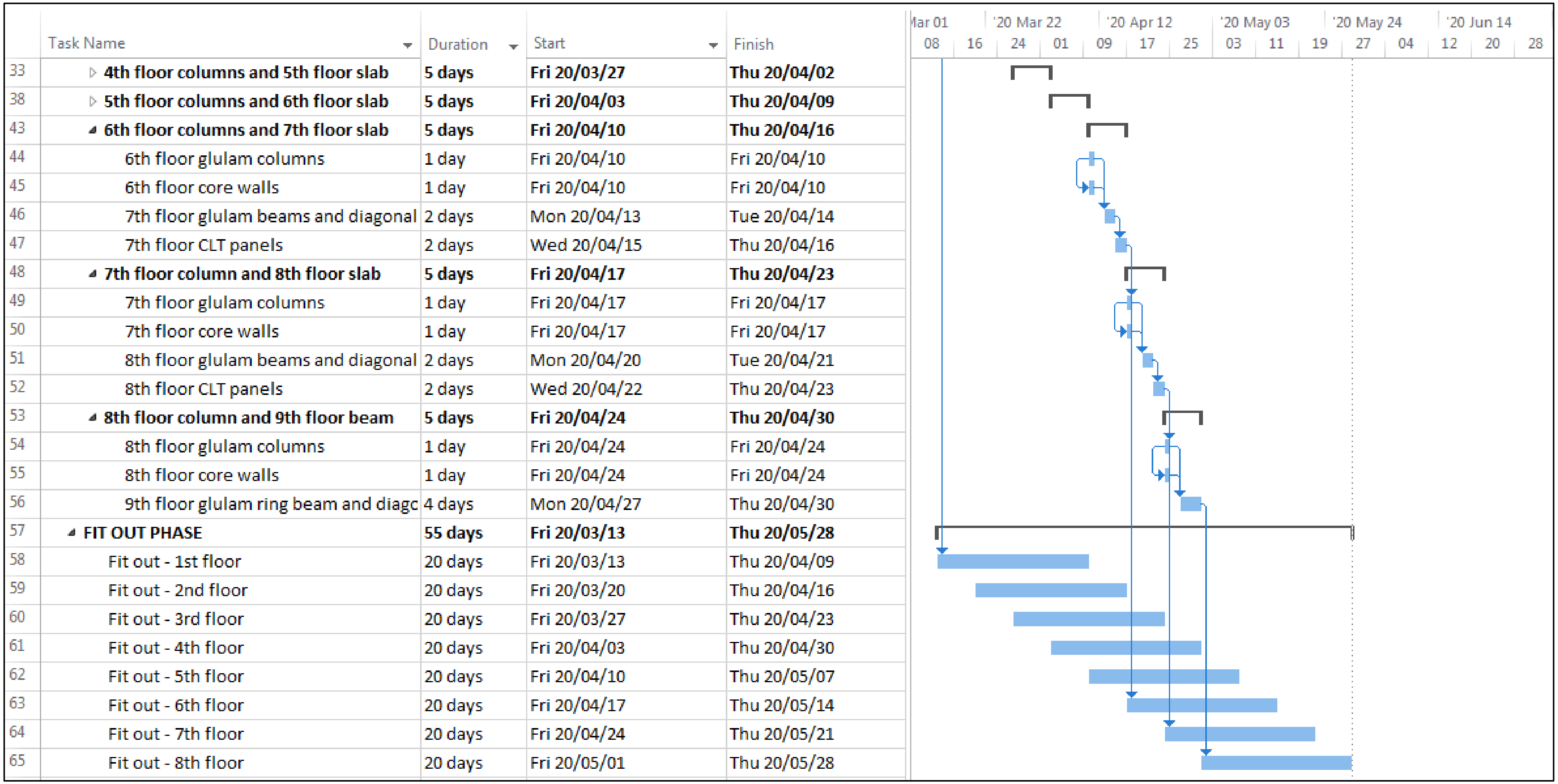


	Task Name	Duration	Start	Finish
86	**5th floor columns and 6th floor slab**	**15 days**	**Fri 20/06/19**	**Thu 20/07/09**
93	**6th floor columns and 7th floor slab**	**15 days**	**Fri 20/07/10**	**Thu 20/07/30**
100	**7th floor column and 8th floor slab**	**15 days**	**Fri 20/07/31**	**Thu 20/08/20**
101	Reinforcing to 7th floor c	2 days	Fri 20/07/31	Mon 20/08/03
102	Shutter to 7th floor colur	2 days	Tue 20/08/04	Wed 20/08/05
103	Concrete to 7th floor colu	1 day	Thu 20/08/06	Thu 20/08/06
104	Staging for 8th floor slab	7 days	Fri 20/08/07	Mon 20/08/17
105	Reinforcing to 8th floor s	7 days	Tue 20/08/11	Wed 20/08/19
106	Concrete to 8th floor slab	1 day	Thu 20/08/20	Thu 20/08/20
107	**8th floor column and 9 floor ringbeam**	**26 days**	**Fri 20/08/21**	**Fri 20/09/25**
108	Reinforcing to 8th floor c	5 days	Fri 20/08/21	Thu 20/08/27
109	Shutter to 8th floor colu	5 days	Fri 20/08/28	Thu 20/09/03
110	Concrete to 8th floor col	1 day	Fri 20/09/04	Fri 20/09/04
111	9th floor ring beam / SLAB	15 days	Mon 20/09/07	Fri 20/09/25
112	**FIT OUT PHASE**	**136 days**	**Tue 20/04/14**	**Tue 20/10/20**
113	Fit out - ground floor	20 days	Tue 20/04/14	Mon 20/05/11
114	Fit out - first floor	20 days	Tue 20/05/05	Mon 20/06/01
115	Fit out - second floor	20 days	Tue 20/05/26	Mon 20/06/22
116	Fit out - third floor	20 days	Tue 20/06/16	Mon 20/07/13
117	Fit out - fourth floor	20 days	Tue 20/07/07	Mon 20/08/03
118	Fit out - fifth floor	20 days	Tue 20/07/28	Mon 20/08/24
119	Fit out - sixth floor	20 days	Wed 20/09/02	Tue 20/09/29
120	Fit out - seventh floor	20 days	Wed 20/09/23	Tue 20/10/20



	Task Name	Duration	Start	Finish
1	**Timber Structure**	**104 days**	**Mon 20/01/06**	**Thu 20/05/28**
2	**Foundation and Building Substructure**	**44 days**	**Mon 20/01/06**	**Thu 20/03/05**
3	**RC bases**	**31 days**	**Mon 20/01/06**	**Mon 20/02/17**
4	Excavate/trim bases	10 days	Mon 20/01/06	Fri 20/01/17
5	Concrete Bindings	5 days	Mon 20/01/13	Fri 20/01/17
6	Reinforcing to bases	10 days	Mon 20/01/20	Fri 20/01/31
7	Shutter to bases	10 days	Mon 20/01/27	Fri 20/02/07
8	Concrete to bases	3 days	Mon 20/02/10	Wed 20/02/12
9	Backfilling	3 days	Thu 20/02/13	Mon 20/02/17
10	**Stub Columns**	**16 days**	**Thu 20/02/13**	**Thu 20/03/05**
11	Reinforcing to GF stub columns	10 days	Thu 20/02/13	Wed 20/02/26
12	Shutter to GF stub columns	10 days	Thu 20/02/20	Wed 20/03/04
13	Concrete to GF stub columns	1 day	Thu 20/03/05	Thu 20/03/05
14	**Surface Bed**	**16 days**	**Mon 20/01/20**	**Mon 20/02/10**
15	Under slab services	15 days	Mon 20/01/20	Fri 20/02/07
16	Prepare for/cast surface bed	1 day	Mon 20/02/10	Mon 20/02/10
17	**Timber Frame**	**40 days**	**Fri 20/03/06**	**Thu 20/04/30**
18	**1st floor columns and 2nd floor slab**	**5 days**	**Fri 20/03/06**	**Thu 20/03/12**
19	1st floor glulam columns	1 day	Fri 20/03/06	Fri 20/03/06
20	1st floor core walls	1 day	Fri 20/03/06	Fri 20/03/06
21	2nd floor glulam beams	2 days	Mon 20/03/09	Tue 20/03/10
22	2nd floor CLT panels	2 days	Wed 20/03/11	Thu 20/03/12
23	**2nd floor columns and 3rd floor slab**	**5 days**	**Fri 20/03/13**	**Thu 20/03/19**
28	**3rd floor columns and 4th floor slab**	**5 days**	**Fri 20/03/20**	**Thu 20/03/26**
33	**4th floor columns and 5th floor slab**	**5 days**	**Fri 20/03/27**	**Thu 20/04/02**

Figure 15.2: Mass timber building construction schedule



	Task Name	Duration	Start	Finish
33	**▷ 4th floor columns and 5th floor slab**	**5 days**	**Fri 20/03/27**	**Thu 20/04/02**
38	**▷ 5th floor columns and 6th floor slab**	**5 days**	**Fri 20/04/03**	**Thu 20/04/09**
43	**◢ 6th floor columns and 7th floor slab**	**5 days**	**Fri 20/04/10**	**Thu 20/04/16**
44	6th floor glulam columns	1 day	Fri 20/04/10	Fri 20/04/10
45	6th floor core walls	1 day	Fri 20/04/10	Fri 20/04/10
46	7th floor glulam beams and diagonal	2 days	Mon 20/04/13	Tue 20/04/14
47	7th floor CLT panels	2 days	Wed 20/04/15	Thu 20/04/16
48	**◢ 7th floor column and 8th floor slab**	**5 days**	**Fri 20/04/17**	**Thu 20/04/23**
49	7th floor glulam columns	1 day	Fri 20/04/17	Fri 20/04/17
50	7th floor core walls	1 day	Fri 20/04/17	Fri 20/04/17
51	8th floor glulam beams and diagonal	2 days	Mon 20/04/20	Tue 20/04/21
52	8th floor CLT panels	2 days	Wed 20/04/22	Thu 20/04/23
53	**◢ 8th floor column and 9th floor beam**	**5 days**	**Fri 20/04/24**	**Thu 20/04/30**
54	8th floor glulam columns	1 day	Fri 20/04/24	Fri 20/04/24
55	8th floor core walls	1 day	Fri 20/04/24	Fri 20/04/24
56	9th floor glulam ring beam and diagc	4 days	Mon 20/04/27	Thu 20/04/30
57	**◢ FIT OUT PHASE**	**55 days**	**Fri 20/03/13**	**Thu 20/05/28**
58	Fit out - 1st floor	20 days	Fri 20/03/13	Thu 20/04/09
59	Fit out - 2nd floor	20 days	Fri 20/03/20	Thu 20/04/16
60	Fit out - 3rd floor	20 days	Fri 20/03/27	Thu 20/04/23
61	Fit out - 4th floor	20 days	Fri 20/04/03	Thu 20/04/30
62	Fit out - 5th floor	20 days	Fri 20/04/10	Thu 20/05/07
63	Fit out - 6th floor	20 days	Fri 20/04/17	Thu 20/05/14
64	Fit out - 7th floor	20 days	Fri 20/04/24	Thu 20/05/21
65	Fit out - 8th floor	20 days	Fri 20/05/01	Thu 20/05/28

16 Appendix G - Bill of Quantities

Table 16.1: Mass Timber Frame Bill of Quantities

					Gross	
Item	**Bill Decription**		**UNIT**	**Bill Quantity**	**Rate**	**Amount**
1	**Earthworks**					
1.1	**Column bases:**	Inner	m3	61.44	126.00	7 741.44
		Outer	m3	33.60	126.00	4 233.60
		Corner	m3	7.74	126.00	975.74
		Core	m3	32.00	147.00	4 704.00
1.2	**Excavation in hard rock (5% of total excavation area)**		m3	6.74	1732.50	11 675.66
1.3	**Cut back sides of excavation for working space**	Inner	m2	76.80	39.90	3 064.32
		Outer	m2	52.00	39.90	2 074.80
		Corner	m2	14.08	39.90	561.79
		Core	m2	16.00	39.90	638.40
1.4	**Extra over all excavations for carting away**		m3	134.78	231.00	31 135.10
1.5	**Risk of collapse of excavation**		m2	158.88	8.40	1 334.59
Subtotal						68 139.46
2	**Concrete, Formwork and Reinforcement**					
2.1	**Foundation Bases**		m3	134.78	1808.34	243 735.30
2.2	**30 MPa Surface Bed**	Floor 1	m3	86.4	1845.39	159 441.70
2.3	**50mm Structural Screed on CLT Floor**	Floors 1-8	m3	239.4	1845.39	441 786.37
2.4	**Rough Formwork**	Foundations	m2	158.88	147.00	23 355.36
		Surface Bec	m2	5.4	147.00	793.80
		Floors 2-8	m2	37.8	147.00	5 556.60
2.5	**Powerfloat Finish**	Floor 1	m2	720	35.66	25 675.20
2.6	**High tensile welded steel wire fabric reinforcement** **Fabric mesh reinforcement ref 193 having a mass of 1.93 kg per m2 horizontally in slabs**		m2	5472.00	42.04	230 042.88
2.7	**Mild & high tensile steel reinforcement not exceeding 13m lon**	Foundation	tons	15	11565.58	173 483.70
Subtotal						1 303 870.90
3	**Timber Frame**					
3.1	**Outer Columns:** 400mm*400mm*3500mm (SA Pine)	Floors 1-8	No	144	6720.00	979 200.00
3.2	**Inner Columns:** S7 SA Pine: 400mm*400mm*3500mm	Floors 1-2	No	24	6720.00	161 280.00
	S7 SA Pine: 350mm*350mm*3500mm	Floors 3-5	No	36.00	5145.00	185 220.00
	S7 SA Pine: 300mm*300mm*3500mm	Floors 6-8	No	36	3780.00	136 080.00
3.3	**Internal Beams** 520mm*240mm*6000mm			120	10886.40	1 306 368.00

3.4	**GL 24h Ring Beam:**					
	320mm*240mm*6000mm	Floors 1-8	No	144	5529.60	796 262.40
3.5	**GL 24h Diagonal Beam:**					
	260mm*240mm*18320mm	Floors 1-8	No	24	13718.02	329 232.38
3.6	**220L75-2 CLT Floor**					
	220mm*3000mm*6000mm	Floors 1-8	No	266	47520.00	12 640 320.00
3.7	**180 C35 CLT Core**					
	180mm*31500mm*3500mm	Floors 1-8	No	8	238140.00	1 905 120.00
3.8	**Mass Timber Staircase**					
	S7 SA Pine beams: 320mm*140mm	Floors 1-8		7.00	5376.00	37 632.00
	S7 SA Pine column: 250mm*250mm	Floors 1-8		1.00	18375.00	18 375.00
	180C35 CLT Landing: 1550 mm*3400 mm	Floors 1-8		7.00	11383.20	79 682.40
	180C35 CLT steps: 1600mm*250mm	Floors 1-8		126.00	864.00	108 864.00
3.9	**CLT Transportation** *(Cape Town to Sandton)*		km	24650	32	-
	Glulam Transportation *(Windhoek to Sandton)*		km	5600	32	-
	Subtotal					18 683 636.18
4	**Steel Connections**					
4.1	**Column-Column**					
	2No 10mm Steel Plate with holes.		No	240	700.00	168 000.00
	24No 7*233mm dowels			240	1027.20	246 528.00
4.2	**Internal Beams-Column**					-
	2*Alumidi with holes per connection	Floors 2-8	No	700	382.55	267 785.00
	12*240mm dowels (8 per connection)			2800	21.81	61 054.00
	6*100mm anchor nails			56000	1.59	89 180.00
4.3	**Edge Beam-Column**					-
	HBS Counterhead Screw (8No 10*400)		No	2304	29.30	67 495.68
4.4	**CLT Floor-Beam**					-
	2No VGZ 7*220 Fully Threaded screws @300mm spacing	Floors 2-8	No	11200	14.21	159 152.00
4.5	**CLT core wall-CLT slab**					-
	2No VGZ 7*220 Fully Threaded screws @300mm spacing		No	1280.00	14.21	18 188.80
	TITAN angle brackets		No	96.00	140.00	13 440.00
4.6	**CLT core wall-CLT core wall**					-
	WHT Plate T		No	96.00	66.50	6 384.00
	TITAN Plate T		No	192.00	91.35	17 539.20
	TITAN Angle Brackets		No	320	140.00	44 800.00
4.7	**Diagonal Bracing Connection**					-
	2No 10mm Steel Plate with holes		No	192	700.00	134 400.00
	24No 7*233mm dowels			192	1027.20	197 222.40
4.8	**Mass Timber Staircase**					
	Column-Column connection		No	8.00	1727.20	13 817.60
	Beam-Column Connection		No	14.00	405.95	5 683.27
	VGZ Screws		No	140	14.21	1 989.40
	Subtotal					1 512 659.35

5	**Labour**					
5.1	**Precut**	Beams	m	1584.00	99.00	156 816.00
		Bracing bea	m	439.68	99.00	43 528.32
		Columns	m	840.00	99.00	83 160.00
5.2	**Installation**	Beams	m	1584.00	144.00	228 096.00
		Bracing bea	m	439.68	144.00	63 313.92
		Columns	m	840.00	144.00	120 960.00
		CLT Floor	m	1596.00	144.00	229 824.00
		CLT Core	m	308.00	144.00	44 352.00
5.3	**Fixing**		min	14400.00	6.48	93 312.00
	Subtotal					1 063 362.24
6	**Sound Insulation, Fire Protection, Water Protection**					
6.1	**Type X Gypsym Boards:**					
	Columns - Timber cover		m2		-	-
	Beams - Timber Cover		m2		-	-
	CLT Core Interior - 30minutes fire protection		m2	1 098.72	85.00	93 391.20
	CLT Core Exterior - 30minutes fire protection		m2	672.00	85.00	57 120.00
6.2	**Membrane Sealing Tape** **Rothoblaas Flexi Band (60mm*25m)**		m	896.00	9.81	8 793.34
6.3	**Core membranes**					
	Core Interior: Vapour Stop (1.5m*50m)		m2	896.00	15.09	13 522.43
6.4	**Impact Sound Insulation**					
	Rothoblaas SilentFloor (1m*10m)		m2	4788	100.30	480 236.40
	Subtotal					653 063.38
	TOTAL					**23 284 731.50**

Table 16.2: Concrete Frame Bill of Quantities

					Gross	
Item	**Bill Decription**		**UNIT**	**Bill Quantity**	**Rate**	**Amount**
1	***Earthworks***					
1.1	**Excavation of Column bases (not exceeding 2m deep):**	Inner	m3	208.08	126.00	26 218.08
		Outer	m3	91.84	126.00	11 571.84
		Corner	m3	21.60	126.00	2 721.60
		Shear Wall	m3	25.60	126.00	3 225.60
		Core	m3	80.00	147.00	11 760.00
1.2	**Excavation in hard rock (5% of total excavation area)**		m3	21.36	1732.50	36 999.27
1.3	**Cut back sides of excavation for working space**	Inner	m2	163.20	39.90	6 511.68
		Outer	m2	102.20	39.90	4 077.78
		Corner	m2	28.80	39.90	1 149.12
		Shear Wall	m2	19.20	39.90	766.08
		Core	m2	32.00	39.90	1 276.80
1.4	**Extra over all excavations for carting away**		m3	427.12	231.00	98 664.72
1.5	**Risk of collapse of excavation**		m2	345.40	8.40	2 901.36
1.6	**Fillings have been ommitted**					
	Subtotal					207 843.93
2	***Concrete, Formwork and Reinforcement***					
2.1	***Concrete***					
2.2	**Foundation Bases**		m3	448.48	1808.34	810 997.09
2.3	**30 MPa Surface Bed**		m3	86.4	1845.39	159 441.70
2.4	**30 MPa Inner Columns**	Floor 1-2	m3	17.5	1968.53	34 449.28
		Floor 3-5	m3	16.8	1968.53	33 071.30
		Floor 6-8	m3	9.45	1968.53	18 602.61
2.5	**30 MPa Outer Columns**	Floor 1-8	m3	112	1968.53	220 475.36
2.6	**35MPa Slab including beams**	Floor 2-8	m3	1367.1	1 796.25	2 455 653.38
2.7	**Ring Beam**	Roof	m3	15.3	1968.53	30 118.51
2.8	**30 MPa Lift Shaft Walls**		m3	236.6	1739.48	411 560.97
2.9	**30 MPa Shear Walls**		m3	33	1739.48	57 402.84
2.10	**Finishing: Power Float**	Floor 1-8	m2	5472	35.66	195 131.52
2.11	**Stairs**		m3	35	1663.13	58 209.55
	Subtotal					4 485 114.10

3	*Rough Formwork*					
3.1	**Sides of column bases**		m2	313.4	147	46 069.80
	Sides of lift pit bases			32	168	5 376.00
4	*Smooth Formwork*					
4.1	**Formwork to edge of surface bed**		m	108	157.5	17 010.00
4.2	**Soffits of slabs exceeding 250mm and n.e. 500mm thick**		m2			
4.3	**Propped not exceeding 3.50m above bearing level**		m2	4788	270.90	1 297 069.20
4.4	**Beams:**					
	Sides and soffit of beams, propped not exceeding 3.50m high		m2	1060.8	525.00	556 920.00
4.5	**Columns:**					
	Sides of square/rectangular columns	Inner	m2	140	262.5	36 750.00
		Outer	m2	168	262.5	44 100.00
		Corner	m2	126	262.5	33 075.00
4.6	**Walls:**					
	Lift Pit Walls not exceeding 3.5m		m2	535.5	472.5	253 023.75
	Inner face of shaft walls with no support below		m2	1337	787.5	1 052 887.50
	Shear Walls		m2	276	350	96 600.00
4.7	**Stairs**					
	Soffit of landing slab		m2	39.809	577.5	22 989.70
	Raking soffit of stairs slab		m2	79.6	472.5	37 611.00
	Riser not exceeding 300mm high		m	28.3	168	4 754.40
	Subtotal					3 504 236.35
	Reinforcement					
5.1	**High tensile welded steel wire fabric reinforcement**					
	Fabric mesh reinforcement ref 193 having a mass of 1.93 kg per m2 horizontally in slabs		m2	5472.00	42.04	230 042.88
5.2	**Mild & high tensile steel reinforcement not exceeding 13m long**	Foundations	tons	43.9	11565.58	507 728.96
		Columns		23.4	11565.58	270 634.57
		Beams		15.6	11565.58	180 423.05
		Slabs		167.5	11565.58	1 937 234.65
		Core Wall		35.5	11565.58	410 578.09
		Shear Wall		5	11565.58	57 827.90
		Stairs		4.2	11565.58	48 575.44
	Subtotal					3 643 045.54
	TOTAL					**11 840 239.91**

Appendix H: Equivalent Dimensions Calculation

Properties

$f_y := 350\ \mathrm{MPa}$

$E_{C24\_mean} := 11.5\ \mathrm{GPa}$ $E_{S10\_mean} := 12\ \mathrm{GPa}$ $E_{S7\_mean} := 9.6\ \mathrm{GPa}$

$E_{C24\_0.05} := 9.6\ \mathrm{GPa}$ $E_{S10\_0.05} := 7.12\ \mathrm{GPa}$ $E_{S7\_0.05} := 5.7\ \mathrm{GPa}$

$G_{C24} := 77 \cdot 10^3\ \mathrm{MPa}$ $G_{S10} := 77 \cdot 10^3\ \mathrm{MPa}$ $G_{S7} := 77 \cdot 10^3\ \mathrm{MPa}$

$f_{C24\_k\_comp} := 24\ \mathrm{MPa}$ $f_{S10\_k\_comp} := 26.2\ \mathrm{MPa}$ $f_{S7\_k\_comp} := 22.8\ \mathrm{MPa}$

$f_{C24\_m\_k} := 21\ \mathrm{MPa}$ $f_{S10\_m\_k} := 23.3\ \mathrm{MPa}$ $f_{S7\_m\_k} := 15.8\ \mathrm{MPa}$

$f_{C24\_v\_k} := 4.0\ \mathrm{MPa}$ $f_{S10\_v\_k} := 2.9\ \mathrm{MPa}$ $f_{S7\_v\_k} := 2.0\ \mathrm{MPa}$

$l := 6000\ \mathrm{mm}$ Span of CLT flooring system

$\rho_{screed} := 23\ \dfrac{\mathrm{kN}}{\mathrm{m}^3}$ $t_{screed} := 50\ \mathrm{mm}$ Screed Properties

$\rho_{CLT} := 470\ \dfrac{\mathrm{kg}}{\mathrm{m}^3} \cdot 9.81\ \dfrac{\mathrm{m}}{\mathrm{s}^2} = 4.6107\ \dfrac{\mathrm{kN}}{\mathrm{m}^3}$ $t_{CLT} := 220\ \mathrm{mm}$ CLT Properties

Loading Calculations:

$G_{k\_slab} := \rho_{screed} \cdot t_{screed} + \rho_{CLT} \cdot t_{CLT}$ 220L75-2 CLT dead weight plus screed

$G_{k\_slab} = 2.1644\ \mathrm{kPa}$

$G_{k\_ceiling\_services} := 0.3\ \mathrm{kPa}$

$G_{k\_tiles} := 0.22\ \mathrm{kPa}$ vinyl tiles

$G_k := G_{k\_slab} + G_{k\_ceiling\_services} + G_{k\_tiles} = 2.6844\ \mathrm{kPa}$

$Q_k := 2.5\ \mathrm{kPa}$ As per SANS 10160-2

$h_{C24\_beam} := 520\ \mathrm{mm}$ $b_{C24\_beam} := 240\ \mathrm{mm}$ $\rho_{beam} := 420\ \dfrac{\mathrm{kg}}{\mathrm{m}^3} \cdot 9.81\ \dfrac{\mathrm{m}}{\mathrm{s}^2} = 4.1202\ \dfrac{\mathrm{kN}}{\mathrm{m}^3}$

Ultimate limit state: Imposed Load Leading

$w_{ULS\_slab} := 1.2 \cdot G_k + 1.6 \cdot Q_k = 7.2212\ \dfrac{\mathrm{kN}}{\mathrm{m}^2}$

$R_{ULS\_slab} := \left(\dfrac{w_{ULS\_slab} \cdot l}{2}\right) \cdot 2 = 43.3273\ \dfrac{\mathrm{kN}}{\mathrm{m}}$ Loading on beam from slab

$R_{beam} := \rho_{beam} \cdot h_{C24\_beam} \cdot b_{C24\_beam} = 0.5142\ \dfrac{\mathrm{kN}}{\mathrm{m}}$ Dead weight of beam

$w_{ULS} := 1.2 \cdot R_{beam} + R_{ULS\_slab} = 43.9444 \, \frac{kN}{m}$ Factored Line load on beam

$M_{ULS\_spanning} := 150 \, kN \, m$

Design Moment at ambient form Prokon Frame Analysis

$M_{ULS\_hogging} := 150 \, kN \, m$

Serviceability Limit State

$w_{SLS\_slab} := 1.1 \cdot G_k + 1.0 \cdot Q_k = 5.4528 \, \frac{kN}{m^2}$

$R_{SLS\_slab} := \left(\frac{w_{SLS\_slab} \cdot l}{2} \right) \cdot 2 = 32.7167 \, \frac{kN}{m}$

$w_{SLS} := 1.1 \cdot R_{beam} + 1.0 \cdot R_{SLS\_slab} = 33.2824 \, \frac{kN}{m}$

2.Final Modulus of Elasticity

$E_{C24\_meanfinal} := \frac{E_{C24\_mean}}{1 + \psi_2 \cdot k_{def}}$

$E_{C24\_mean} = 11.5 \, GPa$ Stiffness values for deformation calculations

$\psi_2 := 0.3$ Offcie areas from Table 2.2

$k_{def} := 0.6$ Factor accounting for moisture from Table 9.1

$E_{C24\_meanfinal} = 9.7458 \, GPa$

$E_{S10\_meanfinal} := \frac{E_{S10\_mean}}{1 + \psi_2 \cdot k_{def}}$

$E_{S10\_mean} = 12 \, GPa$

$\psi_2 := 0.3$

$k_{def} := 0.6$

$E_{S10\_meanfinal} = 10.1695 \, GPa$

$E_{S7\_meanfinal} := \frac{E_{S7\_mean}}{1 + \psi_2 \cdot k_{def}}$

$E_{S7\_mean} = 9.6 \, GPa$

$\psi_2 := 0.3$

$k_{def} := 0.6$

$E_{S7\_meanfinal} = 8.1356 \, GPa$

Initial beams size check based on L/d limits:

$\Delta = \frac{5}{384} \cdot \frac{w_{SLS} \cdot l^4}{E_{meanfinal}}$ $\frac{l}{500} = 12 \, mm$ Therefore set $\Delta := 12 \, mm$

$I_{required} := 0.0065 \cdot \frac{w_{SLS} \cdot l^4}{E_{C24\_meanfinal} \cdot \Delta} = 2.3974 \cdot 10^9 \, mm^4$ Deflection for 4 span continuous beam (SAISC Red Book)

$b_{C24\_beam} = 240 \, mm$ $h_{C24\_beam} = 520 \, mm$

$I_{C24\_beam} := \frac{1}{12} \cdot b_{C24\_beam} \cdot h_{C24\_beam}^3 = 2.8122 \cdot 10^9 \, mm^4$ $I_{C24\_beam} > I_{required}$ Okay for deflection

3.1 Bending Resistance at ambient

$f_{C24\_m\_k} := 24\ \text{MPa}$ Bending parallel to grain for GL24h from Table 3.4

$l_{ef} := 0.9 \cdot l = 5.4\ \text{m}$ Effective length as a ratio of the span

ULS partial coefficient from Table 3.1, Glued laminated timber

$\gamma_M := 1.25$

Strength modification factor from Table 3.2, medium term load

$k_{mod} := 0.8$

$$f_{C24\_m\_d} := \frac{\left(k_{mod} \cdot f_{C24\_m\_k}\right)}{\gamma_M} = 15.36\ \text{MPa}$$ Design bending strength

$$y := \frac{h_{C24\_beam}}{2} = 260\ \text{mm}$$ Assume slab provides suffcient lateral support

$$W_{C24} := \frac{I_{C24\_beam}}{y} = 1.0816 \cdot 10^{7}\ \text{mm}^{3}$$ Section modulus about the strong axis

$$\sigma_{m\_crit} := \frac{0.78 \cdot b_{C24\_beam}^{\ 2}}{h_{C24\_beam} \cdot l_{ef}} \cdot E_{C24\_0.05} = 153.6\ \text{MPa}$$

$$\lambda_{relm} := \sqrt{\frac{f_{C24\_m\_k}}{\sigma_{m\_crit}}} = 0.3953$$ $\lambda_{relm} < 0.75$ Therefore $k_{crit} := 1$

$$M_{Rd} := f_{C24\_m\_d} \cdot W_{C24} \cdot k_{crit} = 166.1338\ \text{kN m}$$ Design is okay for bending

$M_{ULS\_spanning} = 150\ \text{kN m}$ $M_{Rd} > M_{ULS\_spanning}$

$M_{ULS\_hogging} = 150\ \text{kN m}$ $M_{Rd} > M_{ULS\_hogging}$

S10 Bending Moment

First dimension check based on SLS requirements

$b_{S10\_beam} := 240\ \text{mm}$ $h_{S10\_beam} := 520\ \text{mm}$

$$I := 0.0065 \cdot \frac{w_{SLS} \cdot l^{4}}{E_{S10\_meanfinal} \cdot \Delta} = 2.2975 \cdot 10^{9}\ \text{mm}^{4}$$ Deflection for 4 span continuous beam (SAISC Red Book)

$$I_{S10\_beam} := \frac{1}{12} \cdot b_{S10\_beam} \cdot h_{S10\_beam}^{\ 3} = 2.8122 \cdot 10^{9}\ \text{mm}^{4}$$ $I_{S10\_beam} > I_{required}$ Okay for deflection

Bending Resistance Calculations:

$f_{S10\_m\_k} = 23.3\ \text{MPa}$ Bending parallel to grain for S10 from SANS 10163-1

$l_{ef} := 0.9 \cdot l = 5.4\ \text{m}$ Effective length as a ratio of the span

$f_{S10\_m\_d} := \frac{\left(k_{mod} \cdot f_{S10\_m\_k}\right)}{\gamma_M} = 14.912\ \text{MPa}$ Design bending strength

$y := \frac{h_{S10\_beam}}{2} = 260\ \text{mm}$ Assume slab provides suffcient lateral support

$W_{S10} := \frac{I_{S10\_beam}}{y} = 1.0816 \cdot 10^{7}\ \text{mm}^{3}$ Section modulus about the strong axis

$\sigma_{m\_crit} := \frac{0.78 \cdot b_{S10\_beam}^{\ \ 2}}{h_{S10\_beam} \cdot l_{ef}} \cdot E_{S10\_0.05} = 113.92\ \text{MPa}$

$\lambda_{relm} := \sqrt{\frac{f_{S10\_m\_k}}{\sigma_{m\_crit}}} = 0.4522$ $\lambda_{relm} < 0.75$ Therefore

$M_{Rd} := f_{S10\_m\_d} \cdot W_{S10} \cdot k_{crit} = 161.2882\ \text{kN m}$

$M_{ULS\_spanning} = 150\ \text{kN m}$ $M_{Rd} > M_{ULS\_spanning}$

Design is okay for bending

$M_{ULS\_hogging} = 150\ \text{kN m}$ $M_{Rd} > M_{ULS\_hogging}$

S7 Bending Moment

First dimension check based on SLS requirements

$I := 0.0065 \cdot \frac{w_{SLS} \cdot l^{4}}{E_{S7\_meanfinal} \cdot \Delta} = 2.8719 \cdot 10^{9}\ \text{mm}^{4}$ Deflection for 4 span continuous beam (SAISC Red Book)

$b_{S7\_beam} := 240\ \text{mm}$ $h_{S7\_beam} := 630\ \text{mm}$

$I_{S7\_beam} := \frac{1}{12} \cdot b_{S7\_beam} \cdot h_{S7\_beam}^{\ \ 3} = 5.0009 \cdot 10^{9}\ \text{mm}^{4}$ $I_{S7\_beam} > I_{required}$ Okay for deflection

Bending Resistance Calculations:

$f_{S7\_m\_k} = 15.8\ \text{MPa}$

Bending parallel to grain for S7 from SANS 10163-1

$l_{ef} := 0.9 \cdot l = 5.4\ \text{m}$

Effective length as a ratio of the span

$f_{S7\_m\_d} := \frac{\left(k_{mod} \cdot f_{S7\_m\_k}\right)}{\gamma_M} = 10.112\ \text{MPa}$

Design bending strength

$y := \frac{h_{S7\_beam}}{2} = 315\ \text{mm}$ Assume slab provides suffcient lateral support

$W_{S7} := \frac{I_{S7\_beam}}{y} = 1.5876 \cdot 10^{7}\ \text{mm}^{3}$ Section modulus about the strong axis

$\sigma_{m\_crit} := \frac{0.78 \cdot b_{S7\_beam}^{\ \ 2}}{h_{S7\_beam} \cdot l_{ef}} \cdot E_{S7\_0.05} = 75.2762\ \text{MPa}$

$\lambda_{relm} := \sqrt{\dfrac{f_{S7\_m\_k}}{\sigma_{m\_crit}}} = 0.4581$

$\lambda_{relm} < 0.75$ Therefore

$M_{Rd} := f_{S7\_m\_d} \cdot W_{S7} \cdot k_{crit} = 160.5381\ \text{kN m}$

$M_{Rd} > M_{ULS}$

$M_{ULS\_spanning} = 150\ \text{kN m}$

$M_{ULS\_hogging} = 150\ \text{kN m}$

$M_{Rd} > M_{ULS\_spanning}$

$M_{Rd} \le M_{ULS\_hogging}$

Design is okay for bending

Note:S7 Beam size is effectively increased by 21% to compare with S10 and C24

4.1 Beam subjected to shear

$f_{C24\_v\_k} = 4\ \text{MPa}$ Characteristic shear strength value from Table 3.4

$f_{C24\_v\_d} := \dfrac{f_{C24\_v\_k}}{\gamma_M} \cdot k_{mod} = 2.56\ \text{MPa}$ ULS Design shear strength

$k_{cr} := \dfrac{3\ \text{MPa}}{f_{C24\_v\_k}} = 0.75$ Modification for influence of cracks in bending

$b_{C24\_ef} := k_{cr} \cdot b_{C24\_beam} = 180\ \text{mm}$

$l_{adj} := 6\ \text{m} - 400\ \text{mm} = 5.6\ \text{m}$

$A_{C24} := b_{C24\_ef} \cdot h_{C24\_beam} = 93600\ \text{mm}^2$

$V_{Rd} := \dfrac{A_{C24} \cdot f_{C24\_v\_d}}{1.3} = 184.32\ \text{kN}$ Shear capacity at ULS

$V_{D\_uls} := 135\ \text{kN}$ From Prokon Frame analysis $V_{Rd} > V_{D\_uls}$ Okay

$f_{S10\_v\_k} = 2.9\ \text{MPa}$

$f_{S10\_v\_d} := \dfrac{f_{S10\_v\_k}}{\gamma_M} \cdot k_{mod} = 1.856\ \text{MPa}$

$A_{S10} := b_{S10\_beam} \cdot h_{S10\_beam} = 1.248 \cdot 10^5\ \text{mm}^2$

$V_{Rd\_S10} := \dfrac{A_{S10} \cdot f_{S10\_v\_d}}{1.5} = 154.4192\ \text{kN}$

$V_{D\_uls} = 135\ \text{kN}$ $V_{Rd\_S10} > V_{D\_uls}$

$f_{S7\_v\_k} = 2\ \text{MPa}$

$f_{S7\_v\_d} := \dfrac{f_{S7\_v\_k}}{\gamma_M} \cdot k_{mod} = 1.28\ \text{MPa}$

$A_{S7} := b_{S7\_beam} \cdot h_{S7\_beam} = 1.512 \cdot 10^5\ \text{mm}^2$

$V_{Rd\_S7} := \dfrac{A_{S7} \cdot f_{S7\_v\_d}}{1.5} = 129.024\ \text{kN}$

$V_{D\_uls} = 135\ \text{kN}$ $V_{Rd\_S7} < V_{D\_uls}$

There is only a 7kN difference in shear capacity and shear resistance.

As such, the S7 cross section was accepted due to the assumptions made beforehand

5.1 Compression in Ground floor columns at Ambient

$h_{C24\_col} := 380\ \text{mm}$ $b_{C24\_col} := 380\ \text{mm}$ $l_e := 3.5\ \text{m}$ Column Height

$I_{C24\_col} := \frac{1}{12} \cdot h_{C24\_col} \cdot b_{C24\_col}^{\ 3}$ $A_{C24\_col} := h_{C24\_col} \cdot b_{C24\_col}$

$\rho_{column} := 420\ \frac{\text{kg}}{\text{m}^3} \cdot 9.81\ \frac{\text{m}}{\text{s}^2} = 4.1202\ \frac{\text{kN}}{\text{m}^3}$

$R_{column} := \rho_{column} \cdot h_{C24\_col} \cdot b_{C24\_col} \cdot l_e = 2.0823\ \text{kN}$ Weight of a single column

$N_{ULS} := \frac{w_{ULS} \cdot l}{2} \cdot 2 \cdot 8 + 1.2 \cdot R_{column} \cdot 8 = 2129.3213\ \text{kN}$ Imposed Load Leading

Design Compression Strength

$f_{C24\_d\_comp} := \frac{\left(k_{mod} \cdot f_{C24\_k\_comp}\right)}{\gamma_M}$ Service Class 1 is for elements in indoor environment

$\gamma_M := 1.25$ ULS partial coefficient from Table 3.1, Glued laminated timber

$k_{mod} := 0.8$ Strength modification factor from Table 3.2, medium term load

$f_{C24\_k\_comp} = 24\ \text{MPa}$ From Table 3.4 of Design Guideline for C24

$f_{C24\_d\_comp} = 15.36\ \text{MPa}$ Design compression parallel to grain

$f_{S10\_d\_comp} := \frac{\left(k_{mod} \cdot f_{S10\_k\_comp}\right)}{\gamma_M}$

$\gamma_M := 1.25$

$k_{mod} := 0.8$

$f_{S10\_k\_comp} = 26.2\ \text{MPa}$ SANS 10163-1

$f_{S10\_d\_comp} = 16.768\ \text{MPa}$

$f_{S7\_d\_comp} := \frac{\left(k_{mod} \cdot f_{S7\_k\_comp}\right)}{\gamma_M}$

$\gamma_M := 1.25$

$k_{mod} := 0.8$

$f_{S7\_k\_comp} = 22.8\ \text{MPa}$ SANS 10163-1

$f_{S7\_d\_comp} = 14.592\ \text{MPa}$

C 24 Capacity of Column at ambient

$i_{C24} := \sqrt{\frac{I_{C24\_col}}{A_{C24\_col}}}$

$\lambda := \frac{l_e}{i_{C24}} = 31.9062$ Slenderness Ratio

$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{C24\_k\_comp}}{E_{C24\_0.05}}} = 0.5078$

$\beta_c := 0.1$ Initial out of straightness parameter

$k := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^{\ 2}\right) = 0.6393$

$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^{\ 2}}} = 0.973$ for $\lambda_{rel} > 0.3$ Instability Factors

$N_{Rd} := f_{C24\_d\_comp} \cdot A_{C24\_col} \cdot k_c = 2158.1168$ kN $N_{Rd} > N_{ULS}$ Okay at ambient for first case

$N_{ULS} = 2129.3213$ kN

S10 Capacity of Column at ambient

$h_{S10\_col} := 368$ mm $b_{S10\_col} := 368$ mm

$I_{S10\_col} := \frac{1}{12} \cdot b_{S10\_col} \cdot h_{S10\_col}^{\ 3}$ $A_{S10\_col} := h_{S10\_col} \cdot b_{S10\_col}$

$i_{S10} := \sqrt{\frac{I_{S10\_col}}{A_{S10\_col}}}$

$\lambda := \frac{l_e}{i_{S10}} = 32.9466$ Slenderness Ratio

$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{S10\_k\_comp}}{E_{S10\_0.05}}} = 0.6362$

$\beta_c := 0.1$ Initial out of straightness parameter

$k := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^{\ 2}\right) = 0.7192$

$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^{\ 2}}} = 0.9483$ for $\lambda_{rel} > 0.3$ Instability Factors

$N_{Rd} := f_{S10\_d\_comp} \cdot A_{S10\_col} \cdot k_c = 2153.3204$ kN $N_{Rd} > N_{ULS}$ Okay at ambient for first case

$N_{ULS} = 2129.3213$ kN

S7 Capacity of Column at ambient

$h_{S7\_col} := 394$ mm $b_{S7\_col} := 394$ mm

$I_{S7\_col} := \frac{1}{12} \cdot b_{S7\_col} \cdot h_{S7\_col}^{\ 3}$ $A_{S7\_col} := h_{S7\_col} \cdot b_{S7\_col}$

$i_{S7} := \sqrt{\frac{I_{S7\_col}}{A_{S7\_col}}}$

$\lambda := \frac{l_e}{i_{S7}} = 30.7725$ Slenderness Ratio

$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{S7\_k\_comp}}{E_{S7\_0.05}}} = 0.6195$

$\beta_c := 0.1$ Initial out of straightness parameter

$k := 0.5 \cdot \left(1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^{\ 2}\right) = 0.7079$

$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^{\ 2}}} = 0.9521$ for $\lambda_{rel} > 0.3$ Instability Factors

$N_{Rd} := f_{S7\_d\_comp} \cdot A_{S7\_col} \cdot k_c = 2156.6264\ \mathrm{kN}$ $N_{Rd} > N_{ULS}$ Okay at ambient for first case

$N_{ULS} = 2129.3213\ \mathrm{kN}$

18 Appendix I - Capitalised Interest

Table 18.1: Interest during construction for timber frame (Rand)

Month	Proportion	% Cumulative	Cumulative	Month Payment	Equity	Accumulative Equity	Loan Draw Monthly	Accumulative Loan	Interest
1	5	5	4 752 658	4 752 658	4 752 658	4 752 658	-		
2	20	25	23 763 291	19 010 633	9 617 009	14 369 668	9 393 623	9 393 623	62 624
3	50	75	71 289 873	47 526 582	-	14 369 668	47 526 582	56 920 205	379 468
4	20	95	90 300 506	19 010 633	-	14 369 668	19 010 633	75 930 838	506 206
5	5	100	95 053 164	4 752 658	-	14 369 668	4 752 658	80 683 496	537 890
				95 053 164	14 369 668				1 486 188

Table 18.2: Interest during construction for concrete frame (Rand)

Month	Proportion	% Cumulative	Cumulative	Month Payment		Equity	Accumulative Equity	Loan Draw Monthly	Accumulative Loan	Interest
1	2	2	1 665 203	1 665 203		1 665 203	1 665 203	-		
2	5	7	5 828 209	4 163 006		2 130 866	3 796 069	2 032 140	2 032 140	13 548
3	9	16	13 321 620	7 493 411		-	3 796 069	7 493 411	7 493 411	49 956
4	12	28	23 312 836	9 991 215		-	3 796 069	9 991 215	17 484 627	116 564
5	22	50	41 630 064	18 317 228		-	3 796 069	18 317 228	35 801 855	238 679
6	22	72	59 947 292	18 317 228		-	3 796 069	18 317 228	54 119 083	360 794
7	12	84	69 938 507	9 991 215		-	3 796 069	9 991 215	64 110 298	427 402
8	9	93	77 431 919	7 493 411		-	3 796 069	7 493 411	71 603 710	477 358
9	5	98	81 594 925	4 163 006		-	3 796 069	4 163 006	75 766 716	505 111
10	2	100	83 260 128	1 665 203		-	3 796 069	1 665 203	77 431 919	516 213
				83 260 128		3 796 069				2 705 625

19 Appendix J: Mass Timber Building Amortization Schedule

Total Development Cost	115 691 352
Land Equity	19 152 000
Additional Equity	14 369 668
Loan	82 169 684
Monthly Net Rental	929 300
Interest Rate	8,0%
Interim Interest	1 486 188
Capitalization Rate	9,5%
Lease Escalation Rate	7,5%
Tax Rate	28,0%
13 Quin Rate	5,0%
13 Quin Base	95 053 164

			EQUITY		RENTAL	DEBT FUNDING ANALYSIS			TAX ANALYSIS						ASSET VALUE ANALYSIS			PROCEEDS FROM SALE - PROFIT / (LOSS) AFTER SALE					20,9%
Programme	Month	Date	Equity Out Flows	Accumulative Equity	Net Rental	Loan Balance	Interest Payment	Profit / (Loss) Before Tax	Interest Write Off	13 Quin Allowances	Tax Deduction	Taxable Income	Tax Payable	After Tax Surplus	Development Value	Asset Value (Dev Value Less Loan Balance)	Net Asset Value (Asset Value Less Equity)	Cost of Sale - Tax Perspective	Gross Profit	Current Taxable Position	Tax Payable (Selling Price Less Base Cost)	Net Profit / (Loss) After Tax	Month 67 IRR (YEAR 5 OF LEASE)
Land Purchase	1	Dec-19	(19 152 000)	(19 152 000)																			(19 152 000)
Construction Month 1	2	Jan-20	(4 752 658)	(23 904 658)																			(4 752 658)
Construction Month 2	3	Feb-20	(9 617 009)	(33 521 668)																			(9 617 009)
Construction Month 3	4	Mar-20	-	(33 521 668)																			-
Construction Month 4	5	Apr-20		(33 521 668)																			
Construction Month 5	6	May-20		(33 521 668)																			
Lease Commencement	7	Jun-20		(33 521 668)	929 300	82 169 684	547 798	381 502	(1 486 188)	(396 055)	(1 500 740)	-	-	381 502	117 385 263	35 215 579	1 693 911	114 205 164	3 180 099	2 075 413	(581 116)	34 634 463	
	8	Jul-20		(33 521 668)	929 300	81 788 182	545 255	384 045		(396 055)	(1 512 750)	-	-	384 045	117 385 263	35 597 081	2 075 413	114 205 164	3 180 099	2 459 459	(688 648)	34 908 433	
	9	Aug-20		(33 521 668)	929 300	81 404 137	542 694	386 606		(396 055)	(1 522 199)	-	-	386 606	117 385 263	35 981 127	2 459 459	114 205 164	3 180 099	2 846 065	(796 898)	35 184 228	
	10	Sep-20		(33 521 668)	929 300	81 017 531	540 117	389 183		(396 055)	(1 529 071)	-	-	389 183	117 385 263	36 367 732	2 846 065	114 205 164	3 180 099	3 235 248	(905 869)	35 461 863	
	11	Oct-20		(33 521 668)	929 300	80 628 348	537 522	391 778		(396 055)	(1 533 348)	-	-	391 778	117 385 263	36 756 915	3 235 248	114 205 164	3 180 099	3 627 025	(1 015 567)	35 741 348	
	12	Nov-20		(33 521 668)	929 300	80 236 570	534 910	394 390		(396 055)	(1 535 013)	-	-	394 390	117 385 263	37 148 693	3 627 025	114 205 164	3 180 099	4 021 415	(1 125 996)	36 022 697	
	13	Dec-20		(33 521 668)	929 300	79 842 181	532 281	397 019		(396 055)	(1 534 049)	-	-	397 019	117 385 263	37 543 083	4 021 415	114 205 164	3 180 099	4 418 434	(1 237 161)	36 305 921	
	14	Jan-21		(33 521 668)	929 300	79 445 162	529 634	399 666		(396 055)	(1 530 439)	-	-	399 666	117 385 263	37 940 101	4 418 434	114 205 164	3 180 099	4 818 099	(1 349 068)	36 591 034	
	15	Feb-21		(33 521 668)	929 300	79 045 496	526 970	402 330		(396 055)	(1 524 163)	-	-	402 330	117 385 263	38 339 767	4 818 099	114 205 164	3 180 099	5 220 429	(1 461 720)	36 878 047	
	16	Mar-21		(33 521 668)	929 300	78 643 166	524 288	405 012		(396 055)	(1 515 206)	-	-	405 012	117 385 263	38 742 097	5 220 429	114 205 164	3 180 099	5 625 442	(1 575 124)	37 166 973	
	17	Apr-21		(33 521 668)	929 300	78 238 154	521 588	407 712		(396 055)	(1 503 549)	-	-	407 712	117 385 263	39 147 109	5 625 442	114 205 164	3 180 099	6 033 154	(1 689 283)	37 457 826	
	18	May-21		(33 521 668)	929 300	77 830 442	518 870	410 430		(396 055)	(1 489 173)	-	-	410 430	117 385 263	39 554 822	6 033 154	114 205 164	3 180 099	6 443 584	(1 804 204)	37 750 618	
	19	Jun-21		(33 521 668)	998 998	77 420 011	516 133	482 864		(396 055)	(1 402 364)	-	-	482 864	126 189 158	48 769 147	15 247 479	114 205 164	11 983 994	15 730 343	(4 404 496)	44 364 651	
	20	Jul-21		(33 521 668)	998 998	76 937 147	512 914	486 083		(396 055)	(1 312 335)	-	-	486 083	126 189 158	49 252 011	15 730 343	114 205 164	11 983 994	16 216 426	(4 540 599)	44 711 411	
	21	Aug-21		(33 521 668)	998 998	76 451 064	509 674	489 324		(396 055)	(1 219 067)	-	-	489 324	126 189 158	49 738 094	16 216 426	114 205 164	11 983 994	16 705 750	(4 677 610)	45 060 484	
	22	Sep-21		(33 521 668)	998 998	75 961 740	506 412	492 586		(396 055)	(1 122 535)	-	-	492 586	126 189 158	50 227 418	16 705 750	114 205 164	11 983 994	17 198 336	(4 815 534)	45 411 884	
	23	Oct-21		(33 521 668)	998 998	75 469 154	503 128	495 870		(396 055)	(1 022 720)	-	-	495 870	126 189 158	50 720 004	17 198 336	114 205 164	11 983 994	17 694 206	(4 954 378)	45 765 626	
	24	Nov-21		(33 521 668)	998 998	74 973 285	499 822	499 176		(396 055)	(919 600)	-	-	499 176	126 189 158	51 215 873	17 694 206	114 205 164	11 983 994	18 193 381	(5 094 147)	46 121 727	
	25	Dec-21		(33 521 668)	998 998	74 474 109	496 494	502 503		(396 055)	(813 151)	-	-	502 503	126 189 158	51 715 049	18 193 381	114 205 164	11 983 994	18 695 885	(5 234 848)	46 480 201	
	26	Jan-22		(33 521 668)	998 998	73 971 605	493 144	505 853		(396 055)	(703 353)	-	-	505 853	126 189 158	52 217 552	18 695 885	114 205 164	11 983 994	19 201 738	(5 376 487)	46 841 066	
	27	Feb-22		(33 521 668)	998 998	73 465 752	489 772	509 226		(396 055)	(590 182)	-	-	509 226	126 189 158	52 723 406	19 201 738	114 205 164	11 983 994	19 710 964	(5 519 070)	47 204 336	
	28	Mar-22		(33 521 668)	998 998	72 956 526	486 377	512 621		(396 055)	(473 616)	39 005	(10 921)	501 699	126 189 158	53 232 632	19 710 964	114 205 164	11 983 994	20 223 585	(5 662 604)	47 570 028	
	29	Apr-22		(33 521 668)	998 998	72 454 827	483 032	515 965		(396 055)	(353 705)	162 260	(45 433)	470 533	126 189 158	53 734 331	20 212 663	114 205 164	11 983 994	20 739 550	(5 807 074)	47 927 257	
	30	May-22		(33 521 668)	998 998	71 984 294	479 895	519 102		(396 055)	(230 658)	288 444	(80 764)	438 338	126 189 158	54 204 864	20 683 196	114 205 164	11 983 994	21 258 652	(5 952 423)	48 252 441	
	31	Jun-22		(33 521 668)	1 073 922	71 545 957	476 973	596 949		(396 055)	(29 764)	567 186	(158 812)	438 137	135 653 345	64 107 388	30 585 720	114 205 164	21 448 181	31 319 788	(8 769 541)	55 337 847	
	32	Jul-22		(33 521 668)	1 073 922	71 107 819	474 052	599 870		(396 055)	-	599 870	(167 964)	431 907	135 653 345	64 545 525	31 023 858	114 205 164	21 448 181	31 745 607	(8 888 770)	55 656 756	
	33	Aug-22		(33 521 668)	1 073 922	70 675 913	471 173	602 750		(396 055)	-	602 750	(168 770)	433 980	135 653 345	64 977 432	31 455 764	114 205 164	21 448 181	32 141 662	(8 999 665)	55 977 767	
	34	Sep-22		(33 521 668)	1 073 922	70 241 933	468 280	605 643		(396 055)	-	605 643	(169 580)	436 063	135 653 345	65 411 412	31 889 744	114 205 164	21 448 181	32 537 716	(9 110 561)	56 300 851	
	35	Oct-22		(33 521 668)	1 073 922	69 805 870	465 372	608 550		(396 055)	-	608 550	(170 394)	438 156	135 653 345	65 847 474	32 325 807	114 205 164	21 448 181	32 933 771	(9 221 456)	56 626 018	
	36	Nov-22		(33 521 668)	1 073 922	69 367 714	462 451	611 471		(396 055)	-	611 471	(171 212)	440 259	135 653 345	66 285 630	32 763 963	114 205 164	21 448 181	33 329 826	(9 332 351)	56 953 279	
	37	Dec-22		(33 521 668)	1 073 922	68 927 455	459 516	614 406		(396 055)	-	614 406	(172 034)	442 372	135 653 345	66 725 889	33 204 222	114 205 164	21 448 181	33 725 881	(9 443 247)	57 282 643	
	38	Jan-23		(33 521 668)	1 073 922	68 485 083	456 567	617 355		(396 055)	-	617 355	(172 859)	444 496	135 653 345	67 168 262	33 646 594	114 205 164	21 448 181	34 121 936	(9 554 142)	57 614 120	
	39	Feb-23		(33 521 668)	1 073 922	68 040 587	453 604	620 318		(396 055)	-	620 318	(173 689)	446 629	135 653 345	67 612 757	34 091 090	114 205 164	21 448 181	34 517 991	(9 665 037)	57 947 720	
	40	Mar-23		(33 521 668)	1 073 922	67 593 958	450 626	623 296		(396 055)	-	623 296	(174 523)	448 773	135 653 345	68 059 387	34 537 719	114 205 164	21 448 181	34 914 046	(9 775 933)	58 283 454	
	41	Apr-23		(33 521 668)	1 073 922	67 145 185	447 635	626 288		(396 055)	-	626 288	(175 361)	450 927	135 653 345	68 508 160	34 986 492	114 205 164	21 448 181	35 310 100	(9 886 828)	58 621 332	
	42	May-23		(33 521 668)	1 073 922	66 694 258	444 628	629 294		(396 055)	-	629 294	(176 202)	453 092	135 653 345	68 959 087	35 437 419	114 205 164	21 448 181	35 706 155	(9 997 723)	58 961 363	
	43	Jun-23		(33 521 668)	1 154 466	66 241 166	441 608	712 859		(396 055)	-	712 859	(199 600)	513 258	145 827 346	79 586 179	46 064 512	114 205 164	31 622 181	46 276 211	(12 957 339)	66 628 840	
	44	Jul-23		(33 521 668)	1 154 466	65 727 908	438 186	716 280		(396 055)	-	716 280	(200 559)	515 722	145 827 346	80 099 438	46 577 770	114 205 164	31 622 181	46 672 266	(13 068 234)	67 031 203	
	45	Aug-23		(33 521 668)	1 154 466	65 212 186	434 748	719 719		(396 055)	-	719 719	(201 521)	518 197	145 827 346	80 615 159	47 093 492	114 205 164	31 622 181	47 068 321	(13 179 130)	67 436 030	
	46	Sep-23		(33 521 668)	1 154 466	64 693 989	431 293	723 173		(396 055)	-	723 173	(202 489)	520 685	145 827 346	81 133 357	47 611 689	114 205 164	31 622 181	47 464 375	(13 290 025)	67 843 332	
	47	Oct-23		(33 521 668)	1 154 466	64 173 304	427 822	726 644		(396 055)	-	726 644	(203 460)	523 184	145 827 346	81 654 042	48 132 374	114 205 164	31 622 181	47 860 430	(13 400 920)	68 253 121	
	48	Nov-23		(33 521 668)	1 154 466	63 650 120	424 334	730 132		(396 055)	-	730 132	(204 437)	525 695	145 827 346	82 177 226	48 655 558	114 205 164	31 622 181	48 256 485	(13 511 816)	68 665 410	
	49	Dec-23		(33 521 668)	1 154 466	63 124 425	420 829	733 637		(396 055)	-	733 637	(205 418)	528 219	145 827 346	82 702 921	49 181 253	114 205 164	31 622 181	48 652 540	(13 622 711)	69 080 210	
	50	Jan-24		(33 521 668)	1 154 466	62 596 206	417 308	737 158		(396 055)	-	737 158	(206 404)	530 754	145 827 346	83 231 139	49 709 472	114 205 164	31 622 181	49 048 595	(13 733 607)	69 497 533	
	51	Feb-24		(33 521 668)	1 154 466	62 065 452	413 770	740 697		(396 055)	-	740 697	(207 395)	533 302	145 827 346	83 761 894	50 240 226	114 205 164	31 622 181	49 444 650	(13 844 502)	69 917 392	
	52	Mar-24		(33 521 668)	1 154 466	61 532 150	410 214	744 252		(396 055)	-	744 252	(208 391)	535 862	145 827 346	84 295 195	50 773 528	114 205 164	31 622 181	49 840 705	(13 955 397)	70 339 798	
	53	Apr-24		(33 521 668)	1 154 466	60 996 289	406 642	747 825		(396 055)	-	747 825	(209 391)	538 434	145 827 346	84 831 057	51 309 389	114 205 164	31 622 181	50 236 759	(14 066 293)	70 764 764	
	54	May-24		(33 521 668)	1 154 466	60 457 855	403 052	751 414		(396 055)	-	751 414	(210 396)	541 018	145 827 346	85 369 491	51 847 823	114 205 164	31 622 181	50 632 814	(14 177 188)	71 192 303	
	55	Jun-24		(33 521 668)	1 241 051	59 916 837	399 446	841 606		(396 055)	-	841 606	(235 650)	605 956	156 764 397	96 847 560	63 325 892	114 205 164	42 559 232	61 965 920	(17 350 458)	79 497 102	
	56	Jul-24		(33 521 668)	1 241 051	59 310 881	395 406	845 646		(396 055)	-	845 646	(236 781)	608 865	156 764 397	97 453 516	63 931 848	114 205 164	42 559 232	62 361 975	(17 461 353)	79 992 163	
	57	Aug-24		(33 521 668)	1 241 051	58 702 016	391 347	849 705		(396 055)	-	849 705	(237 917)	611 787	156 764 397	98 062 381	64 540 713	114 205 164	42 559 232	62 758 030	(17 572 248)	80 490 132	
	58	Sep-24		(33 521 668)	1 241 051	58 090 228	387 268	853 783		(396 055)	-	853 783	(239 059)	614 724	156 764 397	98 674 168	65 152 500	114 205 164	42 559 232	63 154 085	(17 683 144)	80 991 024	
	59	Oct-24		(33 521 668)	1 241 051	57 475 504	383 170	857 881		(396 055)	-	857 881	(240 207)	617 675	156 764 397	99 288 892	65 767 224	114 205 164	42 559 232	63 550 139	(17 794 039)	81 494 853	
	60	Nov-24		(33 521 668)	1 241 051	56 857 830	379 052	861 999		(396 055)	-	861 999	(241 360)	620 639	156 764 397	99 906 567	66 384 899	114 205 164	42 559 232	63 946 194	(17 904 934)	82 001 632	
	61	Dec-24		(33 521 668)	1 241 051	56 237 190	374 915	866 137		(396 055)	-	866 137	(242 518)	623 619	156 764 397	100 527 206	67 005 538	114 205 164	42 559 232	64 342 249	(18 015 830)	82 511 376	
	62	Jan-25		(33 521 668)	1 241 051	55 613 572	370 757	870 294		(396 055)	-	870 294	(243 682)	626 612	156 764 397	101 150 825	67 629 157	114 205 164	42 559 232	64 738 304	(18 126 725)	83 024 100	
	63	Feb-25		(33 521 668)	1 241 051	54 986 960	366 580	874 472		(396 055)	-	874 472	(244 852)	629 620	156 764 397	101 777 437	68 255 769	114 205 164	42 559 232	65 134 359	(18 237 620)	83 539 816	
	64	Mar-25		(33 521 668)	1 241 051	54 357 340	362 382	878 669		(396 055)	-	878 669	(246 027)	632 642	156 764 397	102 407 056	68 885 389	114 205 164	42 559 232	65 530 414	(18 348 516)	84 058 540	
	65	Apr-25		(33 521 668)	1 241 051	53 724 698	358 165	882 887		(396 055)	-	882 887	(247 208)	635 679	156 764 397	103 039 698	69 518 030	114 205 164	42 559 232	65 926 469	(18 459 411)	84 580 287	
	66	May-25		(33 521 668)	1 241 051	53 089 020	353 927	887 125		(396 055)	-	887 125	(248 395)	638 730	156 764 397	103 675 377	70 153 709	114 205 164	42 559 232	66 322 523	(18 570 307)	85 105 070	
	67	Jun-25		(33 521 668)	1 334 130	52 450 290	349 669	984 462		(396 055)	-	984 462	(275 649)	708 812	168 521 726	116 071 436	82 549 768	114 205 164	54 316 562	78 475 908	(21 973 254)	94 098 182	94 098 182

19 Appendix J: Reinforced Concrete Building Amortization Schedule

Total Development Cost	105 117 753
Land Equity	19 152 000
Additional Equity	3 796 069
Loan	82 169 684
Monthly Net Rental	929 300
Interest Rate	8,0%
Interim Interest	2 705 625
Capitalization Rate	9,5%
Lease Escalation Rate	7,5%
Tax Rate	28,0%
13 Quin Rate	5,0%
13 Quin Base	83 260 128

			EQUITY		RENTAL	DEBT FUNDING ANALYSIS			TAX ANALYSIS						ASSET VALUE ANALYSIS			PROCEEDS FROM SALE - PROFIT / (LOSS) AFTER SALE					25,7%
Programme	Month	Date	Equity Out Flows	Accumulative Equity	Net Rental	Loan Balance	Interest Payment	Profit / (Loss) Before Tax	Interest Write Off	13 Quin Allowances	Tax Deduction	Taxable Income	Tax Payable	After Tax Surplus	Development Value	Asset Value (Dev Value Less Loan Balance)	Net Asset Value (Asset Value Less Equity)	Cost of Sale - Tax Perspective	Gross Profit	Current Taxable Position	Tax Payable (Selling Price Less Base Cost)	Net Profit / (Loss) After Tax	Month 67 IRR
Land Purchase	1	Dec-19	(19 152 000)	(19 152 000)																			(19 152 000)
Construction Month 1	2	Jan-20	(1 665 203)	(20 817 203)																			(1 665 203)
Construction Month 2	3	Feb-20	(2 130 866)	(22 948 069)																			(2 130 866)
Construction Month 3	4	Mar-20		(22 948 069)																			
Construction Month 4	5	Apr-20		(22 948 069)																			
Construction Month 5	6	May-20		(22 948 069)																			
Construction Month 6	7	Jun-20		(22 948 069)																			
Construction Month 7	8	Jul-20		(22 948 069)																			
Construction Month 8	9	Aug-20		(22 948 069)																			
Construction Month 9	10	Sep-20		(22 948 069)																			
Construction Month 10	11	Oct-20		(22 948 069)																			
Lease Commencement	12	Nov-20		(22 948 069)	929 300	82 169 684	547 798	381 502	(2 705 625)	(346 917)	(2 671 040)	-	-	381 502	117 385 263	35 215 579	12 267 510	102 412 128	14 973 135	12 649 012	(3 541 723)	31 673 855	
	13	Dec-20		(22 948 069)	929 300	81 788 182	545 255	384 045		(346 917)	(2 633 912)	-	-	384 045	117 385 263	35 597 081	12 649 012	102 412 128	14 973 135	13 033 058	(3 649 256)	31 947 825	
	14	Jan-21		(22 948 069)	929 300	81 404 137	542 694	386 606		(346 917)	(2 594 223)	-	-	386 606	117 385 263	35 981 127	13 033 058	102 412 128	14 973 135	13 419 664	(3 757 506)	32 223 621	
	15	Feb-21		(22 948 069)	929 300	81 017 531	540 117	389 183		(346 917)	(2 551 957)	-	-	389 183	117 385 263	36 367 732	13 419 664	102 412 128	14 973 135	13 808 847	(3 866 477)	32 501 255	
	16	Mar-21		(22 948 069)	929 300	80 628 348	537 522	391 778		(346 917)	(2 507 097)	-	-	391 778	117 385 263	36 756 915	13 808 847	102 412 128	14 973 135	14 200 625	(3 976 175)	32 780 741	
	17	Apr-21		(22 948 069)	929 300	80 236 570	534 910	394 390		(346 917)	(2 459 625)	-	-	394 390	117 385 263	37 148 693	14 200 625	102 412 128	14 973 135	14 595 014	(4 086 604)	33 062 089	
	18	May-21		(22 948 069)	929 300	79 842 181	532 281	397 019		(346 917)	(2 409 523)	-	-	397 019	117 385 263	37 543 083	14 595 014	102 412 128	14 973 135	14 992 033	(4 197 769)	33 345 313	
	19	Jun-21		(22 948 069)	929 300	79 445 162	529 634	399 666		(346 917)	(2 356 775)	-	-	399 666	117 385 263	37 940 101	14 992 033	102 412 128	14 973 135	15 391 698	(4 309 676)	33 630 426	
	20	Jul-21		(22 948 069)	929 300	79 045 496	526 970	402 330		(346 917)	(2 301 362)	-	-	402 330	117 385 263	38 339 767	15 391 698	102 412 128	14 973 135	15 794 028	(4 422 328)	33 917 439	
	21	Aug-21		(22 948 069)	929 300	78 643 166	524 288	405 012		(346 917)	(2 243 267)	-	-	405 012	117 385 263	38 742 097	15 794 028	102 412 128	14 973 135	16 199 041	(4 535 731)	34 206 366	
	22	Sep-21		(22 948 069)	929 300	78 238 154	521 588	407 712		(346 917)	(2 182 472)	-	-	407 712	117 385 263	39 147 109	16 199 041	102 412 128	14 973 135	16 606 753	(4 649 891)	34 497 218	
	23	Oct-21		(22 948 069)	929 300	77 830 442	518 870	410 430		(346 917)	(2 118 958)	-	-	410 430	117 385 263	39 554 822	16 606 753	102 412 128	14 973 135	17 017 183	(4 764 811)	34 790 010	
	24	Nov-21		(22 948 069)	998 998	77 420 011	516 133	482 864		(346 917)	(1 983 012)	-	-	482 864	126 189 158	48 769 147	25 821 078	102 412 128	23 777 030	26 303 942	(7 365 104)	41 404 043	
	25	Dec-21		(22 948 069)	998 998	76 937 147	512 914	486 083		(346 917)	(1 843 846)	-	-	486 083	126 189 158	49 252 011	26 303 942	102 412 128	23 777 030	26 790 025	(7 501 207)	41 750 804	
	26	Jan-22		(22 948 069)	998 998	76 451 064	509 674	489 324		(346 917)	(1 701 439)	-	-	489 324	126 189 158	49 738 094	26 790 025	102 412 128	23 777 030	27 279 349	(7 638 218)	42 099 876	
	27	Feb-22		(22 948 069)	998 998	75 961 740	506 412	492 586		(346 917)	(1 555 770)	-	-	492 586	126 189 158	50 227 418	27 279 349	102 412 128	23 777 030	27 771 935	(7 776 142)	42 451 276	
	28	Mar-22		(22 948 069)	998 998	75 469 154	503 128	495 870		(346 917)	(1 406 818)	-	-	495 870	126 189 158	50 720 004	27 771 935	102 412 128	23 777 030	28 267 805	(7 914 985)	42 805 018	
	29	Apr-22		(22 948 069)	998 998	74 973 285	499 822	499 176		(346 917)	(1 254 559)	-	-	499 176	126 189 158	51 215 873	28 267 805	102 412 128	23 777 030	28 766 980	(8 054 755)	43 161 119	
	30	May-22		(22 948 069)	998 998	74 474 109	496 494	502 503		(346 917)	(1 098 973)	-	-	502 503	126 189 158	51 715 049	28 766 980	102 412 128	23 777 030	29 269 484	(8 195 455)	43 519 594	
	31	Jun-22		(22 948 069)	998 998	73 971 605	493 144	505 853		(346 917)	(940 037)	-	-	505 853	126 189 158	52 217 552	29 269 484	102 412 128	23 777 030	29 775 337	(8 337 094)	43 880 458	
	32	Jul-22		(22 948 069)	998 998	73 465 752	489 772	509 226		(346 917)	(777 728)	-	-	509 226	126 189 158	52 723 406	29 775 337	102 412 128	23 777 030	30 284 563	(8 479 678)	44 243 728	
	33	Aug-22		(22 948 069)	998 998	72 956 526	486 377	512 621		(346 917)	(612 025)	-	-	512 621	126 189 158	53 232 632	30 284 563	102 412 128	23 777 030	30 797 184	(8 623 211)	44 609 420	
	34	Sep-22		(22 948 069)	998 998	72 443 906	482 959	516 038		(346 917)	(442 904)	73 134	(20 478)	495 561	126 189 158	53 745 252	30 797 184	102 412 128	23 777 030	31 313 222	(8 767 702)	44 977 550	
	35	Oct-22		(22 948 069)	998 998	71 948 345	479 656	519 342		(346 917)	(270 479)	248 863	(69 682)	449 660	126 189 158	54 240 813	31 292 744	102 412 128	23 777 030	31 832 564	(8 913 118)	45 327 695	
	36	Nov-22		(22 948 069)	1 073 922	71 498 685	476 658	597 264		(346 917)	(20 132)	577 132	(161 597)	435 667	135 653 345	64 154 660	41 206 591	102 412 128	33 241 217	41 894 015	(11 730 324)	52 424 336	
	37	Dec-22		(22 948 069)	1 073 922	71 063 017	473 753	600 169		(346 917)	-	600 169	(168 047)	432 122	135 653 345	64 590 327	41 642 259	102 412 128	33 241 217	42 261 064	(11 833 098)	52 757 229	
	38	Jan-23		(22 948 069)	1 073 922	70 630 896	470 873	603 050		(346 917)	-	603 050	(168 854)	434 196	135 653 345	65 022 449	42 074 380	102 412 128	33 241 217	42 607 981	(11 930 235)	53 092 214	
	39	Feb-23		(22 948 069)	1 073 922	70 196 700	467 978	605 944		(346 917)	-	605 944	(169 664)	436 280	135 653 345	65 456 645	42 508 576	102 412 128	33 241 217	42 954 899	(12 027 372)	53 429 273	
	40	Mar-23		(22 948 069)	1 073 922	69 760 420	465 069	608 853		(346 917)	-	608 853	(170 479)	438 374	135 653 345	65 892 925	42 944 856	102 412 128	33 241 217	43 301 816	(12 124 508)	53 768 416	
	41	Apr-23		(22 948 069)	1 073 922	69 322 046	462 147	611 775		(346 917)	-	611 775	(171 297)	440 478	135 653 345	66 331 299	43 383 230	102 412 128	33 241 217	43 648 733	(12 221 645)	54 109 653	
	42	May-23		(22 948 069)	1 073 922	68 881 568	459 210	614 712		(346 917)	-	614 712	(172 119)	442 593	135 653 345	66 771 777	43 823 708	102 412 128	33 241 217	43 995 650	(12 318 782)	54 452 995	
	43	Jun-23		(22 948 069)	1 073 922	68 438 975	456 260	617 662		(346 917)	-	617 662	(172 945)	444 717	135 653 345	67 214 369	44 266 301	102 412 128	33 241 217	44 342 567	(12 415 919)	54 798 451	
	44	Jul-23		(22 948 069)	1 073 922	67 994 258	453 295	620 627		(346 917)	-	620 627	(173 776)	446 852	135 653 345	67 659 086	44 711 018	102 412 128	33 241 217	44 689 485	(12 513 056)	55 146 031	
	45	Aug-23		(22 948 069)	1 073 922	67 547 407	450 316	623 606		(346 917)	-	623 606	(174 610)	448 997	135 653 345	68 105 938	45 157 870	102 412 128	33 241 217	45 036 402	(12 610 193)	55 495 746	
	46	Sep-23		(22 948 069)	1 073 922	67 098 410	447 323	626 600		(346 917)	-	626 600	(175 448)	451 152	135 653 345	68 554 935	45 606 866	102 412 128	33 241 217	45 383 319	(12 707 329)	55 847 605	
	47	Oct-23		(22 948 069)	1 073 922	66 647 258	444 315	629 607		(346 917)	-	629 607	(176 290)	453 317	135 653 345	69 006 086	46 058 018	102 412 128	33 241 217	45 730 236	(12 804 466)	56 201 620	
	48	Nov-23		(22 948 069)	1 154 466	66 193 941	441 293	713 174		(346 917)	-	713 174	(199 689)	513 485	145 827 346	79 633 404	56 685 336	102 412 128	43 415 218	56 251 154	(15 750 323)	63 883 081	
	49	Dec-23		(22 948 069)	1 154 466	65 680 456	437 870	716 597		(346 917)	-	716 597	(200 647)	515 950	145 827 346	80 146 889	57 198 821	102 412 128	43 415 218	56 598 071	(15 847 460)	64 299 429	
	50	Jan-24		(22 948 069)	1 154 466	65 164 507	434 430	720 036		(346 917)	-	720 036	(201 610)	518 426	145 827 346	80 662 839	57 714 770	102 412 128	43 415 218	56 944 989	(15 944 597)	64 718 242	
	51	Feb-24		(22 948 069)	1 154 466	64 646 080	430 974	723 493		(346 917)	-	723 493	(202 578)	520 915	145 827 346	81 181 265	58 233 197	102 412 128	43 415 218	57 291 906	(16 041 734)	65 139 532	
	52	Mar-24		(22 948 069)	1 154 466	64 125 166	427 501	726 965		(346 917)	-	726 965	(203 550)	523 415	145 827 346	81 702 180	58 754 111	102 412 128	43 415 218	57 638 823	(16 138 870)	65 563 309	
	53	Apr-24		(22 948 069)	1 154 466	63 601 751	424 012	730 455		(346 917)	-	730 455	(204 527)	525 927	145 827 346	82 225 595	59 277 526	102 412 128	43 415 218	57 985 740	(16 236 007)	65 989 588	
	54	May-24		(22 948 069)	1 154 466	63 075 823	420 505	733 961		(346 917)	-	733 961	(205 509)	528 452	145 827 346	82 751 522	59 803 454	102 412 128	43 415 218	58 332 657	(16 333 144)	66 418 378	
	55	Jun-24		(22 948 069)	1 154 466	62 547 371	416 982	737 484		(346 917)	-	737 484	(206 496)	530 988	145 827 346	83 279 974	60 331 906	102 412 128	43 415 218	58 679 575	(16 430 281)	66 849 693	
	56	Jul-24		(22 948 069)	1 154 466	62 016 383	413 443	741 024		(346 917)	-	741 024	(207 487)	533 537	145 827 346	83 810 963	60 862 894	102 412 128	43 415 218	59 026 492	(16 527 418)	67 283 545	
	57	Aug-24		(22 948 069)	1 154 466	61 482 846	409 886	744 581		(346 917)	-	744 581	(208 483)	536 098	145 827 346	84 344 500	61 396 432	102 412 128	43 415 218	59 373 409	(16 624 555)	67 719 946	
	58	Sep-24		(22 948 069)	1 154 466	60 946 747	406 312	748 155		(346 917)	-	748 155	(209 483)	538 671	145 827 346	84 880 598	61 932 530	102 412 128	43 415 218	59 720 326	(16 721 691)	68 158 907	
	59	Oct-24		(22 948 069)	1 154 466	60 408 076	402 721	751 746		(346 917)	-	751 746	(210 489)	541 257	145 827 346	85 419 270	62 471 201	102 412 128	43 415 218	60 067 243	(16 818 828)	68 600 442	
	60	Nov-24		(22 948 069)	1 241 051	59 866 819	399 112	841 939		(346 917)	-	841 939	(235 743)	606 196	156 764 397	96 897 578	73 949 509	102 412 128	54 352 269	71 351 212	(19 978 339)	76 919 239	
	61	Dec-24		(22 948 069)	1 241 051	59 260 622	395 071	845 981		(346 917)	-	845 981	(236 875)	609 106	156 764 397	97 503 774	74 555 706	102 412 128	54 352 269	71 698 129	(20 075 476)	77 428 298	
	62	Jan-25		(22 948 069)	1 241 051	58 651 516	391 010	850 041		(346 917)	-	850 041	(238 012)	612 030	156 764 397	98 112 880	75 164 812	102 412 128	54 352 269	72 045 046	(20 172 613)	77 940 267	
	63	Feb-25		(22 948 069)	1 241 051	58 039 487	386 930	854 122		(346 917)	-	854 122	(239 154)	614 968	156 764 397	98 724 910	75 776 841	102 412 128	54 352 269	72 391 963	(20 269 750)	78 455 160	
	64	Mar-25		(22 948 069)	1 241 051	57 424 519	382 830	858 221		(346 917)	-	858 221	(240 302)	617 919	156 764 397	99 339 878	76 391 809	102 412 128	54 352 269	72 738 880	(20 366 886)	78 972 991	
	65	Apr-25		(22 948 069)	1 241 051	56 806 600	378 711	862 341		(346 917)	-	862 341	(241 455)	620 885	156 764 397	99 957 797	77 009 728	102 412 128	54 352 269	73 085 798	(20 464 023)	79 493 774	
	66	May-25		(22 948 069)	1 241 051	56 185 714	374 571	866 480		(346 917)	-	866 480	(242 614)	623 866	156 764 397	100 578 682	77 630 614	102 412 128	54 352 269	73 432 715	(20 561 160)	80 017 522	
	67	Jun-25		(22 948 069)	1 241 051	55 561 849	370 412	870 639		(346 917)	-	870 639	(243 779)	626 860	156 764 397	101 202 548	78 254 479	102 412 128	54 352 269	73 779 632	(20 658 297)	80 544 251	80 544 251