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Mass timber: Improving on-site productivity for multi-storey construction.

by Richard E. Brisland

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Masters by Research

under the supervision of
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Certificate of Original Authorship

I, Richard Brisland, declare that this thesis is submitted in fulfilment of the requirements for the award of Masters by Research degree in the School of Built Environment, Faculty of Design, Architecture and Building at the University of Technology Sydney.

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

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

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List of Publications

1. Forsythe, P., **Brisland, R.** and Sepasgozar, S. (2016) “Measuring Installation Productivity on Panelised and Long Span Timber Construction”, published by Forest and Wood Products Australia.
The author captured prefabricated timber panel installation of four projects by time-based digital video camera and manual sampling. From the video files the author recorded and analysed each of the four project’s panel crane cycles and productivity, included in the paper.

2. **Brisland, R.,** Forsythe, P. and Fini, A.A.F (2019) “Mass timber productivity: the significance of the reduction in non-value-add activities during on-site installation sequence”, presented at and published by Modular and Offsite Construction Conference, Banff, Canada May 2019.

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Abstract

Mass timber is a prefabricated, panelised form of building with many benefits such as faster construction and a reduction in both process waste and environmental impact. With worldwide population forecast to increase to 10 billion by 2055 and buildings using 40% of global energy and contributing over 33% of greenhouse gas emissions, mass timber can improve construction and increase industry's productivity.

However, the uptake of mass timber by Australia's general construction industry has been slow, partly because insufficient quantitative productivity data is available to help contractors and developers forecast cost, time or resources for timber projects. The knowledge gap results in risk-averse pricing by contractors and clients and increased contingency pricing behaviour, which penalises mass timber's uptake.

This study focuses on mass timber on-site productivity in multi-storey construction to develop a method to forecast and identify the significant factors affecting its on-site productivity.

A quantitative research case study approach was adopted. A method to measure installation data in multi-storey construction was designed to develop an indicative baseline productivity matrix and identify significant determinants, including materials handling and resourcing.

Mass timber installation time and motion studies using a time-lapse digital video recording camera were conducted on three multi-storey residential buildings to understand on-site mass timber installation processes. This study included an analysis of repetitive work cycles and productivity factors, including crane cycle times and installation crew sizes.

A mass timber productivity baseline matrix was established to categorise panel type and size for productivity improvement potential and identify a leading input resource.

Five potential areas of process improvement, both in construction and design, were assessed. Larger size panels were found to provide significantly improved productivity over smaller panels. The crane, not labour, was found to be the primary input resource. Wind had the most significant adverse inclement weather effect on productivity. Floor level height did not statistically significantly affect productivity. Mass timber productivity models were developed from the above factors to forecast CLT panels' and mean daily productivity. A merged model is presented with the relevant steps in the design and pre-construction stages to provide maximum efficiencies in mass timber projects. The model identifies the critical factors to address during the design and pre-construction stages.

The findings and the empirical and quantitative models presented extend current theoretical knowledge. It provides tools to improve and forecast on-site productivity for mass timber multi-storey construction and enhance overall productivity for the construction industry.

Key Definitions

Component is a product, which is produced for a specified place or function, in a building or a building system that dictates its design.

Context is the surrounding physical or theoretical conditions of something, through which an object or issue can be understood, by which it can be influenced and on which it can have influence.

Cross-laminated timber (CLT) is a component built up by layers of boards glued together in two or more directions.

Glulam is a composite of timber and glue. It denotes laminated timber of four or more boards/lamellas glued together. The most common elements are columns and beams.

High rise building refers to a building comprising over seven stories above ground level

Light timber construction denotes stud-framed timber structures, commonly in the range of the widespread "two by four" system. The structure then minimises material volume and is built up by several layers with specific functions.

*Mass timber (*or "*massive timber,*" i.e. *massive timber construction)* is broadly defined as layers of wood that have been joined together to create more significant timber elements that are both stronger and more behaviourally predictable than sawn timber (rethink Wood 2014). Mass timber has several meanings and definitions, depending on trademark-registered principles of production. Other terms are "solid wood", "heavy timber" and "laminated timber". "Massivträ" is the proposed Swedish term. In German the term "Massivholz" is common, but "Brettsperrholz" is also used for plate-like elements.

Medium-rise building refers to a building from three to seven stories above ground level.

Module is an independent part or unit, which can be combined with others to form a structure or building.

Multi-storey building is a building with three or more stories.

Non-value-added is an activity carried out that is not critical or is superfluous to the productivity of the product installed.

Prefabrication (construction) is "a process involving the fabrication or assembly of systems and components off-site, which, when complete, are transported to the job site for installation at the required time. It is an innovative process aiming to minimise on-site fabrication activities more efficiently, in a controlled environment, to achieve gains in quality, costs and time on-site" (Committee on Advancing the Competitiveness and Productivity of U.S. Construction Industry CACPUCI (2009).

Productivity is the effectiveness of productive effort, especially in industry, as measured in terms of the rate of output per unit of input (*Oxford English Dictionary).*

Sub-system is a group of parts related to each other on a specific level. The group is related to other groups as well as to governing systems on a higher level.

Surface element is an element with its main extension in two dimensions.

System is a group of related parts, which work together as a whole. System effect can be noted when relations between different parts of a group get developed to work well.

Value-added is an activity critical to the productivity of the product installed.

Webcam is a video camera connected to a computer, allowing its images to be seen by authorised internet users.

Key Abbreviations

ANOVA = Analysis of Variance

CLT = Cross Laminated Timber.

CD = completion date

CL = Centre Line.

DfMA = Designed for Manufacture and Assembly

Glulam = Glued laminated (bonded) timber

HLP = High Level Productivity

IBS = Industrialised Building Systems.

LCL = Lower Control Line.

LVL: Laminated Veneered Lumber

OSM = Off-site Manufacture

SD = start date

TQC = Total Quality Control

UCL = Upper Control Line.

U.K. = United Kingdom

Chapter 1 Introduction

1.1 The importance of construction productivity

A wealth of a nation is determined by its national productivity (Smith, A., 1776). The construction industry is generally considered an important industry sector by most governments for its overall productivity outcome. It is an enabling sector of the economy and a significant performance indicator of the general economic activity for developed and developing countries (Kenley, 2014; Yi and Chan, 2014). Research covering Australia, Finland, New Zealand, Singapore, United Kingdom, Western Europe and the United States has found that the construction industry has a crucial role in growing and sustaining gross domestic product (G.D.P.) of a country (Best, 2008; Kenley, 2014). Due to this, the construction industry's productivity is important through all levels, from macro to microeconomics (Australian Productivity Commission, 2014; Kenley, 2014; Yi et al., 2014). Horner and Duff (2001) put this in context by the example that if construction productivity improved by 10% in the U.K., the savings would be sufficient to procure 30 hospitals or 30,000 houses each year. If the Australian construction industry increased its productivity by a small 0.3%, it is estimated that this would improve national G.D.P. by $6.6bn, more than double that of any other sector (Khalfan and Maqsood, 2014)

1.1.1 Construction productivity: an ongoing issue

Construction productivity has been a subject of interest and discussion over the past decades. Despite its importance, there is statistical evidence that indicates productivity has been an ongoing issue in the construction industry (Barbosa et al., 2017).

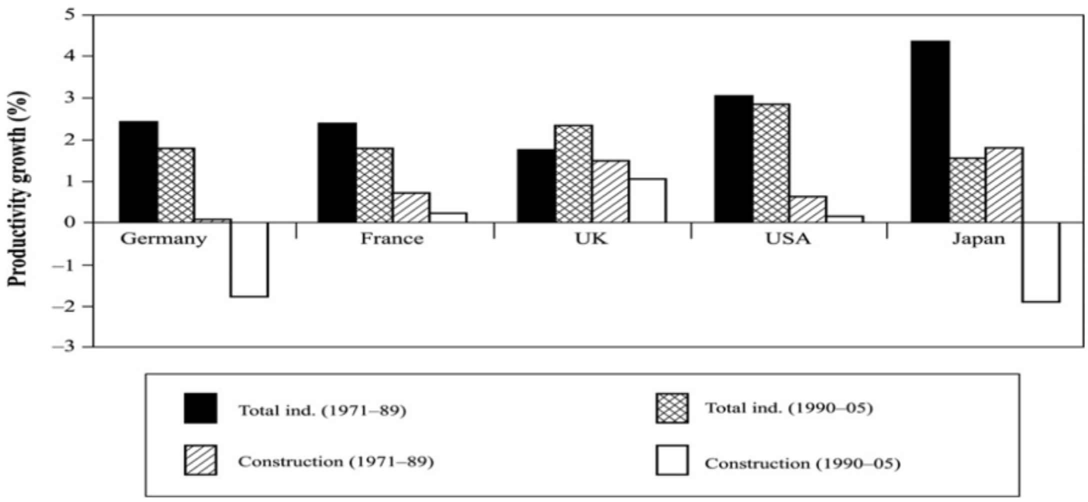

Figure 1.1 OECD productivity growth 1971-2005(Abdel-Wahab and Vogi, 2011)

Despite an argument over how productivity is measured (Allmon et al., 2000; Eastman and Sacks, 2008; Thomas, H.R. et al., 1990; Yi et al., 2014), there are a significant number of people who believe that the construction industry and its productivity has underperformed since the 1970s, as illustrated in Figure 1.1 above (Abdel-Wahab et al., 2011; Arditi, 1985; Christian and Hachey, 1995; Drewer, 1990; Mahapatra and Gustavsson, 2008; McKinsey Group Institute and Practice, 2017; Yi et al., 2014). The chart indicates that labour productivity, generally, has either stagnated or declined during these 34 years. The U.K., was the only exception, although from 1990 its productivity was still less than half of the other industries. (Abdel-Wahab et al., 2011). Productivity growth in the Australian construction sector also stagnated and declined up to 2014 and was not significantly different from other developed countries (Australian Construction Industry Forum, 2014; Chancellor, 2015). This poor performance is still a current issue as the Australian construction industry, although slightly improved 2015-17, declined again by 4% in 2018-19 (Australian Bureau of Statistics, 2019). The weight of the argument suggests that there has been long-term underperformance in construction.

1.1.2 A need for change

To improve both economic outcomes and organisational profitability, this decline and stagnation in construction productivity must be addressed (Australian

Productivity Commission, 2014; Durdyev and Mbachu, 2011; Kenley, 2014; Sandbhor and Botre, 2014; Yi et al., 2014). During the past four decades, as detailed in Figure 1.1, other industries improved their productivity output. In all the countries, the construction industry has underperformed compared to other sectors, and this is partly due to it not adopting new technologies as efficiently as other industries (Goodrum, P. et al., 2009; Hassell et al., 2001; McKinsey Group Institute et al., 2017; Xue et al., 2014). It was also true in Australia, where there was an average growth in productivity across all other industries from 1995 to 2016 as opposed to the reported general decline in construction (Australian Bureau of Statistics, 2016). McKinsey's research eloquently expressed that while other industries have reinvented themselves "construction seems stuck in a time warp". The industry needs to change towards a manufacturing-inspired mass production system, in which the bulk of a construction project is built from off-site prefabricated standardised components (Barbosa et al., 2017).

Innovation has been associated with improved productivity (Soames et al., 2011). According to a study by Hassell et al. (2001), the U.S. construction industry invested less than 0.5% of the value of its sales in research and development, in comparison, the national average was over 3%. Even those who may be sceptical of this reported underperformance, tend to agree that construction productivity has not adequately adopted, and thus benefited from, innovative technologies (Barbosa et al., 2017; McKinsey & Co. et al., 2016).

1.1.3 Governments' support for change

Governments and institutions, especially in Japan, Scandinavia and the U.K., have accepted this view. They have taken action by way of publications and policy changes, as outlined below, to promote improvement in construction productivity and encourage uptake in industrialised methods (Bergstrom and Stehn, 2005; Boyd et al., 2013; Cooperative Research Centre for Construction Innovation, 2007a; McKinsey & Co. et al., 2016; Rashidi and Ibrahim, 2017; Viking and Lidelow, 2015; Yashiro, 2014). The Japanese government was proactive earlier than other countries, in 1948, providing incentives and a technical code for industrialised housing to encourage change (Yashiro, 2014). This encouragement was later reinforced, in 1998, with the "Future direction" of the construction industry structural change" policy (Rashidi et al., 2017).

The Swedish government, in 1965, enacted the "Million Homes Programme", to correct their shortage of housing, to build one million houses over ten years, using large-scale industrialised construction (Hall, T. and Viden, 2005). In 2002, the Finland government issued a policy change and publication of "Re-engineering the construction process using I.T." (Rashidi et al., 2017). The Swedish government rationalised legislation, in 2014, to further promote industrialised building (Viking et al., 2015). The U.K. government took action with their "Towards a 30% productivity improvement in Construction" report in 1996 (Construction Industry Board (Great Britain) and Working Group 11, 1996). This was followed by the Egan report "Construction task force: rethinking construction" in 1998 (Egan, 1998). In 2011 and 2016, the U.K. mandated building information modelling (BIM) into their government contracts (Infrastructure and Projects Authority UK, 2016). The U.S. and Canada updated their national code (the International Code Council, I.C.C.) in 2015, to allow the use of timber prefabrication in offices up to six stories and residential up to five, which is expected to be revised in 2021 to 18 stories for certain classifications (Anderson et al., 2020). It was not until 2016 that the Australian government introduced code changes to assist industrialised building, in its timber format, to be incorporated in structures up to 26 metres tall (Wood Solutions, 2016). Government support is an important criterion in leading construction industry to change from its traditional ways to improve productivity (Barbosa et al., 2017{Smyth, 2018 #317; Lehmann, 2012b; Smyth, 2018).

1.1.4 Is innovation and industrialisation an answer?

It is essential to pursue innovation in construction and ensure the construction industry adopts proven innovative products and systems to uplift its productivity output (Girmscheid, 2010; Van Egmond-de Wilde De Ligny, 2010). A recent McKinsey report recommended that an industrialised and integrated approach be adopted in construction, which they estimated, if implemented, could improve the sector's productivity by up to 60% (Barbosa et al., 2017). The industrial revolution was driven by innovation. Innovation has resulted in significantly improved productivity in sectors other than the building industry over the past four decades (CIB Task Group 57, 2010). Industrialised building systems are, however, relatively new to the construction-related activities in Australia and other developed and developing countries (Yashiro, T., 2014). Therefore, further scientific investigation is required into such innovative systems to realise their possible potential in resolving the current productivity issues.

1.1.5 Macro versus Micro-economic approach

Performance of an economy is only as good as the performance of its components (Abdel-Wahab et al., 2011). As the broad economic issues are a result of industry trends, company competitiveness, project profitability and ultimately activity efficiencies, a bottom-up approach must be implemented. In this context, it is worthwhile differentiating macro and micro economic measurement of productivity. Productivity at the macroeconomic level generally estimates the aggregate productivity across an entire industry, within a country or region (Choi et al., 2013; 5Goodrum, P. M. et al., 2002). At the microeconomic level productivity is measured at an activity level, whereby an activity could be an installation of structural steel to a warehouse or laying bricks to an office facade. It shows what productivity was achieved for a specific trade activity on a given project, or an average of what could be achieved across multiple projects (Goodrum, P. M. et al., 2002; Thomas, H.R. et al., 1992). However, a problem exists insofar as conflicts with these two methods of measuring productivity provide different outcomes.

These differences are because the macroeconomic data is compiled from various government agencies, each using different methodologies and analyses to create their data series (Goodrum, P. M. et al., 2002; Yi et al., 2014). At an activity level, the problems of output measurement associated with aggregated data are avoided. Inputs and outputs are easier to compare at the activity level as the characteristics of the final component output tend to remain the same over time (Goodrum, P. M. et al., 2002). It provides a reliable means of measuring repetitious activities that allows a bottom-up approach to productivity measurement that is useful to building more efficiently.

1.1.6 Focus of measurement

On this basis, the position taken in this research is to focus on the activity level, which provides a more accurate account of project performance. (Forsythe and Sepasgozar, 2019b; Goodrum, P. M. et al., 2002). This level is more suited for assessing project performance and is more appropriate for the contractor's estimating, planning and programming (Forsythe et al., 2019b). The activity level of study is of interest to this research because of its inherent detailed focus on installation of construction components, specifically industrialised building systems. A more specific area of study is an activity level of inquiry into how it occurs within projects (Forsythe et al., 2019b). This approach is underpinned by the extensive productivity studies at this level with over 17,000 papers relating to the subject on the Emerald Publishing database, which is indicative of its importance (Association of Researchers in Construction Management, 2000; Emerald Insight, 2020).

1.2 Improving productivity by industrialisation

The Conseil International du Bâtiment defined industrialisation in construction[1] (C.I.B.) Task Group 57 (CIB Task Group 57, 2010), at its first meeting as "a rationalisation of work processes in the industry to reach cost efficiency, higher productivity and quality". The consequences of industrialised construction are improved performance through mass production, mass customisation, prefabrication, standardisation and modularisation by the use of mechanised, automated and intelligent tools (CIB Task Group 57, 2010). Industrialised construction can be typified by standardisation and off-site manufacture of building parts and modules (Girmscheid, 2010). In addition to the improved performance, off-site manufacturing controlled production provides benefits such as a reduction in waste and emissions, which can contribute in meeting environmentally sustainable construction targets and objectives (Van Egmond, 2010; Zabihi et al., 2013).

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[1] CIB in English: International Council for Building

Recent efforts to introduce "smart" or "modern" methods of construction by way of adopting industrialised practices is due to the importance to improve construction efficiency and productivity (Liu et al., 2018). Innovation has mostly been through industrialisation (CIB Task Group 57, 2010; Van Egmond, 2010). Constructing buildings using industrialised building methods, such as in prefabricated forms, was adopted to rapidly improve productivity and provide greater construction output with cost-efficient outcomes during World War 2 and the post-war years (Elliott, K. S. & Jolly, C. K. 2013: Etxepare, L., Uranga, E., J. & Zuazua, G. N. 2015; Zabihi et al. 2012).

Although the use of off-site manufactured pre-cast concrete declined in the late 1980's (Elliott and Jolly, 2013), due, in part, to its poor quality perception of post war housing (Duc et al., 2014), prefabrication has been identified as a critical component in "lean" construction systems to improve productivity and waste reduction (Ballard et al., 2002; Khalili and Chua, 2013; Pheng and Chuan, 2001). The process of moving pre-assembly activities off-site, increases quality and reduces on-site activities and waste in the assembly of prefabricated components (Pheng et al., 2001). Industrialisation is reasonably advanced in Japan and Scandinavia (Viking et al., 2015; Yashiro, 2014) and is progressing in the United Kingdom due to government initiatives especially with the facet of BIM (Cao and Chen, 2017; Thompson, 2017). However, in Australia, its progress is slow (Kremer, P. and Symmons, 2016; McKinsey Group Institute et al., 2017; Thanoon et al., 2003). The graph below, Figure 1.2 adapted from C.I.B. Task Group (2010), is a generalised representation of the progressive transition in industrialised construction from the use of traditional manufactured small components.

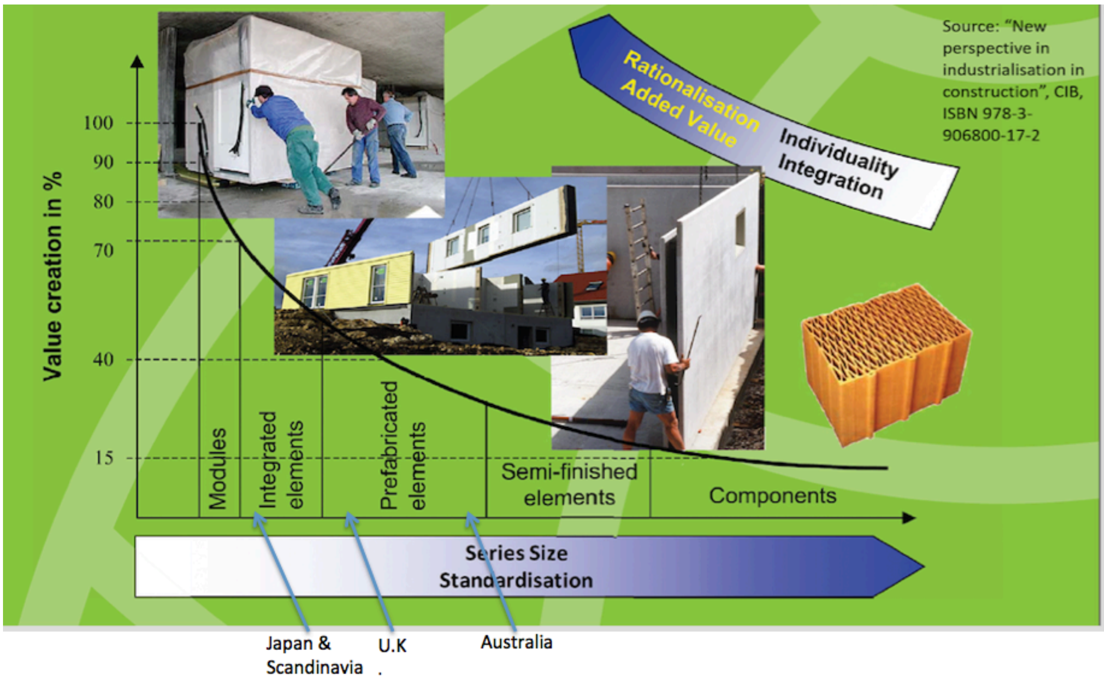

Figure 1.2 Impact of content and spatial integration (CIB Task Group 57, 2010)

This progression commences from industrialised production of standard small series size components towards increased content and spatiality, i.e., prefabricated elements, and ultimately to modules of finished rooms or buildings. As this progression flows to more sophistication, it adds increased monetary value due to the inherent efficiencies of increased factory production (Girmscheid, 2010). Suggested markers, for each of the countries mentioned above, are superimposed in Figure 1.2 to illustrate their progress in this industrialised on-site transition. Although Australia is a developed country, it has not been as progressive in the uptake of industrialised methods as other developed countries (Cooperative Research Centre for Construction Innovation, 2007; Blismas, 2009; Khalfan, 2014). The graph indicates that the further along the industrialisation path to modularisation, productivity improves and the value creation is increased exponentially (Girmscheid, 2010).

Industrialised building systems include various types of prefabrication and modularisation. Off-site prefabrication includes off-site pre-assembly, panelised systems and volumetric modular components and buildings (Li et al., 2014; Shahzad, W. M. and Mbachu, 2013). Off-site pre-assembly refers to small building components manufactured and transported to site for assembly, e.g., roof trusses and beams. Panelised systems refer to manufactured structural systems transported to site and erected; examples include pre-cast concrete panels, mass timber and prefabricated façade panels (Girmscheid, 2010). Modular components and buildings include off-site manufactured rooms and building complete with interior finishes, e.g. restroom pods, completed rooms such as plant rooms and clean rooms to complete apartments or buildings (Boyd et al., 2013; Girmscheid, 2010; Li et al., 2014). Off-site prefabrication is discussed in more detail, chapter 3.

Additional benefits are obtained from the adoption of industrialised building systems, e.g. environmental sustainability and user-friendliness (Zabihi et al., 2013; Zakaria et al., 2018). For example, the Netherlands, Belgium, and Scandinavian countries found industrialised building systems are accompanied by environmental and lifespan gains in buildings and reduction in waste (Van Egmond, 2010).

Despite these benefits, industrialised systems have not gained traction in Australia. Even though historically used, it is generally considered by the industry as a novel or non-traditional form of construction and by the public's historical perception as poor quality and temporary (Bowyer, J. et al., 2016; Riala and Ilola, 2014; Vale, 1995), especially in Australia (Duc et al., 2014; Lehmann, 2012b). As a consequence, industrialised systems are not often adopted in multi-storey construction (Ruuska and Hakkinen, 2016). This lack of take-up is evidenced by limited on-site productivity studies as earlier discussed (Forsythe et al., 2016; Goodrum, P. et al., 2009).

The estimated accelerated population growth of an additional 3 billion people globally by 2050 and a 40% increase in Australia, will translate into a further intensified increase in urbanisation. Thus, the current and future need for multi-storey construction in the cities will magnify (Cohen, 2003; Lehmann, 2012b; Robertson et al., 2012; The United Nations, 2018). Environmental sustainability is an essential criterion in selecting future construction materials. Currently, buildings are responsible for more than 40% of global energy use and one-third of global greenhouse gas emissions, both in developed and developing countries

(United Nations Environment Programme and Sustainable Building and Climate Initiative, 2009). Consequently, an alternative is urgently required to the current inefficient and heavily polluting practices of traditional construction. One such option is by the adoption of sustainable prefabricated systems providing advantages in more efficient and speedy construction and one of low environmental impact (d'Errico, 2016; Kaiser et al., 2018; Lehmann, 2012b). Such outcomes can be achieved through standardised, environmentally sustainable, off-site fabricated components with replicated typical floor layouts in mid and high-rise buildings (Lehmann, 2012a). This process will result in a reduction in time and impact on site, which is briefly discussed in 1.4 below and with more detail in Chapter 3.

1.3 The importance of Mass timber as an industrialised form

Prefabrication is a typical form of industrialised systems, and mass timber is a modern innovative prefabricated system that lends itself to industrialisation. It provides additional benefits that could change the construction process. Mass timber is of interest because it is made from wood, the only sustainable building material, which can enhance a building's energy-efficiency (Bowyer, J. et al., 2016; d'Errico, 2016; Ruuska et al., 2016). Wood provides inherent benefits of an environmentally friendly carbon sequestration footprint and considerable greenhouse gas reduction compared to concrete or steel (Bowyer, J. et al., 2016; Dovetail Partners, 2013; Falk, 2010; Gustavsson and Sathre, 2006; Lehmann, 2013; Van Egmond, 2010). Timber is abundant and renewable, and is a suitable economic resource for use in prefabricated products to construct building structures (Bowyer, J. et al., 2016; Lehmann, 2013). Timber befits prefabrication as it is lightweight, easily cut and fabricated utilising digital design modelling by "file to factory" format, which provides a high degree of accuracy (Forsythe et al., 2019b; Kaiser et al., 2018; Larsson et al., 2012).

Recently, there have been reports of significantly improved on-site construction productivity with the use of mass timber systems particularly on multi-storey buildings (Bowyer, J. et al., 2016; d'Errico, 2016; Lehmann, 2012a). Early mass timber projects include the Stadhaus, an 8-storey mass timber structure completed in 2009 and the 9-storey Bridport House project, both in East London, completed in 2010. Using similar technology, each project saved more than 25% in overall project time compared to traditional construction (d'Errico, 2016; Lehmann, 2012b; Mallo, 2014; Robertson et al., 2012).

There are many factors in the choice of industrialised building systems. It is not just improved productivity, but its end-user liveability and comfort and environmental sustainability (Anderson et al., 2020; Lehmann, 2012b). Mass timber, which includes cross-laminated timber (CLT), glulam, laminated veneer lumber (LVL) and post-tensioned laminated beams and columns, is a modern material that meets these needs (Anderson et al., 2020). In a theoretical perspective, this research uses mass timber as a representation of industrialised building systems.

Australia's low take-up

Despite its advantages, Australia's uptake in mass timber has been fragmented and slow, as indicated in Figure 1.3 below. Its first mass timber project, the ten-storey "Forte" building in Melbourne, was completed in 2012 (d'Errico, 2016; Lehmann, 2012b).

As noted in Fig 1.3, Australia used almost 17,700m^3 of CLT in 2019 (Dunn, 2020a) but this is negligible compared to Europe, which consumed 821,270m^3 in the same year (Imarc Group Market Research, 2020). Japan used 60,000 m^3 in 2016, compared to Australia's 3,500 m^3 with plans to reach an annual production of 500,000m^3 by 2024 (Smyth, 2018).

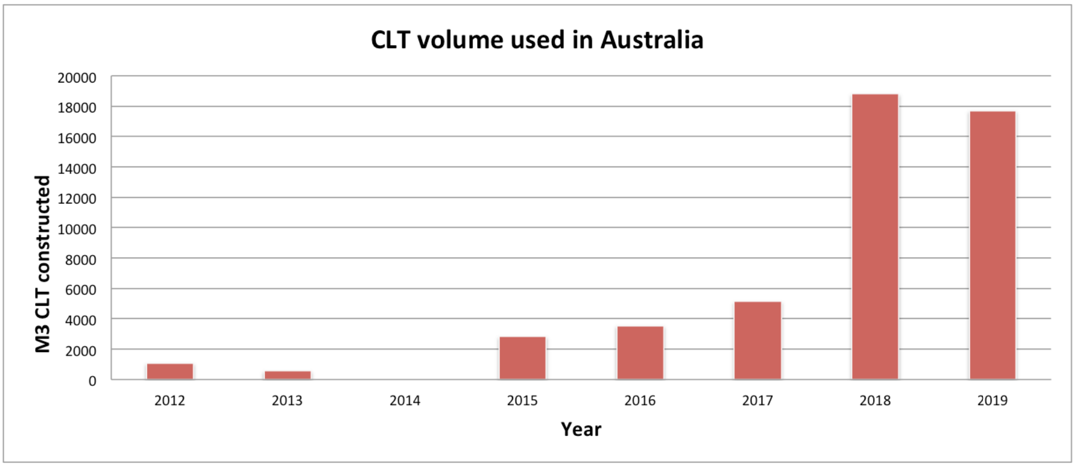

Figure 1.3 Chart of CLT volume (M^3) used in Australia 2012-19 (Dunn, 2020a)

Mass timber is still considered new by the general industry and is relatively uncommon. Between 2018 and 2019, Australia's uptake in mass timber had increased from one in 2012 to a total of 30 projects completed in 2018 and 46 projects in 2019 (Dunn, 2020a). Australia's mass timber penetration has been small compared to the 650,000 non-residential and residential projects (0.01%) constructed during the same period (Australian Bureau of Statistics, 2020). This low market penetration was supported in Kremer's study (2016), which found that mass timber construction lagged behind many other overseas markets due to perceived barriers and lack of local expertise. Canada and the U.S. are slightly ahead but on a similar progression path to Australia, with a total 46 and 290 mass timber projects, respectively, completed up to the end of 2019 (Kremer, P. et al., 2016; Mass Timber Institute, 2020; WoodWorks and Wood Products Council, 2020). The interest in panelised mass timber is slowly increasing over time in Australia, as indicated, but, although it has great potential in improving output and providing numerous benefits, is still yet to be broadly adopted by industry (Kremer, P. et al., 2016). One of the reasons for its lack of take up is the limited quantitative on-site studies available to assist in knowledge transfer to industry (Kremer, P. et al., 2016; Mahapatra et al., 2008; Schmidt et al., 2018). Additional empirical on-site productivity and on-site application of industrialised timber systems is required to assist in this take up (Forsythe et al., 2019b; Khalfan et al., 2014; Lehmann, 2012b; Smith, R. et al., 2018).

1.4 Off-site versus on-site efficiency

In the limited research on the subject, there appears an expectation that efficiency of industrialised systems, such as mass timber, is derived purely from off-site manufacture. Many believe that off-site manufacture provides a "silver bullet" to improve overall project outcome, both in time and cost efficiency without consideration of on-site process (Duc et al., 2014; Ruuska et al., 2016). There appears to be an assumption that by taking components to off-site manufacture (OSM), it will organically trigger changes in on-site processes to provide savings to offset the additional cost premium of the component's OSM. However, attainment of on-site savings is not currently the case (Duc et al., 2014; Khalfan et al., 2014; Vrijhoef and Koskela, 2000). To provide the on-site cost savings required (to offset the OSM costs), it is essential to change the current traditional on-site process for installation of OSM components.

For these savings to occur, changes in on-site procedures for OSM components need to be planned, a knowledge transfer and retraining of workforce enacted, to enable efficient installation (Barbosa et al., 2017; Khalfan et al., 2014; Ruuska et al., 2016). Unless on-site installation is efficiently managed, processed and planned, the expected cost and time savings will not be realised, and OSM adoption will not occur. (Kamar, K.A.M et al., 2012; Kamar, K.A.M. et al., 2014; Rashidi et al., 2017; Van Egmond-de Wilde De Ligny, 2010; Yunus, 2012). On-site construction processes need to change and improve from the current haphazard approach to provide high-performance and improved output (Sacks, 2016; Seppanen, 2009).

Production management theories and methods are applicable to industrialised work processes for improvement in on-site production. OSM components lend themselves to adoption of on-site industrialised production processes rather than the traditional approach. Pertinent theories for industrialised construction production management are Swift Even Flow theory, which was adapted and followed by Transformation, Flow and Value (T.F.V.) theory and, also applicable are management tools such as supply chain management (Koskela, 2000; Schmenner and Swink, 1998; Vrijhoef et al., 2000). The focus, in both of the theories, is on the "flow" in the production process. Swift Even Flow theory holds that the swifter and even the flow of materials through a process, the more productive that process is. The production improves with the speed and evenness by which materials flow through the process, and it falls with increases in the variability associated with the flow (Schmenner et al., 1998). The TFV theory espouses that production management needs to focus, not only the "transformation" of the product, as just activities or tasks, but also on the smooth flow of transformation of the product (activities) along the production line to its end: that is the finished product. The more continuous and faster the flow, the less variability, delays and non-value-added time are experienced. This achieves less waste in resources, material and cost, providing the highest value to the client (Koskela, 2000). These theories are later discussed in more detail in Chapter 2. By application, the theories provide a context for study in evaluating the on-site production process and to identify and remove the unproductive (non-value-added) tasks, in so doing assess net (value-add) productivity.

Supply chain management integrates into the production flow with the supply of materials and resources arriving at the scheduled time to align with the flow (Barbosa et al., 2017). Recent efforts to introduce "smart" or "modern" methods of construction by way of adopting industrialised practices is due to the importance of improving construction efficiency and productivity (Liu et al., 2018). There is a need to select a production approach and to view the on-site process as a flow, where its efficiency can be improved by reduction of non-value-add activities, stoppages and variability, which leads to consequential added customer value (Koskela, 2000). Industrialised mass timber has the potential to enhance productivity outcomes and provide valuable benefits with a change to on-site production processes. However, there appears to be resistance in its take-up.

1.5 Identifying gap in literature restricting uptake of mass timber

Several issues are restricting the mainstream adoption of industrialised mass timber building, including resistance to its adoption by industry, the need to adapt on-site production processes for OSM, the limited availability of empirical research and lack of knowledge. This appears to result in construction professionals perceiving barriers and adopting a risk-averse attitude to mass timber, relative to the traditional methods that is in general use. This manifests into actions such as contingency estimating, restrained uptake and non-consideration to its benefits. (Mahapatra et al., 2008; Shahzad, W. M. et al., 2013; Xia et al., 2014). Although there has been considerable interest in this new form of industrialised construction, there has been reluctance by contractors and developers to adopt industrialisation on their projects, preferring traditional types of construction (Kremer, P. et al., 2016; Mahapatra et al., 2008; Schmidt et al., 2018; Xia et al., 2014). Lehmann (2012b) proposed several strategies to minimise these barriers, which included providing more empirical research, knowledge transfer and suitable upskilling of the industry's professional workforce. Quantitative empirical on-site research is an essential requirement for the uptake of mass timber and is of particular interest for this study, especially quantification of onsite productivity achievable using mass timber construction. For instance, this type of knowledge could reduce the risk averse attitudes around contingency estimating of cost and time.

There are a limited number of papers found within scientific databases relating to on-site productivity for industrialised building systems. The existing literature on construction industrialisation has primarily focused on the off-site manufacturing environment. This view was supported by a keyword search of Emerald Publications (Emerald Insight, 2020) where only four quantitative on-site prefabricated studies were found out of 17,000 focused on construction productivity. Only 13 qualitative and quantitative on-site prefabricated studies were found out of a total of 1,007 on-site productivity studies within ARCOM's database (Association of Researchers in Construction Management, 2000). Whereas studies pertaining to on-site productivity of traditional construction are abundantly available both in academic literature and industry publications. The scope of conventional construction papers is predominantly on labour-intensive tasks.

Although mass timber construction is said to provide faster completion times and improved productivity compared to current traditional methods, few empirical quantitative studies are known to verify these reported benefits (d'Errico, 2016; Lehmann, 2012b; Mallo, 2014; Robertson et al., 2012). The limited mass timber studies, generally, focus on its benefits such as design impact, urban use, environmental sustainability, biophilic design, its lighter weight (d'Errico, 2016; Lehmann, 2012a, b, 2013; Lehmann and Crocker, 2012; Mallo, 2014; Robertson et al., 2012). In general, those published papers reporting improved productivity on mass timber projects have used qualitative data, sourced through interviews or questionnaire surveys. Available quantitative publications on on-site industrialised mass timber systems are very limited both in Australia and overseas (d'Errico, 2016; Forsythe et al., 2016; Kasbar, 2017; Lehmann, 2012b, 2013; Mallo, 2014; Robertson et al., 2012).

The lack of evidence about site productivity is further exposed by there being only four known quantitative studies oriented to on-site productivity concerning an industrialised building system. One study included a hybrid mass timber project in Canada, completed in 2016 (Kasbar, 2017), two others mainly focused on stick frame panels, but included a CLT detached two-storey house in Australia (Forsythe et al., 2016). A fourth study, by Forsythe and Fini (Forsythe and Fini, 2019a), focused on CLT installation to a single multi-storey aged care building, in Australia. These are discussed later in the literature review.

Lack of study in this area hinders the adoption of industrialised building systems due to the historically conservative and risk-averse industry with a reluctance to adopt unproven innovation (Kremer, P. et al., 2016; McKinsey Group Institute et al., 2017; Xia et al., 2014). More research on this subject is needed to fill this gap and so contribute to an understanding, knowledge transfer in industrialised systems, its improved productivity and associated benefits in cost-effective construction (d'Errico, 2016; Khalfan et al., 2014; Lehmann, 2013, 2015). This gap in study must be urgently addressed to accelerate industrialised methods take up and so, improve the current underperformance of the industry (Kremer, P. et al., 2016; Mahapatra et al., 2008; Schmidt et al., 2018; Xia et al., 2014). To assist this transition in mass timber adoption towards that of the other leading countries, additional empirical productivity data and insight into the on-site application of industrialised systems is required (Forsythe et al., 2019b; Khalfan et al., 2014; Lehmann, 2012b; Smith, R. et al., 2018).

1.6 The research problem, aims and objectives

The preceding discussion leads to the conclusion that there is a gap in on-site productivity research on industrialised systems such as mass timber. If addressed, this would contribute to a better understanding of how it could improve construction productivity and contribute to the industry's current underperformance (Barbosa et al., 2017). Industrialised mass timber could, also, contribute to more cost-effective and sustainable construction, particularly for multi-storey structures, which are becoming increasingly prevalent with general population trends due to intensified densification in cities (Lehmann, 2013, 2015). However, the lack of information in mass timber installation is preventing traction in its take-up. Mass timber is still reasonably new to Australia, so knowledge, as is this study, is vital to increase its impact and to achieve its benefits in this context.

Lack of knowledge is holding back its general adoption and ability to penetrate the broad market (d'Errico, 2016; Forsythe et al., 2019b; Smith, R. et al., 2018). As discussed earlier, most studies to date on mass timber have been by interview or survey with very few empirical quantitative measurements, which is essential for its uptake. It is crucial to overcome the current reluctance and resistance to prefabrication, primarily mass timber, through empirical quantitative studies and knowledge transfer to significantly improve the current status (Bayne and Taylor, 2006; Khalfan et al., 2014; Smith, R. et al., 2018).

To objectively explore the above claims, this thesis investigates measurable on-site productivity of industrialised systems. To this end, this thesis uses case study research to focus on on-site productivity in an Australian context for CLT cellular framed mass timber on three multi-storey structures and to identify significant productivity factors over a six-month period in 2016.

The previous discussion identified a number of strands in the positioning of the study. These can be summarised as quantitative research at an activity level of enquiry taking into account the on-site production process of replicable standardised products. Such strands complemented a study within a multi storey residential apartment environment.

The underlying aim of the research is to determine whether there is a relationship between mass timber systems and improved on-site construction productivity potential. To augment this, the other research aims are to:

- Undertake quantitative empirical research on multi-storey mass timber buildings as an example of industrialised building systems.
- Provide a measurable benchmarking model of on-site productivity for various categories of mass timber CLT panels (floors, walls, beams and columns) to assist in estimating its productivity on projects.
- Identify potential areas for productivity improvements in mass timber construction.
- Identify the significant site related variables such as size-related panel productivity, floor height, principal input resource (i.e., crane versus labour), and weather.

From the above, a merged process model of mass timber design and construction is presented, outlining the critical factors for improved productivity This is central to assist the industry's understanding of mass timber and provide a potential method of its adoption.

It is hoped that this study may contribute, in part, in the transition from its present stage in Australia towards that of the other leading countries in the field by providing additional empirical productivity data and insight into the on-site application of off-site manufactured components.

1.7 Thesis structure

The thesis has seven chapters and five appendices.

Chapter 2 provides a literature review of construction productivity concepts and principles. It addresses the primary element of on-site productivity, the definition, related production theory, improvement in process potential and selection of a suitable model for this study.

Chapter 3 provides a review of industrialisation and prefabrication, its introduction to the construction industry and its importance for productivity improvement. The development of timber usage in this context and modern approaches to industrialised production and technology are discussed. Also addressed are the benefits in the adoption of mass timber and the current issues that are hampering its take up. It concludes with the specific question of the development of a baseline productivity-forecasting model and propositions to be investigated by empirical research. Five propositions are listed.

Chapter 4 explains the theoretical position, the responsive methods used to address the empirical research needs, including the pilot study used to determine measurement techniques, the chosen case study methodology, the data gathering techniques and sampling methods, and the statistical analysis methods used.

Chapter 5 provides the research findings from the three case study buildings, an assessment of the main research proposition and each of the five secondary propositions.

Chapter 6 discusses the case studies' findings and their implications for design and construction in mass timber. It concludes with a merged model framework of the proposed overall mass timber design and construction process for improved on-site productivity.

Chapter 7 contains a conclusion of the thesis with recommendations for future research.

Appendices 1–5 contain the sample projects used for the pilot study, the ethics compliance, high-level review summary, intermediate level worksheets and the interview questions.

Chapter 2 Productivity Concepts

The preceding chapter identified the importance of productivity and the potential for improvement through industrialisation in construction. This chapter adopts protocols from construction and economics literature to examine this in more detail. The outcome is a clear theoretical evaluation of construction productivity, its definition and the key variables to be considered for field research.

The flowchart below, Figure 2.1, outlines the process used in determining the productivity measurement criteria for this study and identifies the individual stages in its examination.

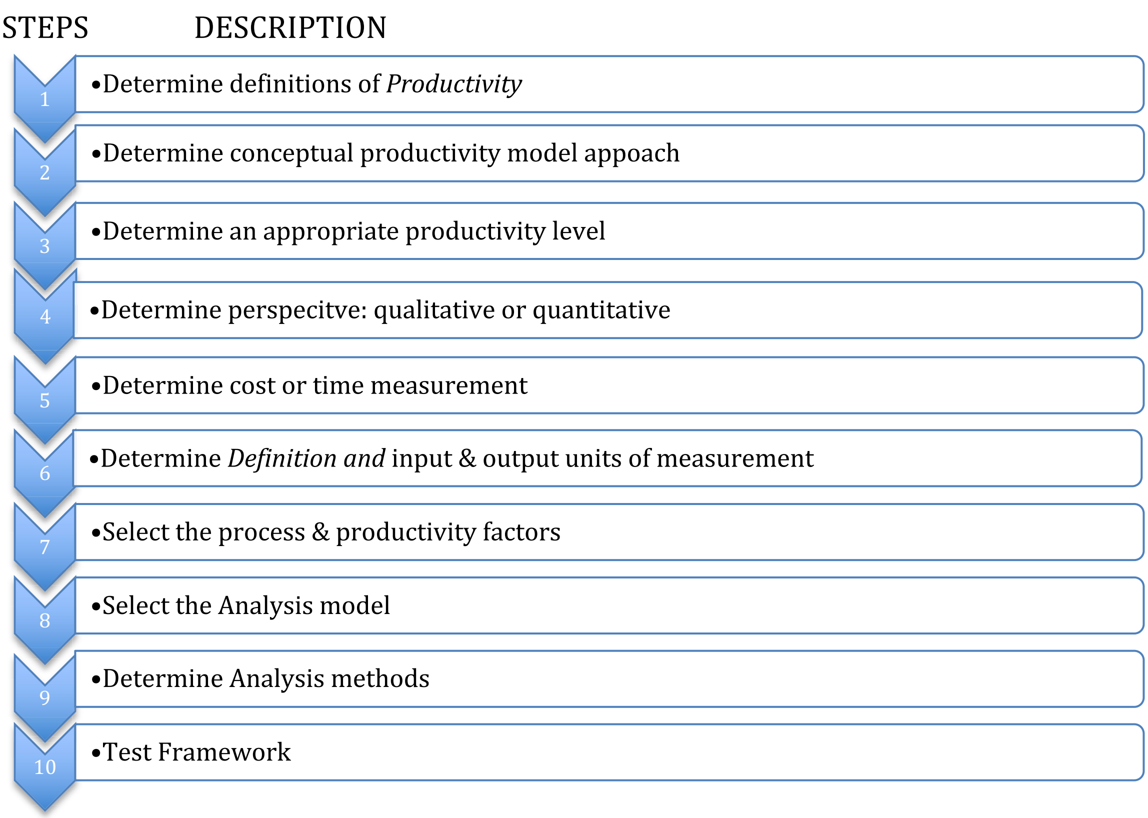

Figure 2.1 Flowchart to determine criteria to measure mass timber productivity

2.1 Definition selection

There are currently no universally agreed on criteria for units of measurement for productivity (Thomas, H., R. and Zavrski, I., 1999; Yi et al., 2014). There is, also, misunderstanding and disagreement on the terminology and definition of productivity and its application (Thomas, H.R. et al., 1990, Yi et al., 2014).

Productivity findings are dependent on the adopted method of data gathering. This has resulted in the productivity findings of many research studies being contradicted by proceeding studies (Chancellor, 2015; Yi et al., 2014).

Such actions are generally due to the different ways of considering productivity issues, which range from a broad national macro-economic approach to a more precise micro-economic nature that manifests into a more technical level often at project, activity or task perspective (Thomas, H., R. and Mathews, 1986; Yi and Chan, 2013). Consequently, it is essential to establish a productivity definition and units of measure most appropriate for the objectives of this thesis. To address these issues, we commence with the selection of the most appropriate definition from the many found.

2.1.1. Definitions (*theories*) of productivity

Although the term productivity is widely used, it is often misunderstood due to the lack of general agreement of what productivity represents. This lack of consensus is one of the main reasons why many researchers believe that productivity is neglected by those who manage the production process (Tangen, 2005). Table 2.1 below, indicates the various interpretations of productivity (Tangen, 2005); in cases, identifying how previous researchers and academics have defined productivity, together with its units of measurement. Even though in a broader sense, definitions of "output" and "input" are standard, there are varying interpretations of these essential elements, as outlined in Table 2.1. The differing definitions highlight those issues faced by researchers, industries, economists and governments alike when measuring and comparing productivity.

Table 2.1 Examples of definitions of productivity (extract from Tangen, 2005)

No.	Definition	Reference
1	*Productivity* = faculty to produce	(Littre´, 1883)
2	*Productivity* is what man can accomplish with material, capital and technology. *Productivity* is mainly an issue of personal manner. It is an attitude that we must continuously improve ourselves and things around us.	(Japan Productivity Centre, 1958 (from Bjo¨rkman, 1991))
3	*Productivity* = units of output/units of input	(Chew, 1988)
4	*Productivity* = actual output/expected resources used	(Sink and Tuttle, 1989)
5	*Productivity* = total income/(cost + goal profit)	(Fisher, 1990)
6	*Productivity* = value-added/input of production factors	(Aspe´n et al., 1991)
7	*Productivity*: the ratio of what is produced to what is required to produce it. *Productivity* measures the relationship between output such as goods and services produced, and inputs that include labour, capital, material and other resources	(Hill, 1993)
8	*Productivity* (output per hour of work) is the central long-run factor determining any population's average standard of living	(Thurow, 1993)
9	*Productivity* = the quality or state of bringing forth, of generating, of causing to exist, of yielding large result or yielding abundantly	(Koss and Lewis, 1993)
10	*Productivity* means how much and how well we produce from the resources used. If we produce more or better goods from the same resources, we increase *productivity*. Or if we produce the same goods from lesser resources, we also increase *productivity*. By "resources", we mean all human and physical resources, i.e. the people who produce the goods or provide the services, and the assets with which the people can produce the goods or provide the services	(Bernolak, 1997)
11	*Productivity* is a comparison of the physical inputs to a factory with the physical outputs from the factory	(Kaplan and Cooper, 1998)
12	*Productivity* = efficiency * effectiveness = value-adding time/total time	(Jackson and Petersson, 1999)
13	*Productivity* = (output/input) * quality = efficiency * utilisation * quality	(Al-Darrab, 2000)
14	*Productivity* is the ability to satisfy the market's need for goods and services with a minimum of total resource consumption	(Moseng and Rolstada˚s, 2001)

From a review of papers on construction productivity (Allmon et al., 2000; Best, 2012; Hasan et al., 2017; Sonmez and Rowings, 1998; Thomas, H.R. et al., 1990; Thomas, H.R. et al., 1992; Yi et al., 2014) and from the above definitions (Tangen, 2005), productivity was found to have been measured in various ways including:

- multiple units of measure, e.g., value, cost, time and quantity,

- numerous formulae to calculate productivity,
- different conceptual models, ranging from micro to macroeconomic levels,
- various input resources, however, labour was one generally selected.

The various definitions and units of measure, previously adopted for construction productivity, have restricted the ability to compare the prior studies' findings. To derive an appropriate meaning with units of measurement that best suit this study, the definitions in Table 2.1 are now evaluated.

2.2 Clarification of models for measuring productivity

There are different ways of considering productivity issues. These range from a broad national macroeconomic level to a more detailed microeconomic perspective of study. Each is explained briefly below.

2.2.1 A review of macro & micro perspective

There has been difficulty in obtaining precise productivity results at a macroeconomic for the construction industry, which is mainly due to the heterogeneous nature of the construction industry (Arditi, 1985; Kenley, 2014) and its transient workforce (Srour et al., 2017). These points are often the causation of discrepancies between macro and microeconomic data. The construction industry has a record of inadequately measuring productivity due to many unconsidered factors (Goodrum, P. et al., 2009). To arrive at accurately measured productivity, such factors need to be considered.

Thomas, Yiakoumis and Zavrski discussed the general differences of a macroeconomic to a microeconomic approach, in their papers (Thomas, H., R. et al., 1999; Thomas, H.R. and Yiakoumis, 1987; Yi et al., 2014). Factors that affect on-site productivity, which are not generally considered at a macroeconomic level, were identified as:

- heterogeneous nature of construction: case studies analyse productivity with different definitions and consequential outcomes,

- activities usually being carried out in an outdoor environment and therefore subject to inclement weather,
- (un)availability of suitable storage area,
- management decisions and competency,
- crew sizes, etc.

Macroeconomic studies and national comparisons do not generally consider these variables and processes but refer to the relevant government bureau of statistics, aggregates or equivalent databases, often using different analyses methodologies (Goodrum, P. M. et al., 2002; Best, 2012). These primarily recognise the monetary value of work completed in a specific financial year. The lack of consideration given to the above listed factors, affect the macroeconomic conclusions and annual findings, often the causation of contradictions (Goodrum, P. M. et al., 2002; Thomas, H., R. et al., 1999; Thomas, H.R. ; et al., 1987; Thomas, H. R. and Zavrski, I., 1999; Yi et al., 2014). Macroeconomics is regarded as an imprecise method for measuring or working out a resolution at a company or project level (Goodrum, P. et al., 2009). Due to the criticism in macro-level productivity measurement, measurement in micro and process-based studies was found a more useful tool to provide in-depth assessment and identify non value added tasks (Pekuri et al., 2011).

There is a need, therefore, to delve to a more microeconomic level to portray the subparts. It is essential for its practical application that this study's selected method for productivity measurement provides accurate and replicable results. Based on the discussion above, there is need to scale down from a macro to micro-level and to a more technical level of enquiry that helps to inform on the most efficient ways of improving on-site processes and productivity. The question is: which of these levels is the most suitable for this study?

2.2.2 Productivity level perspective

Productivity is viewed at different hierarchical perspectives, levels or scales, depending on those involved and their need or purpose. These levels or scales include national, industry, company, project, activity or task (Carrisson, 1987; Kenley, 2014).

At an industry level, it uses criteria such as skills investment, research, competitive advantage, regional culture and regulation to compare one industry's productivity to another (Kenley, 2014; Yi et al., 2014). Industry-level, as at a national level, is the epitome of the macroeconomic approach that was found unsuitable for this study.

At the company level and project level, the productivity of one company or project can be compared to another (Ellis and Lee, 2006; Park, H.-S., 2006; Thomas, H., R. et al., 1999; Thomas, H. R., 2012; Thomas, H. R. et al., 1999). At the company level, productivity measurement needs to consider skills, management (e.g. workflow reliability), machinery, tools and the automation and integration of information systems across the whole company (Kenley, 2014). As this is too wide-ranging, it was deemed inappropriate for this study.

A building comprises of several parts, i.e., substructure, structure, façade, interiors, services, finishes and fittings. With industrialisation, as mass timber, it is utilised, generally, in one part of a building, i.e., in this case, its structure. Consequently, if the mass timber's productivity and critical criteria were measured at a project level, it would be diluted by other activities from various parts of the project. Further, the unit of productivity measurement differs across the project depending on the individual activity. As an example, a concrete activity is generally measured in cubic metres per hour, whereas a structural steel placement activity is often measured in tonnes of steel placed per hour (Goodrum, P. et al., 2009). This creates a lack of uniformity in the compilation and lacks universal acceptability. Focusing on measuring a defined work area within a project provides an inbuilt exclusion of unwanted intervening variables that could impact on productivity measurement, e.g. sick leave (Forsythe et al., 2019b). The specific area of interest is, therefore, not at a whole project level but an activity or task level of study.

The activity level provides several benefits, such as detailed data for estimating, scheduling and programming. Thomas based his baseline and benchmark models on productivity measured at an activity level, at which facilitate comparisons and benchmarking across projects for similar activities throughout the industry (Thomas, H., R. et al., 1999; Thomas, H. R., 2012; Thomas, H.R. et al., 1990; Thomas, H. R. et al., 1986; Thomas, H.R. et al., 1992; Thomas, H.R. ; et al., 1987; Thomas, H. R. et al., 1999; Yi et al., 2014).

Adrian & Boyer (1976) found that the method for collection of productivity data needed detailed information, which could only be achieved at an activity or task level. At an activity level of study, the focus is on activities in detail and how they occur within projects, which is of particular interest for industrialised systems. Activity level provides a more straightforward comparison of output and input data over time (Goodrum, P. M. et al., 2002). At this micro-level, prefabricated construction can be studied as a system as it occurs within a building project (Forsythe et al., 2019b).

The activity level measures and elucidates the benefits of industrialisation, allowing comparison to a labour driven approach, as at this level the leading resource can be identified and measured (Adrian et al., 1976). This point is very apt, as in industrialised construction, with the advent of automation, labour most likely will not be the lead resource (Forsythe 2019). It can be seen as an essential gateway in the transition in the study to more industrialised methods. From the above, the one most appropriate for this study is at an activity level because it has the ability to measure the productivity of the industrialised panelised system most directly (Forsythe et al., 2019b). Consequently, this excludes items 7, 10 and 11, Figure 2.1, from further consideration.

2.2.3 Quantitative versus qualitative approach

Measurement has been defined as "a quantitatively expressed reduction of uncertainty based on one or more observations" (Hubbard, 2014). Therefore, productivity needs to be quantitatively and accurately measured to reduce uncertainty. The productivity definitions/models of items 1, 2, 4, 9, 12 and 14 in Table 2.1 entails qualitative and subjective data analysis. The purpose of this thesis is to provide an empirical review of factual on-site productivity for on-site mass timber installation. Therefore, a quantitative approach is more appropriate, rather than a qualitative one, in meeting this requirement, and consequently, a qualitative approach is not further considered.

Although item 13 includes quantitative data for part of its formula, it requires qualitative or subjective consideration of the subjects of quality, utilisation and efficiency. Therefore, item 13, along with definitions 1, 2, 4, 9, 12 and 14 are excluded from further consideration in measuring productivity for this study. This successfully narrows the focus onto the remaining items 3, 5, 6 and 8 in Table 2.1 as to their acceptability and suitability.

2.2.4 Cost versus time

In trying to measure things quantitatively, there is a need to have an absolute unit (Hubbard, 2014) and the salient units are cost and time. These salient units are absolute measures: in cost, two dollars cost are twice as much as one dollar and in time, two hours are twice as that of one hour. Therefore, both cost and time are the primary units of consideration.

Benchmarking comparison findings are often contradictory and inaccurate, where cost is a measure of productivity (Best, 2012). This conversion produces many anomalies because units of different currency are subject to variability, currency fluctuations, local tax rules, building codes, unemployment rate, and comparable labour costs (Best, 2012; Vermande and Van Mulligan, 1999; Walsh et al., 2006). Previous attempts to develop labour productivity at the activity level based on economic (currency) considerations have been mostly unsuccessful (Thomas, H., R. et al., 1999). Eastman and Sacks (Eastman et al., 2008) argued that measurement by hourly outputs helped to avoid many external factors that cause cost variances.

In their research, the prominent construction productivity researchers, Thomas and Hanna considered and measured productivity at both an activity and project level, using m^2/hours (Hanna, A.S. et al., 2002b; Hanna, A.S. et al., 2005; Thomas, H., R. et al., 1999; Thomas, H. R., 2012; Thomas, H.R. et al., 1990; Thomas, H. R. et al., 1986; Thomas, H.R. et al., 1992; Thomas, H.R. ; et al., 1987; Thomas, H. R. et al., 1999; Yi et al., 2014). For construction activities, Yi and Chan (2014) found that hourly output was commonly recognised as a more reliable measurement of productivity. Cost-based measurement of productivity, at the microeconomic activity level, was considered too variable to be used as a meaningful measurement of productivity and consequently not suitable for this study. Definitions 5 and 6 in Table 2.1 both relate to an economic interpretation of productivity measured in cost. They are, therefore, excluded from further consideration, which now focuses on items 3 and 8 based on time.

2.2.5 Leading input resource and output quantity

Adrian and Boyle's work provided guidance in the methods to be adopted for determining the measurement of on-site productivity. They cited the need to identify a leading input resource, the production unit and the production cycle relating to time between the production unit's consecutive occurrences; and (Adrian et al., 1976,). They further stated that to get the most out of the collected data the chosen production unit should not be too broad which may limit the ability to explain how to improve productivity or too small, which may exclude many of the relevant details to make it useful. We now consider the leading /primary resource, the production unit, i.e., the output and then a suitable production cycle.

Leading input resource

In applying Adrian and Boyle's principles, an issue of interest is the selection of the building system. It has been generally taken for granted that on-site construction activities are typically labour intensive with productivity measured in labour hours (CLP) (Hanna, A.S. et al., 2002b; Thomas, H., R. et al., 1986; Thomas, H.R. et al., 1992; Forsythe et al., 2019b). Consequently, labour has, historically, been considered as the leading input resource for on-site productivity measurement (Jang et al., 2011; Nasirzadeh and Nojedehi, 2013; Sandbhor et al., 2014; Yi et al., 2014). However, with the introduction of industrialised building systems, labour may not be the appropriate input resource to determine their activity's true productivity efficiency (Allmon et al., 2000). The construction industry's continual use of labour, when calculating productivity, creates uncertainty and shortcomings in findings with the increase in the use of technology and a move to more industrialised building methods (Forsythe et al., 2019b; Goodrum, P. et al., 2009).

With the introduction of new technology into construction, advances in equipment have gained credibility in improving productivity and may need to be considered (Arditi, 1985). Known construction productivity studies, which considered new construction technologies, found that equipment, for example, a "sheep's foot" roller, had a principal role in productivity input (Allmon et al., 2000). Prefabricated elements delivered to site are large and heavy, and installation of these elements require hoisting into place, often by cranes. In such cases, Forsythe & Sepasgozar found craneage, not labour, was considered the leading input resource and the single most important variable in influencing prefabricated timber installation productivity (Forsythe et al., 2019b). Industrialisation and prefabrication relate to a mechanised on-site approach, replacing manual labour with machinery (Girmscheid, 2010; Richard, 2010). As the focus changes towards industrialised methods and automation, labour will have reduced relevance with the subsequently reduced labour, and crane operation arguably will be the lead resource in on-site prefabricated panel construction (Forsythe et al., 2019b). It is therefore proposed that, with industrialised construction, plant and equipment input time will likely be correlated with its activity's productivity, similar to machines in a factory, and will be the principal input resource (Koskela, 2000; Yashiro, 2014). Therefore, the equipment, for example crane, may need to be considered as the leading resource in future on construction industrialisation productivity studies.

Measuring productivity provides a means to identify the leading input resource (Adrian et al., 1976). To test the above argument, therefore, this study will measure both the labour and equipment input resources per hour in order to identify, which plays the vital leading input role in industrialised on-site productivity. It will determine whether the proposition that the lifting equipment, i.e., the crane operation, is the primary/ leading input resource for on-site installation of prefabricated systems, is supported. It is important to further highlight that the study’s first proposition (proposition # 1) focuses on equipment, not labour, as the primary and leading on-site productivity input resource for the installation of mass timber systems.

Output (production) unit

As this study focuses on-site installation of CLT panels, the output focus is the panel's surface element, and the output unit of measure is the quantity of work installed, i.e., surface area of the panel in m^2. In the majority of existing construction productivity studies, the focus has been primarily on input process (time) or resource (labour), e.g. how many workers' hours will it take to lay a unit area of bricks (Hanna, A.S. et al., 2008; Hanna, A.S. et al., 2005; Thomas, H.R. et al., 1990; Thomas, H. R. et al., 1986; Thomas, H.R. ; et al., 1987). Studies have not generally focused on or considered the individual component's (output) size installed, i.e., what is the area of the actual brick? Or will larger bricks improve productivity? This lack in focus is predominantly the case, to date, within the industrialised prefabricated and mass timber studies (Forsythe et al., 2016; Forsythe et al., 2019a; Kasbar, 2017).

As a consequence of this apparent gap, i.e., will large panels improve productivity compared to smaller panels, this study assesses the significance of the component area (m2) to its activity's productivity. Therefore, this productivity study will measure the output of each panel's surface area, in square metres and categorise them into three standard sizes, small, medium and large. This leads to the formation of another proposition for this study (proposition#3), which was increase in panel size will cause significantly positive upturn in productivity rates.

Production cycle

Adrian and Boyer introduced the production cycle time as a critical criterion in measuring productivity (Adrian et al., 1976). In the few previous mass timber studies to date, the crane cycle has been selected as the production cycle and the panel as the production unit (Forsythe et al., 2016; Forsythe et al., 2019a; Forsythe et al., 2019b; Kasbar, 2017). The crane cycle consisted of the cycle time from pick up of the panel from store or delivery point to installation in the building and return. In this study, cycle time can be considered as the assembly (i.e., the panel) flow from delivery point or store to installation.

Applying Adrian & Boyer's reasoning that highly visual and repetitive and predictable processes need to be identified for the measurement of productivity, crane cycle and crane time suit these criteria (Adrian et al., 1976; Forsythe et al., 2019b). The crane cycle time was the repetitive process separation with set boundaries and as such was the identified production cycle for this study. This provided the context for comparison of productivity findings with that of previous studies on the same topic that had used the same criterion.

2.2.6 Productivity definition/formulae for measurement

"Input" and "output" are the common units of measure for the two remaining definitions 3 and 8, Table 2.1. Definition 8 defines productivity as "output per hour of work", which equates to definition 3's "units of output/ units of input" (hours). Amongst the numerous definitions of productivity, there is also a broad consensus by many researchers defining "output" and "input" as a ratio of measurement, aligning with definitions 3 and 8 (Hanna, A.S. et al., 2008; Jang et al., 2011; Nasirzadeh et al., 2013; Park, H. et al., 2005; Park, H.-S., 2006; Sandbhor et al., 2014; Tangen, 2005; Thomas, H., R. et al., 1999; Thomas, H.R. et al., 1990; Yi et al., 2014). Further supporting this view, Thomas and Sanders (Thomas, H.R. et al., 1992), in a common standardised approach, collected data using "input" in measurements in labour time and "output" as the quantity of work placed. It found that the productivity outcomes were comparable and similar across projects internationally. However, there is no real agreement as to the denominator of ratio of "input" and "output" for the measurement of productivity (Tangen, 2005; Thomas, H.R. et al., 1990; Yi et al., 2014). The acceptable definition formula could be either:

P = Input / Output OR

P= Output / Input.

The difference between the two is purely a difference of preference. Although both are used, this is an Australian study where the colloquial method is units of output/ units of input, which is selected for this study. It aligns with many prominent researchers focusing on productivity (Forsythe et al., 2016; Jang et al., 2011; Park, H. et al., 2005; Yi et al., 2014) and supported in the U.S. Bureau of Labour Statistics' paper *Labour Productivity and Cost* (Yi et al., 2014). The use of this selected formula also provides the benefit that as productivity improves the measured productivity value increases (Forsythe et al., 2016). For this thesis, the selected and agreed theoretical definition of productivity is in accordance with definitions 3 and 8 in Table 2.1 as

Equation (1):

$$\textbf{P} \text{ (Productivity)} = \frac{\textbf{Output units} \text{ (work quantity (m}^2\text{) completed)}}{\textbf{Input units} \text{ (primary resource (labour or equipment hours)}} \quad (1)$$

2.3 On-site industrialised work process considerations

With a suitable definition of productivity selected, we need to identify and better understand the processes that could influence its potential for improvement and the factors that affect its on-site outcome. We commence with a review of on-site operations from the aspect of industrialised building systems.

As raised in chapter one, there is a need to change traditional on-site construction operations to be more appropriate for off-site manufactured (OSM) engineered components, in order to maximise its potential on-site cost savings to offset off-site costs. Therefore, a more production process-oriented approach is required to be introduced in the on-site operation. This will reduce the inherent waste, improve productivity and add value (Sacks et al., 2016). Girmscheild (2010) established that an industrialised approach to construction would provide options for organisations, of all sizes, to increase their potential by adopting optimised on-site processes with detailed pre-planning of work. Taking such measures would focus companies on the activities that offered the most value-add. As a result, this industrialised approach would reduce non-productive actions, improve product quality and internal costs (Girmscheid, 2010).

2.3.1 Production Theory: Flow and Value-Adding & Non-Value-Adding

The production management theory of Swift Even Flow (Schmenner et al., 1998) holds that the more swift and even the flow of materials pass through the work process, the more productivity that process is. In manufacturing, the production concept of "flow" is the path through which a product progresses from raw material to a finished product or the physical movement of the component along that route. The productivity for any process, whether labour, machine or material, increases with speed and evenness it flows through the process. It falls with the variability within the flow of, or associated with, the process steps (Schmenner et al., 1998).

The law of variability proposes that the greater the random variability either inherent in the process itself or the items processed, the less productive the process is (Schmenner et al., 1998). Therefore, any randomness in the work process, i.e. changes, delays and stoppages, etc., and randomness in product material, shape or size, are required to be eliminated or minimised to provide optimum productivity (Schmenner et al., 1998). This flow path is often called a "value stream" and the actions performed along the path are classified into either value-added or non-value-added activities (Rother and Shook, 2003; Sacks, 2016). Supporting this view is the Swift Even Flow theory, which elucidates that all work can be divided into either value-added work or non-value-added work (Schmenner et al., 1998).

Work that transforms materials into quality products is considered a value-added activity (Schmenner et al., 1998). While work that moves materials and catalogues, inspects, counts or reworks them is regarded as non-value added. Anything that adds waste to the process is non-value-added, such as waiting, transportation, unnecessary processing steps, storing and defects (Hall, R. W., 1987; Schmenner et al., 1998). "Ideal productivity" is that which occurs when identified productivity delays are absent (Adrian et al., 1976). The premise is that the more swift and even the flow of materials are through a process, the more productive and value-added the process is, with waste minimised (Schmenner et al., 1998).

2.3.2 Construction Flow and Cycle time

Koskela in his study (Koskela, 2000) determined that a root cause of the underperformance in construction was that it was predominantly managed according to transformation concepts, and the principles related to the concepts of flow and value generation were largely ignored. From empirical evidence, construction is currently viewed as a project-based production with a very jumbled flow and one of a kind products. From a process view, a construction project is composed of distinct spaces with varying degrees of similarity between them (Sacks, 2016; Seppanen, 2009). Just in time production (JIT), later known as lean construction, introduced the concept of flow as a way to understand production in construction due to the significant productivity gains reported from manufacturing since the 1970s (Koskela, 2000). This concept was central to Koskela's theory of Transformation-Flow-Value (TFV) of a construction process (2000). "Transformation" is the traditional results-oriented construction management approach, which focuses on individual operations and not the overall process. He proffered that the traditional way of organising construction, that is a transformation focus, was the cause of the current demise of improvement in its production and management should focus on flow and value.

Flow, however, is viewed as a new process-oriented direction (Sacks et al., 2016). Unlike in a factory where the product moves or "flows" through the fixed workstations along a production line, on a construction site the crews, and sometimes equipment move through the project via locations (Sacks et al., 2016). The flow of prefabricated components or pre-assemblies, as in mass timber, or modular mechanical, electrical or hydraulic units, is comparable to that of products in a manufacturing process (Sacks, 2016).

As in manufacturing, this view of flow focuses on eliminating the waste in construction, e.g., wasted time from the off-site and on-site perspective of both construction products and construction crews. Wasted time is where time is spent on non-value-added activities such as inspections, waiting, rework or moving from place to place. Crew's lost time is waiting for materials, information, equipment, space, completion of preceding activities, etc., but products wait for crews. In construction, as in a factory, a good flow is where there are minimum non-value-add actions, i.e. minimum waste (Koskela, 2000; Sacks et al., 2016).

A conceptualisation of production from a value generation view is a process where the value for the customer is created through the fulfilment of its requirements, the main principles being the elimination of value loss. Where waste from a transformation perspective has the form of material loss, in flow perspective it is time loss and in a value perspective, it is a value loss. Value loss can be achieved from the reduction of waste from both transformation (materials) and flow (time) perspectives.

Flow metrics

Lean production metrics often refer to Little's Law, which relates to flow or, as Little refers to as, *throughput* (T.H.) to *work in progress* (L), i.e. inventory, and the average number of units arriving at a unit time, λ, in the equation TH=L/λ (Hopp and Spearman, 1996; Little and Graves, 2008). This law revealed the importance of queues in his focus of work in progress (WIP) (Koskela, 2000). WIP is measured by counting the number of products present, or queued, in a production line and T.H. is the output rate of the last machine in the line. Adrian and Boyer introduced the production cycle time as a critical criterion in measuring productivity (Adrian et al., 1976). Sacks adapted Little's law, introducing it to lean construction by incorporating cycle time (CT), as a measure of location or assembly flow, in the equation TH=WIP/CT (Sacks et al., 2016). In this study, cycle time was considered as the assembly (i.e., the panel) flow from delivery point or store to installation and return.

Cycle time is different from the term "Takt" time. Takt time, in production, is the unit of time within which a product must be produced (supply rate) to match the rate at which that product is needed (demand rate)(Fandson, 2019). In construction, Takt time is sometimes used as the unit of time that a location, for example, a floor level, in a multi-storey building or the whole building, has to be completed to match the rate that is planned or required by the client. As Takt time is specific for a project, where cycle time is a more detailed activity study which can be compared across projects.

Good construction flow can be said to occur when locations and sub-assemblies are built continuously with no waiting time between operations. The flow should also be at a stable production rate with minimised cycle times and minimal WIP resulting in negligible waste (non-value-added) (Sacks, 2016). In assessing the productivity of industrialised construction systems consideration needs to be given to on-site production flow and consequential reduction of non-value-add activities.

2.3.3 Lack of planning and consequential waste

Waste primarily originates from prior stages of the project rather than from the phase of its occurrence (Koskela, 2000). Waste is commonly caused by problems of client decision-making, design management, lack of planning, supply chain management and site production management (Koskela, 2000). It has been found the lack of planning at the start of a project, lack of coordinating the various departments or trades and the routing of work throughout each operation, resulted in congestion of unfinished work at many locations. This in turn slows down the output, occupies space and ties up capital (Kendall, 1912; Koskela, 2000). The consequences are often erratic deliveries with overcapacity in suppliers resulting in coordination problems. Poor control and unfavourable design of the production systems creates a cascade of waste and value loss (Koskela, 2000). Previous studies of traditional construction found that the average share of working time used on non-value-added (waste) activities is estimated to be between 64 to 68% of a project's total time (Koskela, 2000; Levy, 1990). Supply chain management and detailed planning need to be enacted at the preconstruction stage and at a company level to minimise waste (Vrijhoef et al., 2000).

In summary, good production flow improves construction productivity by minimising non-value-add activities, variables, reducing cycle time at stable production rates. Implementing detailed planning before the construction stage will minimise such factors and improve performance (Vrijhoef et al., 2000).

2.4 Factors affecting productivity

The review of the production process has highlighted several factors that provide fast and even flow, resulting in improvement in construction production. However, several factors mediate between the input and output units of productivity, which need to be identified. Unlike manufacturing, on-site construction is, generally, in an outdoor environment and is influenced by many factors and variables due to the problematic nature of construction activities. These factors and variables may have consequential effects on the actual productivity outcomes but are often not considered. A review of appropriate models can quantify the impact of these factors and variables. These may include items such as variations and changes, crew size, environmental conditions, physical location, management, design complexity, training, and learning curve (Jang et al., 2011; Yi et al., 2014), as discussed below.

The term "learning curve" is applied where the work process is repetitive with standardised components. Accordingly, increased knowledge is gained from the additional experience and practice, which is reflected in improved productivity outputs (Thomas, H. R. et al., 1986). A learning curve is a representation of the improvement observed in productivity through a natural learning process from continuous repetition. As an example, an incremental increase in productivity would be observed on identical kitchens as their repetitive installation progressed in a multi-storey apartment building. The crew workers by repetition, experience and practice will determine the most efficient method to install an assembly. Repetition may also lead to better management of equipment, crew and materials, resulting in productivity improvements (Thomas, H. R. et al., 1986).

2.4.1 Factor identification

Adrian and Boyer (1976) were one of the first to classify delays in activities into five types: Environment, Equipment, Labour, Material and Management. In their

Method Productivity Delay Model (MPDM), they broke down activities into cycles and the mean non-delay cycle time for each activity was established by deducting the identified delays from the observed cycles in each of the samples. This was an early construction study that argued that a method for collection of productivity data needed to collect data concerning the time required for the completion of production cycles and document productivity delays (Adrian et al., 1976).

Although Adrian and Boyer identified several factors that could cause delays, Thomas and Yiakoumis (Thomas, H.R. ; et al., 1987) took their conclusions further by identifying additional factors and quantifying their adverse effect on productivity. They argued that to calculate the actual on-site productivity, one had to quantify and discount for the factors (variables) that affected or disturbed the crew's performance to arrive at the ideal productivity outcome. Thomas and Yiakoumis proposed a factor model, which identified the adverse factors under four headings, illustrated in Figure 2.2 below, which were:

- environment factors, such as inclement weather and absenteeism,
- site factors, i.e., congestion, access and layout,
- management factor, e.g., management control, crew size, structure methods and work schedule,
- design factors, e.g., constructability, document quality, specification and quality control requirements.

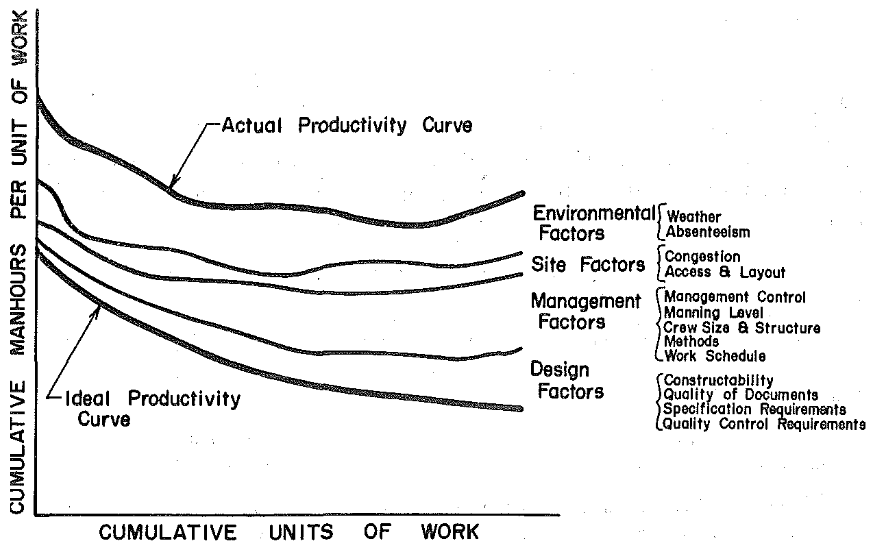

Figure 2.2 Thomas' factor model of construction productivity (Thomas, H.R. ; et al., 1987)

The Factor model considered all the above factors to achieve an accurate measurement of construction labour productivity (CLP). By using the factor model, a productivity curve could be established before work commenced on site (Thomas, H.R. et al., 1987). The model provided an ability to compare an activity's measured productivity against that estimated for a given project. One factor that Thomas had focused on, in an earlier study, was the learning curve effect, which they were able to apply to his factor model (Thomas, H. R. et al., 1986), as discussed above. Thomas continued the development of this factor model, with Sanders and Bilal, (Thomas, H.R. et al., 1992) to validate his earlier findings. They concluded that by standardising the data collected and using hours and not cost, the productivity outcomes measured from identical activities across several international project case studies were similar.

Although previous models identified various factors that affected productivity, they did not focus on the causation of non-productive, or non-value-add, work. Christian and Hachey (1995) proposed an "expert system" model that focused on these non-productive factors and the causes and effect that delay times had on productivity. They collected data from on-site activities, by using video recordings on seven field studies, to determine which variables affected productivity and divided these into categories:

1. Essential and contributing work – that positively influences the progress of the activity, (value-add).
2. Non-productive (non-value-add) work:
    - Waiting time (i.e., waiting for materials or external delays)– negative contributors to productivity,
    - Idle time (worker(s) not working)– negative contributors to productivity.

By analysing the data, Christian and Hachey were able to assess the non-productive time of direct management. Their study collected data by a "time and motion" approach using a video recorder, first introduced by Drewin (Drewin, 1982) to analyse productivity of on-site construction activities. This video methodology was found to provide a total capture of operations and was a more economical option than manual observation. Questionnaires and interviews were undertaken by Christian and Hachey (1995) to verify non-productive work, both idle and waiting times. The uniqueness of this earlier study was separating idle time from waiting time, which they considered was the root cause of non-productive time. Christian and Hachey categorised "idle time" to be when workers were not working even though work could progress. However, if workers were unable to perform a task because of an uncontrollable external delay, such as late concrete delivery, then the lost time was categorised as "waiting time".

As identified in the Factor model and industrialised process section, these were not the only factors that were identified as attributing to non-productive time. The factors identified in the above productivity model review that are important and of interest are non-productive delays, environmental factors (e.g., weather and height of work), leading resource, management factors (e.g., crew size and schedules), site factors (e.g., congestion and height level of work) and learning curve. In this study a proposition will be formulated to predict daily panel productivity which captures the identified important factors.

2.4.2 Towards benchmarking

The theoretical evaluation progresses from factor identification towards benchmarking via baseline productivity, by way of an assessment of previous relevant studies. Benchmarking allows inter project comparisons of individual activities or project productivity outcomes and a baseline approach provides the best and most consistent productivity of activity from one project to the next. Significantly, the model finally selected needed to be repeatable and able to be replicated by a mid-size construction company. Repetition leads to improved management of equipment, crew, and material, resulting in productivity gains (Thomas, H. R. et al., 1986; Yi et al., 2014).

Appropriate construction productivity models (CPM*)* that conform to the above criteria and decisions from section 2.2 are now reviewed.

Thomas and Zavrski's baseline model c1999

Expanding on his factor model of 1987, discussed above, Thomas with Zavrski (Thomas, H. R. et al., 1999) determined that they could calculate baseline productivity units considering only the activity's best 10% productivity data recorded each workday. The definition of baseline productivity being the best and most consistent productivity for a particular project, or database, Thomas argued was not to be confused with the absolute best productivity (1999b). From the recorded data, they were able to calculate the average of all the mean productivity results from each workday for individual activities. This determined the baseline rate for each activity studied. The baseline approach proposed a model for estimating, feasibility study and forecasting productivity. The principles of this model aligned with Adrian's MPDM model (1976) and Thomas's Factor model (1987), in which delays and other extraneous causes are removed from the collected data sample set to arrive at the most unaffected and consistent productivity achieved.

The concept of baseline was later adapted, by Thomas, as the foundation for his subsequent construction labour productivity benchmarking model (Thomas, H., R. et al., 1999; Thomas, H. R., 2012). Benchmarking is widely accepted in the construction industry for comparison between similar activities, projects' or company's productivity (Park, H. et al., 2005; Thomas, H., R. et al., 1999; Thomas, H. R., 2012; Yi et al., 2014; Zhao and Dungan, 2014). The provision of baseline rates for individual activities provided the principal constituent for accurate benchmarking comparison.

Although many agreed with the concept of baseline, there was disagreement with Thomas' calculation of baseline. Many believed his model produced unrealistic outcomes, as it only considered the best, and applied "an arbitrary" 10% best achieved daily productivity of each activity (Gulezian and Samelian, 2003b; Zhao et al., 2014). An improved alternative method was necessary to provide an acceptable robust baseline outcome. Many academics argued that the baseline should be determined from both "lightly impacted" and "not impacted" productivity measurements (Gulezian et al., 2003b; Lin and Huang, 2010; Park, H.

et al., 2005; Zhao et al., 2014). They claimed that this approach would determine an acceptable representation of standard uninterrupted productivity.

Gulezian and Sumelian's improved baseline model

Gulezian and Sumelian proposed an improved baseline methodology (Gulezian and Samelian, 2003a; Gulezian et al., 2003b), which incorporated Thomas' baseline productivity approach. It also included Shewhart and Deming's Total Quality Control management principles using statistical control analysis methodology (Deming, 1982; Shewhart, 1931; Thomas, H. R. et al., 1999).

Gulezian and Samelian proposed to calculate baseline from the mean of productivity sample sets of pre-determined time periods represented within a normal distribution chart. The methodology used only normally distributed data, which in the process had removed all of the data that had been affected by unusual and abnormal causations. These abnormal causations the authors classified as assignable causes, leaving only data with common causes, as illustrated in Figure 2.3 below. By this process, it was argued that it considers only "lightly impacted" and "not impacted" productivity measurements.

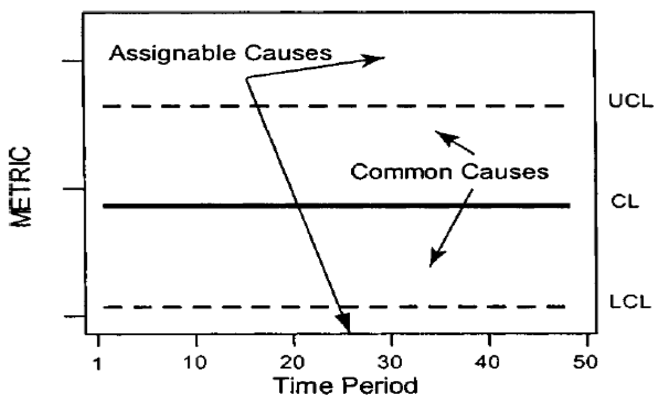

Figure 2.3 Basic control chart structure (Gulezian and Sumelian, 2003)

The means of each sample set were plotted on the control chart and the overall mean, on the centre line (CL), determined the overall productivity mean of that activity, which was the baseline productivity. This baseline approach used statistical analysis methods commonly used in Total Quality Control management with testing for normality, by way of control charts, Q-Q plots and Shapiro Wilk tests. Excluding only the extreme (outliers) data, caused by "assignable causes", provided a more acceptable and realistic baseline productivity outcome, which construction projects would achieve during normal operations. This approach provided the ability to record and determine baseline rates for accurate forecasting and to estimate future projects.

Other models

Zhao and Dungan also proposed an improved baseline method (Zhao et al., 2014) to incorporate Thomas' (1999) and Gulezian and Sumelian's (2013a) baseline methodology. However, this model only used the mean of the best 50% of the outcome that Gulezian's proposed, from each daily sample set. It is argued that Zhao and Dungan's improved baseline method (2014) erred towards the best outcome rather than the actual productivity that was not affected by assignable causes. It is concluded that this would neither be an accurate representation of the on-site productivity of activities measured nor reflect the productivity outcome obtained under a contractor's typical operating performance.

Many modelling options have been used for construction labour productivity (Yi et al., 2014) such as regression analysis, statistical clustering, "fuzzy" set theory, artificial neural network modelling, analytic hierarchy process and data envelopment analysis (Hanna, A.S. et al., 2002a; Jang et al., 2011; Pradhan and Akinci, 2012; Sonmez et al., 1998; Yi et al., 2014). Many of these models proposed methods for analysis, which were found too complicated for general use in the construction industry.

For detailed analyses of findings, previous prefabricated timber panel quantitative studies have applied homogeneity of variance using One-way, Two-way ANOVA and t-tests to analysis their data (Ajweh, 2014; Forsythe et al., 2016). General contractors with tuition can be proficient in these analysis methods. Consequently, these methods were deemed the most appropriate to test the propositions chosen for this study (Ajweh, 2014; Forsythe et al., 2016).

2.5 Summary

In summary, to enable benchmarking, one has first to ascertain baseline productivity or output of the activity in question. Motwani, Zhao, Gulezian, Samelian, Thomas and Zavrski proposed models in which productivity baseline rates could be obtained by using basic statistical techniques (Gulezian et al., 2003a; Motwani et al., 1995; Thomas, H.R. et al., 1990; Zhao et al., 2014). Both Thomas and Zhao proposed methods considered only the optimum productivity percentile, which was not considered as the word suggests, a "baseline" measure but instead is an optimistic outcome. Gulezian and Sumelian proposed a model (2013a) that provided a common-sense approach to determine productivity rates obtainable at normal operations that excluded assignable causes. In this latter approach, the baseline is calculated from non-affected and lightly affected productivity, that is, considered only from value-add activities. It applies basic analysis methods that can be used by general contractors. Gulezian and Sumelian's methodology provided a more robust statistical approach to establish baseline productivity units, and work process cycle time, for the selected case study. Based on the review of models, Gulezian and Sumelian's improved baseline approach establishes the productivity baseline findings for this research study, supplemented by the homogeneity of variance, t-tests and regression analysis for testing propositions.

This chapter discussed the importance of productivity, its various definitions and proposed measurement methods for analysis, to develop a theoretical approach.

The appropriate definition was determined by Equation (1):

$$\text{Productivity} = \frac{Output\ (M2)}{Input\ (hrs.)}$$

The pertinent factors identified were:

- Non-value-added activities, e.g. delays and disruptions (Christian et al., 1995; Koskela, 2000; Sacks et al., 2016; Schmenner et al., 1998),
- Site factors (e.g. floor height, storage, congestion & learning curve (Thomas, H. R. et al., 1986; Thomas, H.R. ; et al., 1987)),
- Environmental (e.g. inclement weather)(Thomas, H.R. ; et al., 1987; Yi et al., 2014),

- Pre-planning, crew size, supply management /delivery logistics) (Koskela, 2000; Thomas, H.R. ; et al., 1987; Vrijhoef et al., 2000, Kasbar, 2017),
- Primary or leading input resource (Adrian et al., 1976; Richard, 2010; Forsythe et al., 2019b),
- Output dimension, i.e., size of assembly: panels,
- Cycle time.

The flowchart framework, Figure 2.4 below, used for quantitative application in this thesis, is the updated version from Figure 2.1 from this chapter's theoretical review. Both labour and crane times were identified to be measured and analysed to ascertain, which was the primary input resource item. The factors influencing mass timber productivity have been discussed, as summarised in Figure 2.4. In this chapter the concept propositions have been identified:

- Equipment*,* not labour, is the primary and leading on-site productivity input resource for the installation of mass timber systems (section 2.2.5),
- A differential in floor level height above ground will not cause significant variance in productivity rates (section 2.5),
- Increase in panel size will cause significantly positive upturn in productivity rates (section 2.2.5.),
- Inclement weather negatively affects the on-site installation productivity of prefabricated timber panels (section 2.5),
- An equation can be formulated to predict panel daily productivity inclusive of the significant factors above (section 2.4.1).

However, other relevant factors identified in the following review of prefabrication and mass timber literature in Chapter 3 also need to be considered.

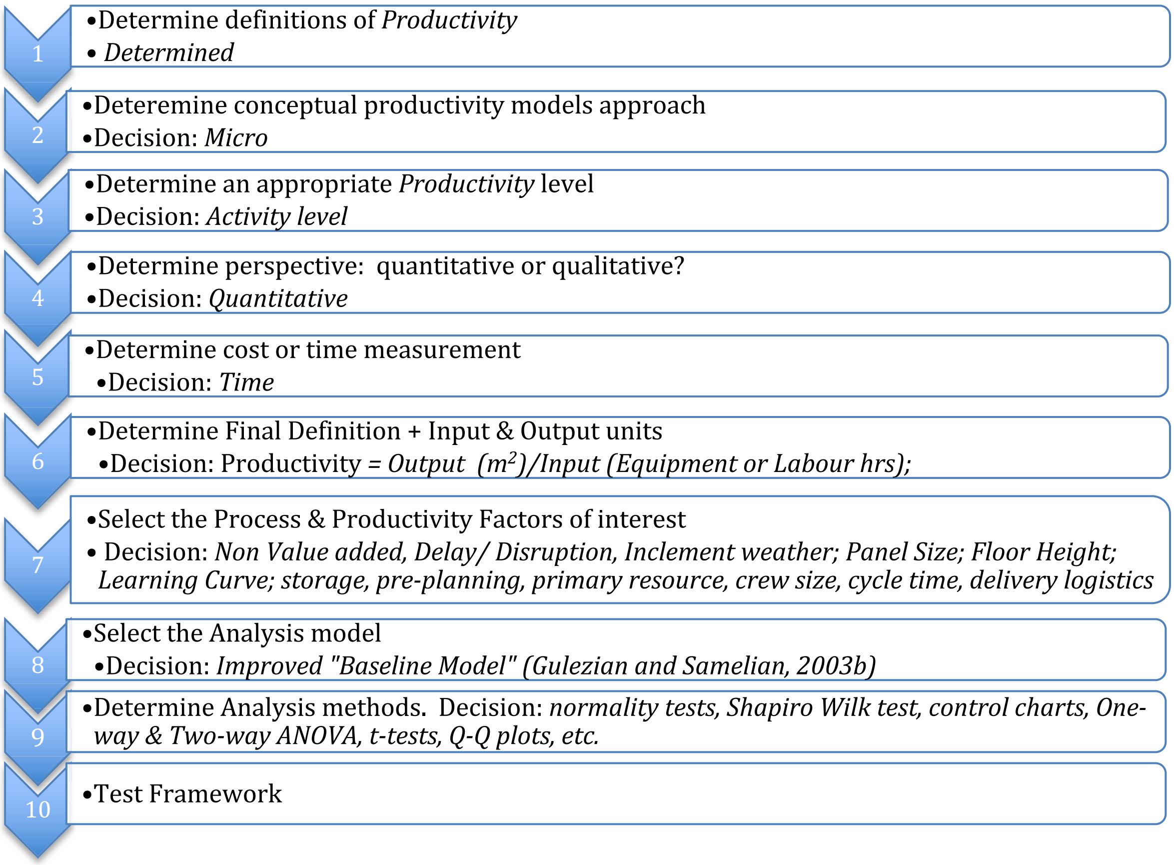

Figure 2.4 Monitored flowchart for measuring mass timber productivity

Chapter 3 Industrialisation, Prefabricated Mass Timber and its Benefits

The previous chapter examined the concepts and application of productivity and assessed manufacturing production process methods to on-site construction. This chapter explores industrialised construction in the context of prefabrication, specifically mass timber. The result is a theoretical evaluation of industrialisation, with a focus on timber, its inherent benefits, the current barriers in uptake and its potential for productivity improvement during the on-site process.

Progress and improvements in new industrialised technologies, such as advances in prefabrication techniques in the construction industry, have changed the process of building over the last four decades (Allmon et al., 2000; Goodrum, P. et al., 2009; Kenley, 2014). Although improvements in productivity can be due to changes in technology, a comparative understanding of the relationship between the increased use and advancements in industrialised building technology to improved outputs remains unclear (Goodrum, P. et al., 2009). This chapter reviews the possibilities of improved construction productivity by industrialisation through the use of prefabrication system technology, its methodology and its alignment to an on-site production process.

3.1 Industrialised Building Systems

Often, construction is viewed as inefficient and labour intensive with low levels of innovation and technological advancement compared to manufacturing (McKinsey Group Institute et al., 2017; Van Egmond-de Wilde De Ligny, 2010). Manufacturing is an example that demonstrates the advantages industrialisation can offer construction. It improves performance by innovation and introduction of prefabrication and automation. However, construction is different in many respects to that of manufacturing (Van Egmond-de Wilde De Ligny, 2010). In traditional construction, the production process of materials and components occur on a building site, and therefore the parts are processed and integrated at the formation stage of the proposed building (Van Egmond-de Wilde De Ligny, 2010). As a result, there is a lack of alignment between the parties working side by side on-site. This misalignment often translates into dysfunctional teams, low levels of cooperation and lost opportunities for optimum use of resources and industrialisation (Van Egmond-de Wilde De Ligny, 2010).

Over 50% of project costs are from labour and equipment (Girmscheid, 2010) and 15-22% of the project cost is from time related main contractor's supervision and temporary site infrastructure (AECOM (Ed.), 2015). Where portions of the building work are produced off-site, this consequently decreases labour content, speeds up the process and reduces time-related costs. It has been found that on a traditionally constructed building, on average, only 35% of total project time is directly related to value-add work (Girmscheid, 2010; Koskela, 2000; Levy, 1990).

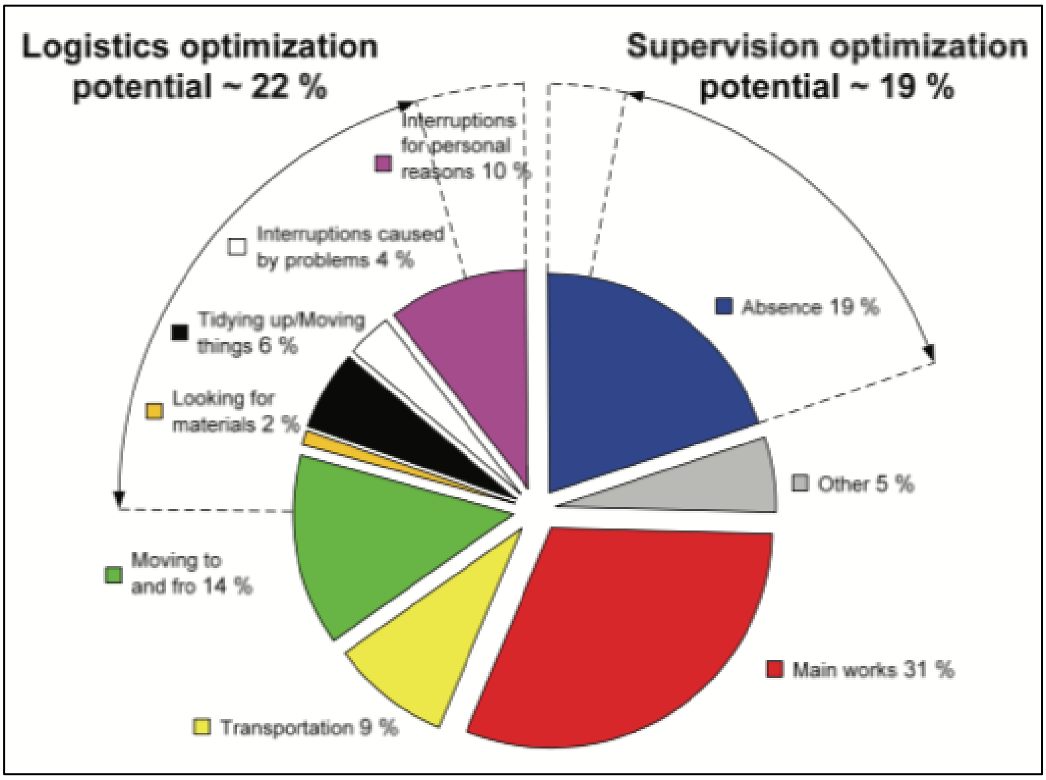

Figure 3.1 Cost reduction potentials: Use of work time for building works (Boenert and Blömeke, 2003)

As illustrated in Figure 3.1 above, more than 40% of the total time was classed as waste or non-value-added, such as looking for materials, tidying up and moving things, interruptions, and trades or workers not on-site when required (Boenert and Blomeke, 2003; Girmscheid, 2010). If the non-value-added work is minimised,

it would result in a reduction of cost and time. This clearly demonstrates that there is a need for improvement in the traditional on-site construction approach.
Off-site manufacture (OSM) has been defined as a term for industrialised building, where a wide range of applications are implemented and building structures or components are manufactured and assembled away from the construction site prior to final installation (Gibb and Pendlebury, 2013; Yashiro, 2014). Off-site technologies utilisation can solve the slow supply and poor quality of buildings (Pan et al., 2007). Industrialisation is a structural means for eliminating, or significantly reducing, on-site activities and waste in construction (Koskela, 2003). With the recent growth of many national construction industries, globally, it has increased the demand to deliver projects quicker, with the need to improve quality levels and environmental sustainability. This demand has strengthened the importance of industrialised building system (IBS) adoption for construction projects (Zakaria et al., 2018). CIB Task Group 57 (2010) identified examples of industrialisation drivers which were:

- a need for improved productivity,
- cheaper production,
- demand for faster projects,
- improved safety,
- better quality control,
- enhanced environmental care,
- occupational health and
- lack of skilled labour.

Industrialisation in construction, offers various approaches by way of standardisation and streamlining work processes to improve cost efficiencies, productivity and quality (Girmscheid, 2010). The consequences of industrialisation are mass production, mass customisation, prefabrication, standardisation and modularisation (CIB Task Group 57, 2010). Not only does this create new opportunities, but it also forces the construction industry to adopt new practices. The most applied industrial practice is prefabrication (CIB Task Group 57, 2010).

The benefits of prefabrication or off-site fabrication include improved performance, reduction in time-consuming on-site activities, and affects from adverse climate conditions (Van Egmond-de Wilde De Ligny, 2010). IBS embraces sustainability and to be more accountable to sustainability principles than the traditional construction methods. Prefabrication makes available a considerable reduction in environmental degradation, while at the same time providing significant productivity improvement, reduced labour requirements and improved working conditions (Zakaria et al., 2018). The sustainability advantages include reduction in waste, increased building longevity, improved quality control, simplicity, rapid construction process, environmental pollution reduction, and energy consumption reduction (Zabihi et al., 2013). There are significant benefits for building projects with the adoption of IBS through efficiencies in the design and construction process from a broad production and lean approach, particularly in waste reduction. Prefabrication, however, means investing in preparation so that things proceed smoothly on-site. Planning and on-site organisation must be intensified, and interaction, cooperation and coordination in a multi-trade context has to be optimised, to gain its full potential of benefits (Koskela, 2000).

Even though the type and degree of adoption of IBS in construction projects have varied in different countries and despite its impressive potential, its use has increased slowly in the past two decades. The gradual adoption has generally been driven by its performance potential and enhanced environmental impact by sustainable construction procedures (Zakaria et al., 2018). Although IBS is a growing building technology throughout several countries and despite its self-evident benefits, there has been general resistance in its uptake (Zakaria et al., 2018). Building professionals have been discouraged from considering industrialised systems as a viable option due to the lack of available information and exposure to IBS (Sweet and Schneier, 2012; Zakaria et al., 2018).

3.2 Prefabrication

Industrialisation can be viewed as five degrees of advancement as concluded from other industries, i.e. prefabrication, mechanisation, automation, robotics and reproduction (Li et al., 2014; Richard, 2010). The term "pre" in prefabrication infers that the element is made off-site in a factory (Richard, 2010). Construction prefabrication is associated with various acronyms such as off-site construction, off-site manufacture (OSM) (Pan et al., 2007), industrialised building and modern methods of construction (Li et al., 2014).

3.2.1 Prefabrication definition

The Committee on Advancing the Competitiveness and Productivity of the U.S. Construction Industry (CACPUCI, 2009) defined prefabrication in construction, as "a process involving the fabrication or assembly of systems and components off-site, which when complete are transported to the job site for installation at the required time. It is an innovative process aiming to minimise on-site fabrication activities more efficiently, in a controlled environment, to achieve gains in quality, costs and time on-site".

Even though the CACPUCI (2009) definition of prefabrication is clear, it differs from the traditional construction methods where the bulk of a building is produced on-site (Pan et al., 2007; Shahzad, W. M. et al., 2013).

Table 3.1 Prefabrication Categories

Prefabrication Progression → Building Modularisation						
Categories by (Study)	Initial Prefabricat'n Category	More sophisticated Category	Integrat'd Category	Volumetric Category	Modularis'd	Whole building
(Hook and Stehn, 2005)	On-site component sub-assembly	Element prefab	-	Volume element	-	
(Shahzad, W. M. et al., 2013)	On-site stick/ component sub-assembly	Panelised non-volumetric	-	Modularised or volumetric assembly	Modularise plus panel	"Box form" – complete building off site
(Li et al., 2014)	Component manufacture & sub-assembly	Non-volumetric pre-assembly	-	Volumetric pre-assembly	-	Volumetric Whole building
(Girmscheid, 2010)	Semi-fabricated structural elements	Prefab. Structural elements	Integrat'd elements	Structural room modules	Finished room modules	Building systems

Construction prefabrication can take on various forms, which can be categorised in the progression of systemisation of elements, in terms of content and spatiality (Girmscheid, 2010; Li et al., 2014). Table 3.1 above outlines suggestions from previous studies of the progression of prefabrication sophistication. This table demonstrates that there is general agreement in terms but with varying depth of focus in research. To use Girmscheid's categories from the above Table 3.1: "prefabricated structural elements" act as structural elements and lost formwork or composite elements. The "prefabricated structural components" are manufactured in an off-site plant, transported to the site to be installed with the relevant connections, for example flights of stairs and structural wall panels. "Prefabricated integrated elements" however, are functional elements manufactured off-site with integrated insulation, finishes and services to be installed on-site (Girmscheid, 2010).

Currently, the use of prefabrication plays a minor role in Australia and New Zealand's construction industry (Shahzad, W. M. et al., 2013). Typical prefabrication categories used are on-site component assembly, stick and component-based sub-assembly (e.g., structural steel) and to a small degree, semi-finished elements (lightweight beams and timber wall frames). The use of panelised or non-volumetric assembly of prefabrication systems, such as floor cassettes, roof cassettes and cross-laminated timber (CLT), is a relatively new concept, especially in Australia (Forsythe et al., 2016). Structural room modules and finished room modules, such as bathroom pods have been available for over 40 years (Eurocomponents, 2020) but are still slow in its uptake. The focus of interest in this study is the more important prefabricated structural element.

3.2.2 Progression of prefabrication in construction

Even though prefabrication has been in used for over a century, to many in the industry it is considered to be a recent innovation and consequently believe its uptake to be a project risk (Shahzad, W. M. et al., 2013). Earlier literature has, in fact, traced prefabrication back over 130 years to the 1880s with the introduction of wooden frame houses (Luo et al., 2005). The first recorded use of precast concrete prefabrication in 1898 on Weaver's Mill, Swansea, UK (Elliott et al., 2013). Structural steel prefabrication has been used in the construction industry since the early 1920s (Elliott et al., 2013).

However, it was not until the late 1930s and early 1940s, during and immediately after World War 2, that prefabrication became recognised (Etxepare et al., 2015). The European Recovery Plan, known as the Marshall Plan, drove the urgent and rapid construction, after the war, of affordable housing throughout Europe (Etxepare et al., 2015). With the technical advances in precast concrete production, the use of prefabrication systems increased in the construction industry in Western Europe and the United Kingdom up to and during the 1960s (Etxepare et al., 2015). Unfortunately, its progress stalled due to the public and government perception of prefabricated houses being a temporary dwelling and an inferior product to the traditionally built house, regardless of reality (Duc et al., 2014). However, the account of earlier construction prefabrication highlighted its historical importance in maximising productivity.

Prefabrication is not readily adopted as it is currently not considered a traditional form of construction (Pearman, 2005; Shahzad, W. M. et al., 2013), especially in Australia (Blismas et al., 2006; Boyd et al., 2013; Duc et al., 2014). Although a recent study found that if light to medium commercial buildings construction incorporated between 74%–77% prefabrication, it would provide more than 100% improvement in both cost and time performance (Shahzad, W. et al., 2014). However, due to industry's historically risk-averse attitude there is resistance to its use, due to perceived barriers, mainly resulting from a lack of knowledge and understanding of advancements in prefabrication systems (Kenley, 2014; Shahzad, W. et al., 2014; Shahzad, W. M. et al., 2013). This view is supported by the limited number of known prefabrication on-site productivity case studies conducted to date (Goodrum, P. et al., 2009). The exception to this, being the four recent studies, previously mentioned, on timber-prefabricated structures.

Studies on prefabrication have not been on-site oriented, but generally, focused on manufacturing process optimisation, for example precast concrete factories, and its off-site productivity (Dawood, 1994, 1995; Khalili et al., 2013). Studies include topics such as mould uses, storage optimisation, improved off-site construction productivity by automatic process and planning prefabricated building by disassembly (Dawood, 1994; Hu, 2005; Huang et al., 2005). Studies found that re-engineering the production planning process would improve productivity and delivery outcomes. Even though current studies indicate prefabrication does improve on-site micro productivity, there appears to be limited empirical quantitative evidence to verify this.

3.2.3 Benefits to industry

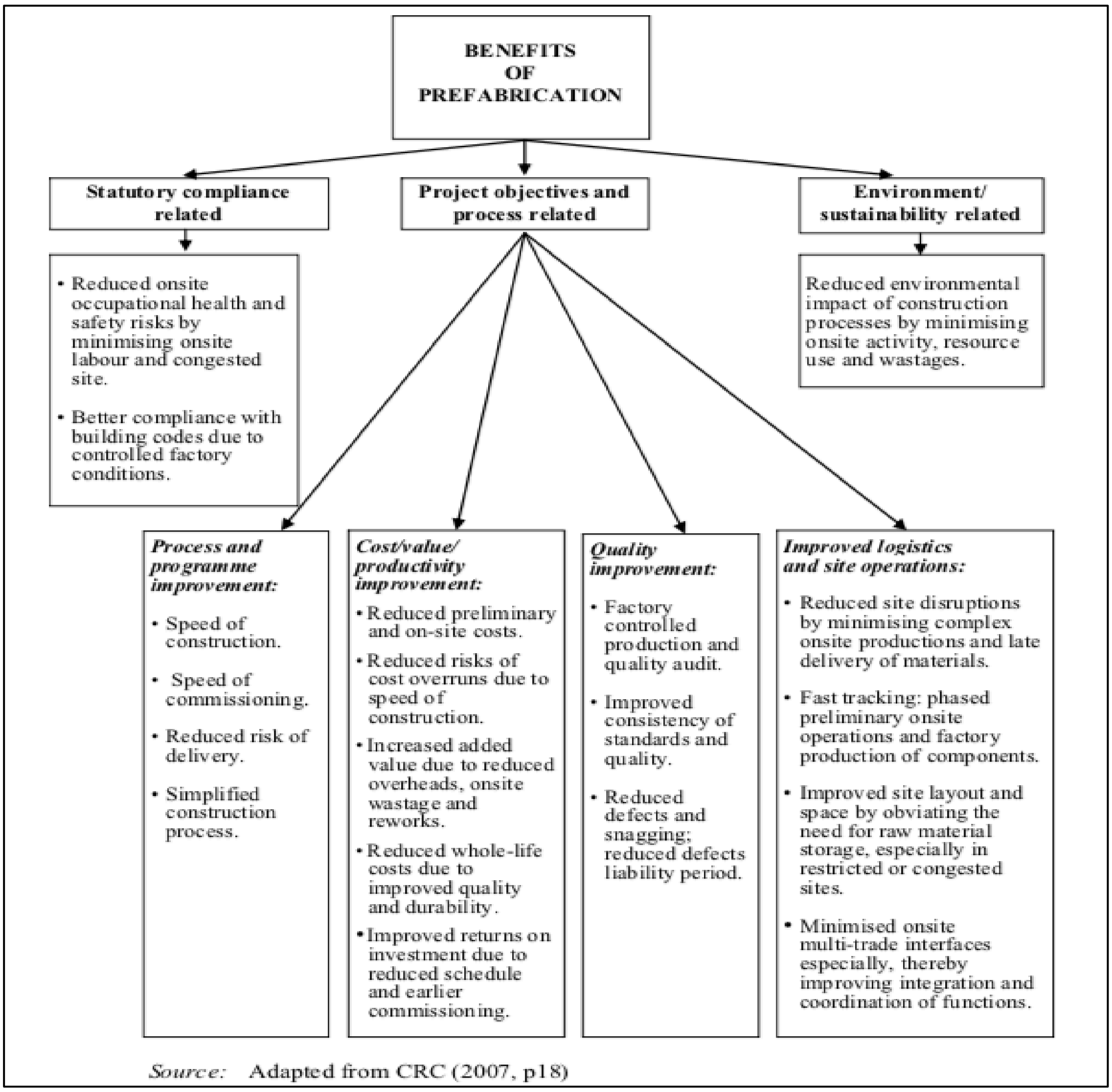

Figure 3.2 Benefits of prefabrication (Shahzad, W. M. et al., 2013), adapted from (Cooperative Research Centre for Construction Innovation, 2007a)

Prefabrication is essential to the construction industry for the many benefits that it provides, as elucidated in Shahzad and Mbachu's diagram above, Figure 3.2, (2013). The benefits identified above, and found from other sources, include improved quality of the product, compliance, enhanced logistics and site operations, improved process and program capabilities, reduced environmental impact, resulting in reduced project cost and enhanced value and productivity outcomes (Ballard et al., 2003; Hook et al., 2005; Jorgensen and Emmitt, 2008; Shahzad, W. M. et al., 2013). As is evidenced in its lack of adoption, the numerous listed advantages in prefabrication appear not to be valued or considered by many professionals when designing and procuring building components.

There has been a strong focus on discovering new methodologies to improve productivity in the construction industry due to declining or stagnating macro productivity over the past four decades, as discussed. These include industrialised building systems (CIB Task Group 57, 2010), construction process re-engineering (CPR) (Green and May, 2003; Love and Li, 1998) and use of lean construction principles (Ballard et al., 2002; Jorgensen et al., 2008). Lean construction, supply chain management, industrialisation and process re-engineering concentrate on the same principles, which is a focus on process (Green et al., 2003). Lean construction lends itself to the adoption of OSM of prefabricated components for on-site assembly for productivity optimisation (Ballard et al., 2003; Jorgensen et al., 2008; Khalili et al., 2013). A lean, or just-in-time, approach for delivery and minimisation of storage, was found to contribute to productivity improvement (Pheng et al., 2001). Lean construction techniques have been found to improve workplace safety by workforce reduction (Court et al., 2009). The adoption of waste awareness and training and development are fundamental to lean construction (Bajjou and Chafi, 2018), as well as re-engineering and industrialisation.

Industrialised construction systems, such as prefabrication, encapsulate and encompass construction process re-engineering and lean construction principles. It reinforces the argument that the adoption of prefabrication methods is an on-site productivity enhancer. Good process flow, in lean and industrialised construction, is deemed to result in minimum non-value-add actions, i.e. the minimum potential waste, to provide customer end value (Sacks, 2016; Womack and Jones, 1996). This study endeavours to apply these guidelines to the case study by drilling down to identify process waste. By removing non-value-added actions, the value-add activities' productivity is determined. In this approach, it may assist in establishing practical methods in improvement for on-site industrialised building processes.

3.3 Timber in a prefabricated form

The use of mass timber, in its prefabricated form, is a relatively modern concept for the construction industry and is especially suited to multi-storey construction. Timber provides several additional benefits over any other prefabrication material. Wood is the only self-renewing material used in building construction, is suitable for prefabrication, approximately 20% the weight of concrete and provides environmental sustainability benefits (Bowyer, J. et al., 2016; Bratkovich et al., 2011; Dovetail Partners, 2013). However, there has been resistance to the use of mass timber, as with other forms of prefabrication, mainly due to a gap in knowledge and understanding of this new technology (d'Errico, 2016; Lehmann, 2012b; Smyth, 2018).

3.3.1 The longevity of multi-storey timber construction

Similar to industry's perception of prefabrication, construction professionals consider multi-storey timber construction as a new phenomenon. It believes that the adoption of prefabricated timber structures for tall buildings will create unknown risks (Forsythe et al., 2016; Smyth, 2018). Wood buildings are not new phenomena they represent a rediscovery as opposed to a new development that has proven longevity (d'Errico, 2016). There are many examples of high timber buildings around the world that are still in use, and many are over 100 years old, a number built over 900 years ago. Examples of timber building longevity are illustrated in Table 3.2 below.

Table 3.2 Examples of timber buildings' longevity

Building	**Use**	**Height**	**Built**	**Longevity (yrs)**	**Source**
Horyuji Pagoda, Nara, Japan,	Temple	5 -storey	c700 AD	1,320	(Bowyer, J. et al., 2016; d'Errico, 2016; United Nations Educational Scientific and Cultural Organisation, 2013)
Yingxian Pagoda, Shangxi, China	Temple	9-storey	c105 6AD	960	(Bowyer, J. et al., 2016; d'Errico, 2016; United Nations Educational Scientific and Cultural Organisation, 2013)
Kyo-o-gokoku-Ji, Kyoto, Japan	Temple	55 metres (equiv't. 15-Storey)	c164 4	375	Author, (World Heritage Toji, 2017)
Hopperstad, Norway	Church	Equiv't. 4-storey	c103 4-1116	900	(d'Errico, 2016; Heddal Stavkyrkje and Norway Travel Bureau, 2019)
Heddal, Norway	Church	Equiv't. 5-Storey	c120 0	820	(d'Errico, 2016; Heddal Stavkyrkje et al., 2019)
Kizhi Pogost	Church	37 metres (10-storey equiv't)	c187 0	150	(World Heritage Convention and United Nations Educational Scientific and Cultural Organisation, 2015)
Butler House, Minneapolis, USA.	Office 4,6450m^2	8-storey	1906	114	(Bowyer, J. et al., 2016).
Landing Building, Boston USA	Mixed-use developme nt, 1,200m^2	9-storey	1905	115	(Bowyer, J. et al., 2016).
Perry House, Brisbane, Australia	Boutique Hotel	7-storey	1913	117	(Bowyer, J. et al., 2016)

Table 3.2, above, lists only a few of many existing tall (multi-storey) timber buildings that are still intact and in use in many parts of the world today. One of the oldest multi-storey timber structures still in use, is the Horyuji Pagoda, near Nara, Japan; it has survived the extreme climate and earthquake region of Japan for over 1,300 years (Bowyer, J. et al., 2016; d'Errico, 2016; United Nations Educational Scientific and Cultural Organisation, 2013). These examples provide evidence that tall timber structures are durable and resilient to various extreme climate conditions and can have a long-life expectancy, contrary to common misconceptions. They also confirm that tall timber buildings are not a new concept but an uncovering of an older traditional way of building, which has proven inherent properties and longevity (Bowyer, J. et al., 2016; d'Errico, 2016).

3.3.2 Environmental sustainability and reduced environmental impact

Currently, the building construction sector, together with the operation of buildings, consumes up to 40% of global energy use (United Nations Environment Programme et al., 2009). Construction is responsible for one-third of the anthropogenic greenhouse gas (GHG) emissions in the form of carbon dioxide into the atmosphere. This is a result of burning fossil fuel to provide processed energy for the manufacture, transportation and installation of traditional construction products by the world's developed and developing countries (Buchannan and Levine, 1999; Gustavsson et al., 2006; Robertson et al., 2012; United Nations Environment Programme et al., 2009). To compound to this, it is forecast that the environment will be further negatively affected by a forecast global population expansion of 33% to 9.7bn people by 2050. To accommodate this, rapid construction of an extensive quantity of buildings will be required for humans to live in and work (Lehmann, 2012a; Robertson et al., 2012; United Nations Environment Programme et al., 2009). To reduce the resultant increased environmental impact on the planet, due to increased GHG emissions from this construction to meet population growth, the industry needs to change its current practice and use more environmentally sustainable resources (Anderson et al., 2020).

One of the key inherent characteristics that differentiate mass timber to other forms of prefabrication is that wood is an environmentally sustainable resource. Wood is the only material that can potentially achieve a net negative carbon footprint for new buildings (Bowyer, J. et al., 2016; Dovetail Partners, 2013). Wood provides oxygen during its growth and stores carbon dioxide during and after installation (Bowyer, J. et al., 2016; d'Errico, 2016; Dovetail Partners, 2013; Falk, 2010; Gustavsson et al., 2006; Lehmann, 2012a, b; Lehmann et al., 2012). The global carbon dioxide storage increases as more wood-based products are used to replace non-carbon dioxide storage capable materials, such as steel and concrete (d'Errico, 2016; Gustavsson et al., 2006; Mahapatra et al., 2008). Wood is the only material capable of satisfying the four principles of green buildings (Canadian Wood Council, 2002; Wang et al., 2014)): i) reducing external pollution and environmental damage, ii) reducing energy use during building service life, iii) reducing embodied energy and resource depletion and iv) minimising internal pollution and damage to health.

The increased use of wood in construction will also reduce its environmental impact. Storing carbon in building structures can be a cost-effective alternative to on site renewables. The 2,044 tons of sequestered carbon, from the CLT Bridport House project, has the equivalent saving in providing 20% of the building's energy requirement in use for 139 years (Zumbrunnen and Fovargue, 2012). A 17% increase in wood content in all future building construction would translate to a 20% decrease in atmospheric carbon emissions from the manufacture of building materials. This would eliminate 66 million tonnes of carbon emissions annually, equivalent to over 1% of global emissions (Buchannan et al., 1999).

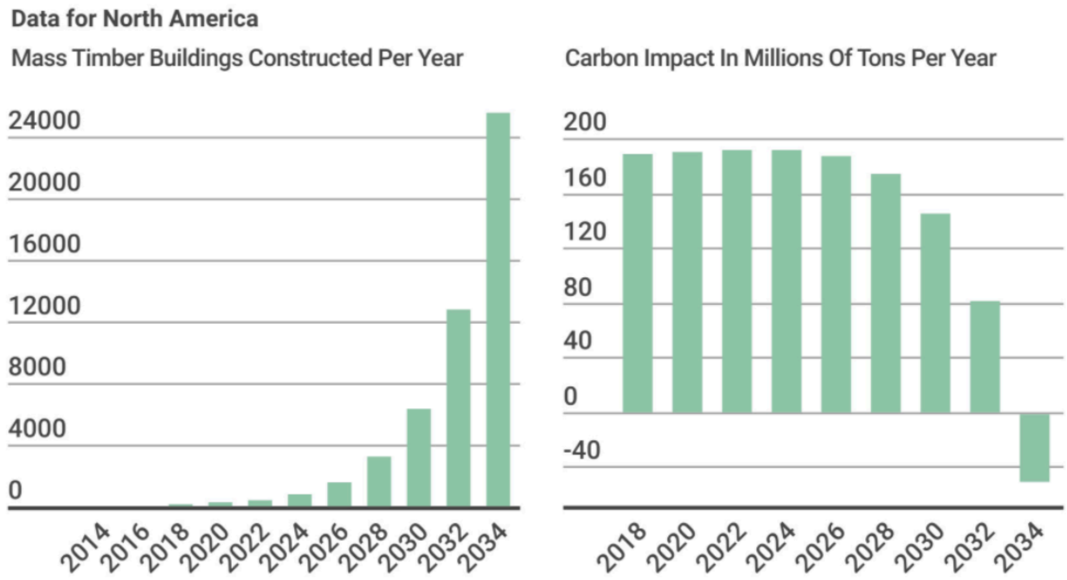

Figure 3.3 The "Marshall Effect" (Anderson et al., 2020)

To bring this into context, Figure 3.3 above, illustrates the "Marshall" effect on carbon impact if the number of new mass timber buildings constructed, doubled every two years, commencing 2018. Using this strategy, it takes North American as an example for the global effect, with the result that the building industry will store more carbon than it emits by year 2034 (Anderson et al., 2020).

In terms of anthropogenic environmental impact, wood is an infinite resource and, if sustainably managed and harvested, has the smallest impact on the environment of any material used by humans (d'Errico, 2016; Falk, 2010; Gustavsson et al., 2006). There is need for a global transition from the use of current traditional fossil fuel produced materials. Alternatively, the planet's environment would be severely affected by the ever-increasing need to build more buildings for the predicted global population expansion (Lehmann, 2015). Converting to wood, such as mass timber systems, would result in an increase in environmentally sustainable buildings providing a positive global construction environmental impact (Anderson et al., 2020; Lehmann, 2013).

3.4 Progression in timber prefabrication technology

3.4.1 History of mass timber

Although mass timber prefabrication is considered relatively new technology, glulam or glued laminated timber method of construction, consisting of straight glue-laminated bonded beam structures, was first used in 1890 in Berlin (Rhude, 1996). In 1910 the Hetzer system, as it initially became known in Europe, was exhibited in a 43-metre span building at the 1910 Brussels World Exposition receiving two Grand Prizes at the 1910 Exposition. By 1922 the Hetzer system had been used in over 15 European countries including Austria, Belgium, England, Germany, Hungary, Italy, Norway and Spain (Rhude, 1996). This type of construction, with its lower finish grade laminated veneer lumber (LVL), initially faced resistance to its use from both the construction and steel industries. However, it became accepted at that time due to economic savings in its use and improved fire resistance compared to steelwork (Rhude, 1996).

Using similar technology to that of glue-laminated beams, a prefabrication manufacturing system known as Cross Laminated Timber (CLT) panel construction was developed in the early 1990s in Austria and Switzerland in a partnership between industry and academic institutions including Graz University of Technology, Austria. CLT emerged, commercially, as a new engineered timber system around 1996, with the early CLT buildings in Europe. The first CLT structure built in Switzerland was in 1993, followed by one in Germany (1995) and then Austria (1998). (KLH Massivholz, 2009; Lehmann, 2012b; Mallo, 2014; Rhude, 1996). Mass timber prefabrication is not new but is a proven prefabrication construction system with proven longevity.

3.4.2 Mass timber manufacture

In contrast to the timber-framed systems, suited to only low-rise buildings, prefabricated mass timber is suited for multi-storey buildings due to its greater load-bearing capacity, seismic performance, fire-resistance rating and charring properties (Anderson et al., 2020; Wood Solutions, 2015c). Mass timber comprises, generally, of two assembly types, which are both dimensionally stable solid elements: engineered beam and column assemblies, such as glued laminated timber (Glulam), and engineered structural solid panels, typically Cross Laminated Timber (CLT) (Wood Solutions, 2015b, c).

Glulam, Figure 3.4 below, is an engineered wood product, similar to laminated veneered lumber (LVL), the difference is in its high-quality surface finish, due to its manufacturing selection process, which provides greater versatility and multipurpose application. The manufacturing process delivers a consistently higher strength product than tradition solid-sawn timber of the same cross section. Glulam is manufactured in a range of softwood and hardwood species of laminates, which are dressed to an exact and uniform thickness. (Timber Development Association NSW, 2011; Wood Solutions, 2015a).

Figure 3.4 Example of glulam beam and columns

The cross-laminated timber (CLT) system consists of engineered prefabricated load-bearing structural panels suitable for both horizontal and vertical structural elements of a building. The panels are manufactured by bonding together a series of solid timber boards with structural adhesives to produce solid timber components. CLT panels are made from seasoned timber species such as spruce, larch, radiata pine or Douglas fir. Each layer of boards forming the panel, generally consist of three to seven layers, is stacked at right angles to the previous layer, i.e. each panel is longitudinal or transverse in direction, see Figure 3.5 below (Anderson et al., 2020; Mallo, 2014; Mayr Melnhof Holz Group, 2016; Timber Development Association NSW, 2011).

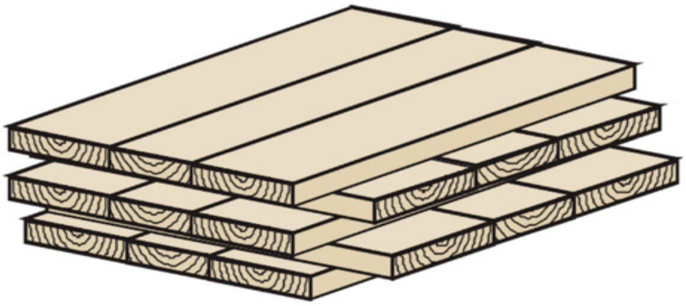

Figure 3.5 Layers of boards making up CLT (extract from Timber Development Association (NSW), 2011)

The completed stacked panels are glued under high pressure, either by vacuum or hydraulic, in perpendicular layers. Polyurethane adhesive, a solvent-free and formaldehyde-free adhesive (zero-emission class), is used by some European manufacturers (KLH UK, 2018). This process achieves very high-quality levels of adhesion, with no risk of toxic emissions at any stage in the product's life cycle (Gagnon et al., 2013; KLH UK, 2018; Timber Development Association NSW, 2015). CLT has significantly improved structural properties to that of sawn timber due to its cross-lamination process, which provides increased split resistance and connector strength. The cross-laminations provide relatively high strength and stiffness properties in both directions, giving it a two-way action capability similar to that of a reinforced concrete slab (KLH Massivholz, 2009; Lehmann, 2012b; Mallo, 2014; Rhude, 1996).

Mass timber lends itself to a file to factory approach in the off-site manufacturing process is via a BIM program digitally transferred to computer numeric cutting (CNC) equipment, which automatically cuts the designated panels accurately in a factory environment (Anderson et al., 2020; Forsythe et al., 2016; Wood Solutions, 2015c). This process delivers the CLT prefabricated wall, floor or roof element to site with quality-controlled pre-cut openings for doors, windows, service chases, etc., enabling rapid on-site assembly, as in Figure 3.6 below (Forsythe et al., 2016). The use of digital technology, i.e. RFID, also assists in site delivery logistics and scheduling to suit project-specific on-site installation detailed scheduling (Sarac et al., 2010). Sizes of panels vary by manufacturer, with maximum lengths of 16.5 metres, maximum widths of 3 metres and thickness from 78 mm up to 500 mm thick with the laminas between 19 and 40 mm thick (Binderholz GmbH, 2016;

KLH Massivholz, 2009; Mayr Melnhof Holz Group, 2016). The limiting factor on the size of panels is generally determined by transport logistics, such as the size of shipping containers, rather than manufacturing capacity (Gagnon et al., 2013; KLH Massivholz, 2012; Timber Development Association NSW, 2015). Mass timber is a robust structural, adaptable and environmentally sustainable industrialised building system providing increased loadbearing capacity, suitable for multi-storey buildings.

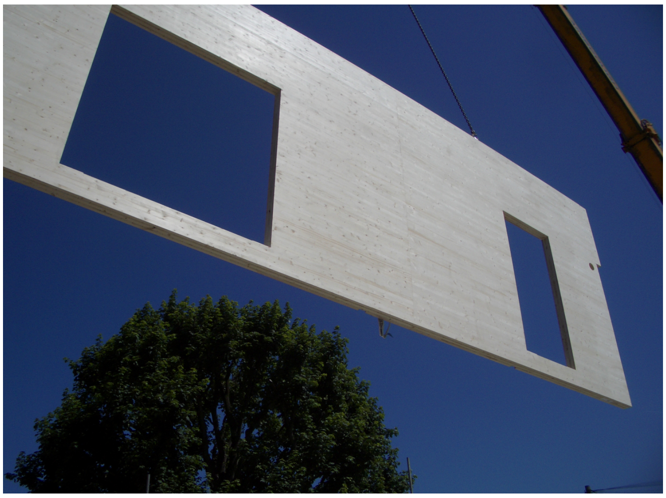

Figure 3.6 Long CLT panel with pre-cut openings craned into position

3.4.3 Mass timber structural design systems

The erection time of a project's mass timber structure and its carbon storage is determined by the volume of timber. This volume is not only determined by the floor area and number of storeys, it also depends on the design selected. There are several structural designs systems that are currently adopted for mass timber buildings, the most notable are: -

- cellular structures in which all the internal walls are loadbearing (as in this study).
- Tenancy/party walls used as the structural elements to transfer the vertical load.
- Post and plate, (Load bearing columns and floor slab).
- Hybrid structures.
- Currently in development: band beams (to provide a greater grid size).

Cellular/ Platform design:

In recent years, CLT has been widely used for different building types, generally adopting a cellular platform method of construction. The cellular platform method is suited for low to medium rise structures, which have a “cellular” floor plan (Hashemi et al., 2016). “Cellular” is reflected in the walls of all rooms within each floor level act as the loadbearing structure. The design uses all internal and external walls in a “stacked” loadbearing function, as those coloured in Figure 3.7 below, allowing vertical loads to travel directly down through the building. Each floor bears onto the load bearing walls below, creating a platform for the next level. Internal wall panels are then used to contribute to the cellular form and act as load bearing components, in addition to resisting the lateral loads (Hashemi et al., 2016).

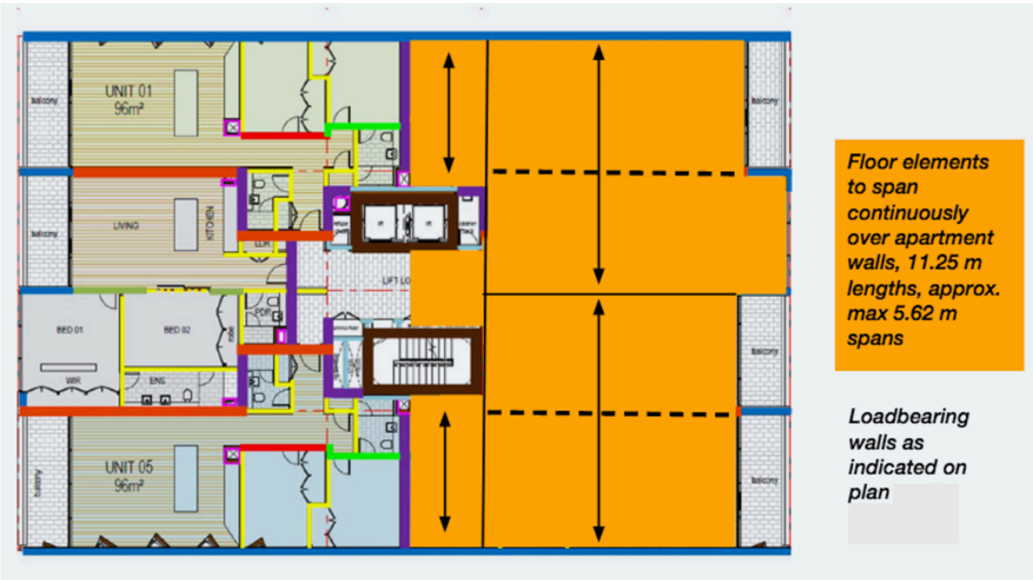

Figure 3.7 Example of a cellular design floor and wall layout (Woodard and Jones, 2019)

The wall panels are connected to each other and to the floor panels by mechanical fasteners such as nail plates, rivets or screws (Hashemi et al., 2016). It is recommended that the same wall layout is applied to all storeys to minimise the requirement of structural transfer. (Woodard et al., 2019; Zumbrunnen et al., 2012). Floor and roof panels can run over at least two bays, as illustrated in Figure 3.5 above, to achieve a multiple span system with fewer crane lifts (Zumbrunnen et al., 2012).

Load bearing party walls

To reduce the need for columns or beams and provide floor layout flexibility, a CLT loadbearing "stacked" external and internal tenancy (party) wall design, Figures 3.8 and 3.9 below, may be found more suitable for residential than the above cellular structure (Zumbrunnen et al., 2012).

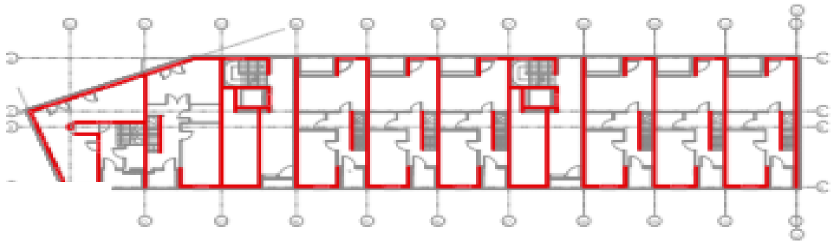

Figure 2: *Ground and First Floor Layouts* © EURBAN Ltd.

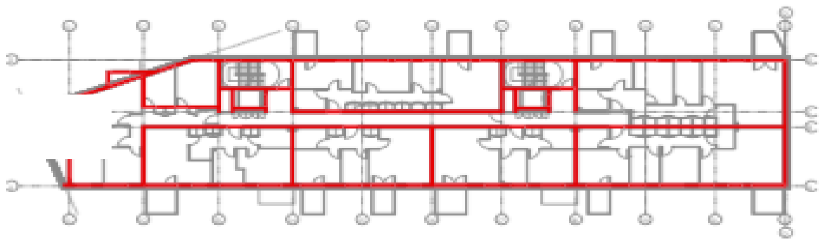

Figure 3: *Upper Floor Layouts* © EURBAN Ltd.

Figure 3.8 Floor Layouts with loadbearing walls (Zumbrunnen et al., 2012)

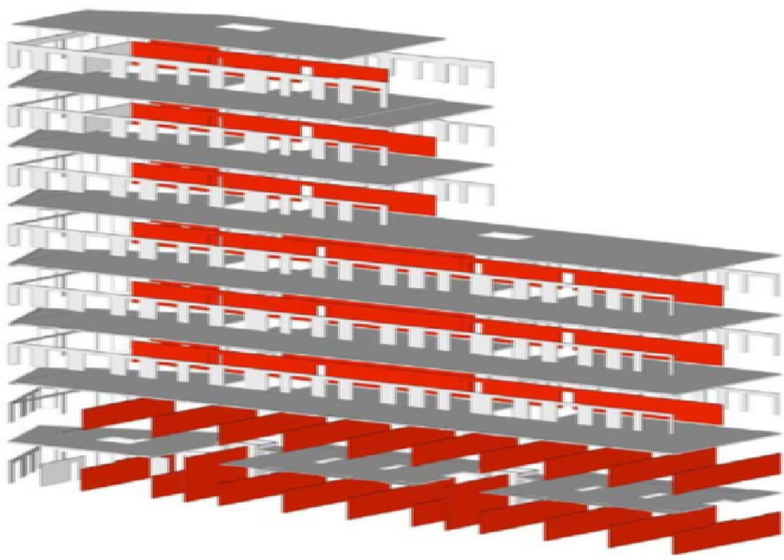

Figure 3.9 Structural layout isometric © EURBAN Ltd. **(Zumbrunnen et al., 2012)**

The tenancy walls, which divide apartments, are usually ideal for loadbearing functions and as shear walls (Woodard et al., 2019; Zumbrunnen et al., 2012). The same tenancy wall layout is recommended on all storeys to minimise the requirement of transfer structures. This provides for continuity of the walls, that is "stacked", allowing vertical loads to travel directly down through the building as illustrated in Figures 3.8 & 3.9 above. Internal loadbearing wall layouts will influence the floor system design, for example the floor spans and the span's direction (Woodard et al., 2019; Zumbrunnen et al., 2012). Internal walls of the apartments are generally lightweight stud partitions but some can be selected to be loadbearing, as in the cellular design but this may be less desirable as it limits future major interior refurbishments (Zumbrunnen et al., 2012). Sufficiently long sections of a load-bearing walls are required in each direction to maximise bracing potential. As openings in the loadbearing walls will lead to concentrated vertical forces on both sides, it is recommended to minimise the size of any opening. (Woodard et al., 2019).

Post and Plate

The structural system selection process may find that a post and plate design, which is often selected for commercial use, may be a preferable alternative. This method was used for Brock Common project, Canada and is illustrated in the Figure 3.10 below of (Kasbar, 2017).

Figure 3.10 Brock Common: example of a post and plate design (Kasbar, 2017)

The post and plate structural systems incorporates glulam columns and CLT floor panels. The system eliminates loadbearing wall panels and introduces columns as vertical load transfer elements providing flexibility of wall layout (Anderson et al., 2020). The vertical load directly passes through the columns, generally, by way of custom designed vertical connection posts with the CLT floor panel corners bearing on four column connection posts. However, this system has its limitation in maximum spans 5.6 metres for CLT floor panels. Where larger spans are required this necessitates deep cross and transverse beams to support them. The deep beams, in turn, creates problems with reticulating services in the ceiling space, as shown in Figure 3.11 below, and consequently, increased floor to floor heights (Hewson, 2019a).

Figure 3.11 Example of a post, beam and plate design

<u>Hybrid</u>

Some building designs include clear floor spans that are difficult to accomplish with mass timber alone. For example, an office or classroom requiring nine by nine metre grid would require floor panels with cost prohibitive thick sections (Anderson et al., 2020). In such cases, consideration would need to be given to introducing concrete/timber composite slabs or deep timber beams as Figure 3.11 or tension cords. Hybrid lateral systems are sometimes required because of the stiffness of mass timber using other options for lateral systems is often cost effective. For low rise buildings, a common approach is light framed wood shear walls. Whereas, for taller buildings, such as Brock Common, reinforced concrete cores have been found advantageous from a performance and constructability perspective. However, cure time and building sequencing should be considered so that the construction of the cores do not penalise the time saving advantages of mass timber (Anderson et al., 2020).

<u>CLT band beams.</u>

To overcome the current limitation in grid size, a recent development has created an increased grid size using a post and plate design, with load transfer to columns, by way of CLT band beams (Hewson, 2019a; Kuzmanovska et al., 2018). Timber band beams are a relatively new engineered concept, in which a wide, minimum depth, (band) beams are used, similar to a secondary floor panel. These are simply supported by glulam columns, locally incorporated to the floor panels, similar to reinforced concrete band beam structures, as illustrated in Figure 3.12 below (Hewson, 2019a).

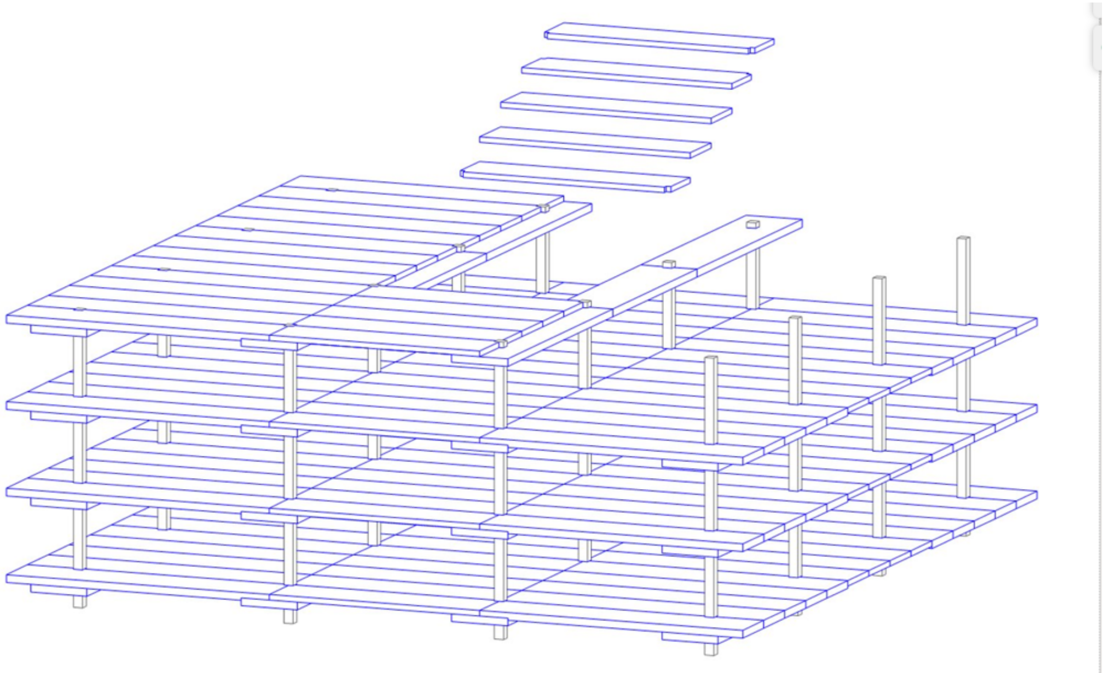

Figure 3.12 Indicative CLT band beam structure (X-Lam)

A timber band beam structural system will be able to provide a 9.00m x 9.00m grid without the need for loadbearing walls (Hewson, 2019a). The installation process for the beams would be similar to that of floor panels and would provide a productively fast method. It will provide the flexibility for internal floor layout design with wall selections of either CLT or lightweight stud and plasterboard lining.

As each project is different with individual needs, there is, consequently, no one design solution that will provide the best outcome for every multi-storey timber building. There are a number of structural considerations to face when designing mass timber structures, for example the panel strength, the connector system and the structural grid layout (Hashemi et al., 2016). Designers also need to consider structural efficiency, fire resistance, acoustic performance, ease of fabrication, buildability and cost in order to optimise project outcome (Woodard et al., 2019). All these factors play a part in the structural design method chosen for the building.

3.4.4 Recent CLT buildings

A notable multi-storey CLT building, the "Stadhaus", was completed in 2009 in Murray Grove, London, United Kingdom. The 8-storey timber structure took 12 calendar weeks, approximately 27 working days, to construct with only four carpenters working a three-day week. The construction of the whole building was completed in approximately 49 weeks and was reported to have saved between 17 - 23 weeks (25-32%), compared to a traditional concrete frame design (d'Errico, 2016; KLH Massivholz, 2009; Lehmann, 2012b; Mallo, 2014; Robertson et al., 2012). The 9-storey Bridport House, London, completed in 2010, was constructed in CLT by way of the designers' interest in the innovative Stadhaus building. The Bridport House timber structure was also installed in 12 weeks and was reported to be 50% faster than a traditional reinforced concrete frame building (d'Errico, 2016; Lehmann, 2012b; Zumbrunnen et al., 2012). The first CLT building to be built in Australia was the Forte building in Melbourne. On completion in 2012, it was claimed to be the tallest prefabricated timber building in the world, at ten stories (Lehmann, 2012b; Mallo, 2014). Five carpenters installed the mass timber structure in an equivalent of 30 working days (Lehmann, 2012b) over a ten weeks calendar period (d'Errico, 2016). Both the structure and the entire building works were reported to be 30% faster than an equivalent traditional reinforced concrete building (d'Errico, 2016; Lehmann, 2012b). These three buildings provide examples of the potential savings in mass timber construction time.

Mass timber building structures are regularly creating new world records with the first 14-storey modularised mass timber building, the Treet, completed in Bergen, Norway in 2016 (Kleppe, 2017). The 18-storey hybrid mass timber Brock Common building at the University of British Columbia campus in Canada was completed in 9.5 weeks in 2017 (Kasbar, 2017). Mjøstårnet (Mjøsa Tower) as at October 2020 was officially regarded, by the Council of Tall Buildings and Urban Habitat (CTBUH), as the tallest timber building in the world (Council of Tall Buildings and Urban Habitat, 2020).

These and further examples of CLT projects with their respective construction time are illustrated below in Table 3.11. Currently, several countries are planning mass timber buildings in excess of 30 stories high. A Japanese company, Sumitomo Forestry, has plans for the world's tallest wooden building in Tokyo, a 350-metre skyscraper (Ravenscroft, 2018), and Hicock Cole Architects are planning 40 and 60-storey mass timber towers in Philadelphia in the United States (Maiolatesi, 2018). A 40 storey hybrid CLT building, for Atlassian in Sydney, Australia, is currently in design and planned to commence construction in 2023 (Masige, 2020). The transition to a general up-take of multi-storey mass timber building could enable productivity and quality improvements through OSM with delivery of the additional benefits that wood provides. These benefits are now examined.

3.5 Benefits of mass timber

The benefits gained from using mass timber are just not limited to the improved environmental impact, speed of erection and its time savings, as discussed above. The main benefits, including those stated, are listed below in Table 3.3.

Table 3.3 Examples of benefits of mass timber (Lehmann, 2012a, b; Lehmann and Crocker, 2015; Shahzad, W. et al., 2014)

Description	Benefit	Supplementary benefit
Productivity	Productivity improvement	Time saving in structure installation
Environment	Environmental sustainability	Sequestered carbon and reduction in environmental impact
Lightweight	Less than 30% weight of concrete	At least 50% lighter than traditional forms of construction
Precision manufacture	Exact dimensions by using the latest CNC production technologies	*File to factory to site* capability
Waste	Reduction of waste due to precise manufacture	Minimum on-site waste due to prefabrication off site
Safety	Reduction in on-site safety incidences due to reduced on-site labour resources	Reduction in injuries and consequential site stoppages
Cost savings	Savings in Main Contractor's Preliminaries	Reduction in time and cost of labour and equipment

These benefits are now discussed, commencing with the primary benefit of improved speed of installation with less labour than traditional construction.

3.5.1 Productivity enhancer

Increased productivity and time efficiency of prefabricated CLT in multi-storey buildings have been discussed from historical and qualitative records. Previous research has estimated between a 25% to 50% reduction in time has been achieved with the use of mass timber compared to traditional reinforced concrete frame buildings. As a representation of this claim, Table 3.4, below, summarises examples of mass timber project from six countries together with the speed of construction, size of installation crew and estimated time saved. Although not quantitatively verified, the evidence from the examples indicate that mass timber multi-storey buildings are able to achieve on-site time-savings, and potential improved productivity, compared to traditional construction.

Table 3.4 Examples of time savings on mass timber projects

Year complete	Building Name	No. of stories	Complt'n time of structure & labour	Complt'n time of building	Timesaving over traditional	Source
2009	Stadhaus, London, UK	8	12 wks. (4 installers)	49 wks.	25-32% on project	(KLH Massivholz, 2009; Lehmann, 2012b)
2011	Bridport House, London, UK	9	10 wks. (4 installers)	Approx. 12 months	50% on structure	(d'Errico, 2016; Lehmann, 2012b; Zumbrunnen et al., 2012)
2012	Forte, Melbourne Australia	10	10 wks. (5 installers)	9.5 months	30% on project	(d'Errico, 2016; Kremer, P. D. and Symmons, 2015; Lehmann, 2012b)
2015	Red Arsenal Hotel, US	4	78 days	11 months	27% on project	(Morrow and Lend Lease, 2015)
2005	Svartlamoen, Trondheim, Norway	5	10 working days	9 months	50% on project	(Lehmann, 2012b)
2011	Reconstruction of Aquila, Italy	7 x 3 storey buildings	NA	80 days	Est. 50% on project	(d'Errico, 2016)
2016	Brock Common, BC, Canada	18 stories	9.5 wks. (9 installers)	14 months	43% on structure	(Kasbar, 2017)

Due to the project's faster construction time, cost savings are achieved from less required time related resources, e.g., the main contractor's supervision and temporary site infrastructure (d'Errico, 2016; Lehmann, 2013; Mahapatra et al., 2008; Robertson et al., 2012; Shahzad, W. M. et al., 2013).

3.5.2 Environmental Sustainability

Environmental sustainability was discussed in section 3.2.2. Timber's unique, environmentally sustainable characteristics enables construction to utilise sequestration carbon benefits through its increased use (Ding and Forsythe, 2015).

3.5.3 Recycling potential

Wood has a recycling potential at the end of its building life cycle. Prefabricated panelised construction systems, such as load-bearing CLT panels, offer significant benefits in carbon reduction and waste mitigation, when used with design for disassembly (lean) principles (Lehmann, 2012a, 2013; Luo et al., 2005; Zumbrunnen et al., 2012). As an example, a temporary innovation hub was built, in 2017, for Macquarie University, Sydney using prefabricated timber panels, beams and columns. The university's intention was for the building to be in its initial location for approximately five years and then to be disassembled, relocated and assembled at another part of the campus (Architectus, 2017).

A mass timber building has the ability for disassembly, in the same way it was installed. Its structural panels can be reused again or converted into another wood product like oriented strand board (OSB) (Zumbrunnen et al., 2012). Prefabricated timber provides a new dimension to building flexibility with de-construction and recycling potential, which opens up benefits of location mobility to suit stakeholders' needs (Architectus, 2017; Hu, 2005; Lehmann, 2012a, 2013).

3.5.4 Wood is lightweight providing cost savings

Wood is lighter than traditional construction structural materials, providing resultant cost savings. Wood is less than half the weight by volume of conventional forms of building structures such as brick, steel and concrete (Robertson et al., 2012). The weight of mass timber is 76% less than concrete, 69% less than brickwork and 92% less than steel: the densest softwood timber, Longleaf pine, is 590 kg/m^3 and one of the heaviest hardwoods, hickory pignut, is 750 kg/m^3 (Bootle, 1983). As a comparison, concrete is 2,450 kg/m^3 and steel is at 7850 kg/m^3 (Struct, 2020). Generally, mass timber is manufactured from softwoods, such as spruce or pine. Due to this, timber provides improved on-site handling with significantly lighter buildings to those built with traditional materials (Lehmann, 2012a, 2013). This reduction in mass and fossil fuel materials translates into project cost savings compared to a traditional form of construction (d'Errico, 2016; Lehmann, 2012b).

As timber buildings are lighter and faster to install there are other cost savings. As the timber building has less dead weight, the required mass and complexity of the foundation component is reduced, resulting in substructure cost savings (Mahapatra et al., 2008; Zumbrunnen et al., 2012). The timber structural panels are lighter to install, facilitating cost savings in reduced crane capacity requirement (Forsythe et al., 2016). The reduced capacity cranes are on-site for less time, so affording additional savings, due to shorter project duration than traditional forms of construction. This lighter structure cost-saving advantage from multi-storey mass timber construction provides an additional benefit in life cycle assessment when compared to similar reinforced concrete buildings (Gasparri et al., 2015; Robertson et al., 2012).

3.5.5 Work, health and safety

Construction is one of the most dangerous industries. In the U.K., over 2,800 people have died from injuries in the past 25 years as a result of construction work (Court et al., 2009). Internationally, it is estimated that there are over 100,000 fatalities on construction sites every year (Zou and Sunindijo, 2015). The Australian construction industry has twice the average national fatalities of other sectors (Zou et al., 2015). The industry has one of the highest rates of Musculoskeletal disorder (MSD) injuries from material handling (Court et al., 2009).

Mass timber installation provides safer construction sites because there is less labour required and less time on-site, compared to traditional construction methods (Robertson et al., 2012). Lend Lease reported that the construction process for its Forte building's, in Melbourne, was safer than for a similar structure with conventional materials because eight stories were in CLT (Kremer, P. D. et al., 2015). Another contributing factor was due to a 30% reduction in time in the overall construction period and less labour on site because of the prefabricated timber structure. The construction process was, also, less complicated than traditional forms of construction because the building structural elements were manufactured off-site and therefore fitted in place more precisely with minimal rework (Kremer, P. D. et al., 2015). The use of timber prefabricated systems combined with lean construction techniques has resulted in safer construction sites. Safer sites were due to the requirement of less labour for the on-site installation process, less waste, therefore cleaner and tidier sites and as a consequence fewer on-site safety incidents (Court et al., 2009; Pasquire et al., 2005).

Using timber also has health and productivity benefits for building's occupants. Employees surrounded with natural wooden surfaces were found on average to have higher personal productivity, mood and concentration resulting in significantly fewer sick leave days (Wood Solutions, 2015c).

3.5.6 Waste reduction

As a result of the mass timber's off-site prefabrication process there is a reduction in waste that provides major benefits. The precision manufacturing of the mass timber components via the CNC precise cutting process minimises on-site rework and on-site and off-site wastage of resources both in material and labour (d'Errico, 2016; Forsythe et al., 2016; Lehmann, 2013). The use of standardisation, such as prefabricated products, in the construction process is a key element of industrialised construction (Girmscheid, 2010). A reduction in waste is due to the pre-designed wastage minimising manufacturing process and reduced on-site process as a consequence of OSM prefabrication (Van Egmond, 2010). The adoption of lean will also reduce waste in both the manufacture and on-site installation. It also reduces on-site storage with just in time deliveries to site, reduction in the quantity of labour resources and potential increased productivity (Hook et al., 2005; Luo et al., 2005; Pasquire et al., 2005). Mass timber implementation gains benefits with reduction in wastage both in material and labour resource by way of its OSM process, which is increased with the adoption of lean construction techniques.

In summary, there are many advantages gained in the adoption of mass timber such as increased productivity, reduction in environmental impact, cost savings, safety and waste reduction compared to traditional construction.

3.6 Resistance, obstacles and barriers to mass timber adoption

Although there are many benefits in mass timber, there are several obstacles and barriers perceived by the industry and the general public, which are causing resistance to its broad up-take (Lehmann, 2012b). The industry has a tendency to remain loyal to the well-known and trusted traditional reinforced concrete and steel structures (Mahapatra et al., 2008; Riala et al., 2014). A risk-averse attitude to new technologies and innovations, such as industrialisation and prefabrication, appears to pervade the majority of the construction industry (Khalfan et al., 2014; Lehmann, 2012b; Zakaria et al., 2018). The five most important factors in the whole industry's resistance to prefabricated timber construction in multi-storey buildings in Australia are categorised in Table 3.5 below, based on questionnaire and interview surveys by Xia et al. (2014).

Shahzad and Mbachu (2013) discovered similar findings from their study to that of Xia et al. The findings in Table 3.5 are also supported by other research studies, indicates that four of the five categories of identified obstacles in timber construction can all be grouped together under the one heading of "lack of knowledge" (Forsythe et al., 2016; Kremer, P. D. et al., 2015; Lehmann, 2012a, b; Mahapatra et al., 2008; Riala et al., 2014; Shahzad, W. M. et al., 2013; Xia et al., 2014). Consequently, the topic of lack of knowledge is addressed below in the following section.

Table 3.5 Perceived obstacles to timber prefabrication in Australia (Xia et al., 2014)

Ranking	Perceived obstacle to mass timber category	Components of category
1	Lack of legislative support	Lack of legislative support from: local government state government federal government
2	Lack of industry interest	Lack of developer interest Limited tertiary education choices Limited technical education and training choices Limited timber industry advertising campaign
3	Lack of experienced (and trained) professionals	Lack of experienced designers Lack of experienced builders Lack of experienced quantity surveyors
4	Perception of timber (prefabrication) disadvantages	Perception of increased insurance cost Perception of increased maintenance cost Perception of increased fire risk.
5	Limited awareness of the advantages of timber	Limited awareness of emerging timber techniques Limited awareness of carbon storage capability

3.6.1 Lack of knowledge

A key reason found for its lack of uptake was because most professionals had a confidence deficiency in mass timber and lack of experience. This was due to limited information availability, limited assistance with timber design and lack of tertiary timber engineering courses. Education of architects, planners and builders in new innovations is lagging in most countries (Bayne et al., 2006; d'Errico, 2016; Forsythe et al., 2019a; Lehmann, 2012b; Smyth, 2018; Xia et al., 2014).

Current education and training are generally focused on traditional practices rather than new innovative techniques. Education facilities need to develop new courses focused on these modern technologies based on peer-reviewed empirical quantitative research (Lehmann, 2012b; Mahapatra et al., 2008; Xia et al., 2014). This would be assisted by worldwide dissemination of standardised information when readily available. However, current empirical quantitative research into on-site prefabrication, including mass timber, is limited (Forsythe et al., 2019b; Lehmann, 2012b; Shahzad, W. et al., 2014). The available education, training, information and knowledge are currently inadequate to convince the industry of the general adoption of new technologies, especially mass timber (Lehmann, 2012a, b; Mahapatra et al., 2008; Shahzad, W. et al., 2014; Shahzad, W. M. et al., 2013; Xia et al., 2014).

There is a need to educate developers, government and the general public, in addition to builders and professional designers, on the full benefit potential in the use of mass timber for new building projects (d'Errico, 2016; Lehmann, 2012b; Mahapatra et al., 2008; Mallo, 2014; Smyth, 2018). The implementation of this transfer of knowledge and training would considerably limit the current perceived barriers. It will encourage the uptake of these new technologies, as successfully experienced in Scandinavia and Japan due to their government's early support and encouragement (Mahapatra et al., 2008; Shahzad, W. M. et al., 2013; Viking et al., 2015; Yashiro, 2014). One of the main concluding points in the 68th UNCECE timber committee meeting (Bowyer, J. L., 2010) was that "essential knowledge had to be developed for the proper design of buildings with wood". There is an urgent need determine as to how mass timber will perform, especially in on-site productivity from a quantitative perspective and transfer this knowledge (Forsythe et al., 2019b).

3.6.2 Limited quantitative studies

Many published papers on the subject have referenced significant time-savings of constructed mass timber multi-storey projects as identified in Table 3.4 above. However, the time-savings have been determined generally by qualitative analysis or third-party information. Data gathering had generally been by way of interview or surveys with reported findings varying from one study to another. For example, research papers quote that the ten storey CLT Forte mass timber building was completed over various times. D'Errico (d'Errico, 2016) found that the mass timber structure took ten weeks to complete. However, Mallo (Mallo, 2014) reported that the installation period was 28 workdays and Lehmann (2012b) determined that the 750 CLT panels were assembled at a rate of "around 25 panels per day" which equated to 31 days. Such findings provide uncertainty and casts doubt on their verifiability to those seeking information.

The exceptions to the generally qualitative papers are from the following four known quantitative studies:

a) Brock Common, Canada, which included a 17 storey hybrid mass timber, repetitive post and plate, structure (Kasbar, 2017),

b) An Australian case study on two to four-storey panelised prefabricated timber structures, of which the mass timber findings was limited to one CLT two-storey detached house (Forsythe et al., 2016),

c) A case study on an Australian single multi-storey mass timber (CLT) aged care building (Forsythe et al., 2019a),

d) An update and in-depth study on the above b) case studies (Forsythe et al., 2019b).

None of these studies nor other known mass timber study focused on associated productivity factors, such as the effects and significance of inclement weather or non-value-add activities. i.e., delays or stoppages. Forsythe and Sepasgozar (Forsythe et al., 2019b) was the only known study to have carried out a productivity assessment of larger timber panels, however these were timber cassette panels in low rise buildings and not mass timber. Neither of the two empirical studies, a) or b), addressed productivit*y* in multi-storey cellular panelised CLT construction. Forsythe's studies focused on crane cycle times as an indicator of productivity. Kasbar's study (2017) focused on timber floor panels and other building elements, for example prefabricated façade components. In the four studies, there were variances in productivity between floor levels but scarce analysis as to whether the causation was due to height of installation. This will be tested by the proposition: a differential in floor level above ground will not cause significant variance in productivity rates.

Quantitative case studies are minimal, with most research for on-site mass timber productivit*y* being qualitative, as exampled above, providing conflicting outcomes.

Differing findings provide uncertainty for industry professionals. The current risk-averse attitude is likely to persist until more empirical quantitative case studies on the subject are available to educate construction industry professionals (Forsythe et al., 2019a; Smyth, 2018).

3.6.3 Lack of legislative support

In Xia's study (Xia et al., 2014) the highest rated obstacle, Table 3.3, was the lack of legislative support. The Australian government took an initial step to rectify this in 2016 when it legislated a revision to the Australian National Construction Code (NCC). This revision, with subsequent amendments in 2019, conditionally permitted the construction of timber buildings up to 25 metres high, equivalent to eight stories (Wood Solutions, 2019). The NCC included, with this amendment, a new defined term for "massive timber", and inserted conditions for fire-protected timber. Similar legislative amendments to construction codes are underway in European and North American countries to reduce the current restrictive legislation and encourage the use of timber in multi-storey buildings, as discussed (p94)(Anderson et al., 2020; d'Errico, 2016; Riala et al., 2014; Xia et al., 2014).

However, it is essential that governments take a leadership role, together with institutions and universities, in providing more assistance and encouragement in the uptake of mass timber. Governments need to set an example of its support of mass timber to industry and the public, as was experienced in Sweden (Mahapatra et al., 2008). Governments could encourage mass timber construction by setting national targets for timber and carbon-negative buildings, by leasing mass timber high-rise buildings and by implementing grant schemes for future mass timber buildings p 71 (Anderson et al., 2020; Lehmann, 2012b). A shift to a growth phase of the timber construction system may be expedited by a change in government and industry policies to "support the expansion of knowledge base" (Mahapatra et al., 2008). Government support for increased mass timber uptake would consequently be encouraged by the entry of new actors, such as new trade contractors, suppliers, consultants and specialists conversant in these techniques (Dovetail Partners, 2013; Mahapatra et al., 2008; Riala et al., 2014).

3.6.4 Increased maintenance cost

Insect attack and fungal decay is often associated with increased maintenance cost (category 4 of Table 3.3) in the use of wood in construction. This is a standard source of resistance to its adoption in multi-storey buildings (Mallo, 2014; Xia et al., 2014). However, a wide range of effective preservatives and barriers are commercially available for use. These can be applied during manufacture or on-site under controlled conditions, to minimise such risk. Traditional construction uses termite and waterproof barriers and is recommended to be replicated in mass timber construction (Lehmann, 2013). Therefore, in reality, the perceived barrier of increase maintenance cost is due to lack of knowledge and has little justification.

3.6.5 Fire risk

One of the identified resistance and barriers to timber products (category 4 of Table 3.3) was due to preconceived fire risk in the use of timber (Mallo, 2014; Xia et al., 2014). This resistance is again due to a lack of knowledge of mass timber's characteristics, its recent fire resistance tests and revised fire rating classification of CLT and glulam (Xia et al., 2014). As mass timber is manufactured in a solid timber format, it does not readily burn but instead chars under a flame. The spread of flame and fire safety is comparable to other established construction methods (Lehmann, 2012a). A study on the fire resistance of CLT panels verified this conclusion, in which unprotected 150 mm thick CLT panels provided 99 minutes of fire resistance (Fragiacomo et al., 2013).

The national construction codes of various countries, including Australia, Sweden and Canada, have been amended to lift restrictions on timber construction due to the certified fire resistance of mass timber components (d'Errico, 2016; Mahapatra et al., 2008; Wood Solutions, 2019). Many mass timber manufacturers are implementing fire rating testing and certification for all of their products (KLH Massivholz, 2018; Mayr Melnhof Holz Group, 2016; XLam Australia, 2019). The pending update of the International Building Code in 2021 with inclusions for mass timber will be particularly relevant (Anderson et al., 2020)(p94). Changes in legislation and international certified fire resistance testing of mass timber products should eliminate the perceived risk of fire.

3.7 Conclusion and research propositions

This chapter discussed the topic of industrialisation and prefabrication as a productivity enhancer. It examined mass timber in its prefabricated form, its benefits and industry's current resistance to its general adoption.

The risk-averse attitude by industry emanates from its perceived barriers to mass timber and industrialised systems in general and, consequently, slows its uptake (Bayne et al., 2006; d'Errico, 2016; Kremer, P. D. et al., 2015; Lehmann, 2012b, 2013; Mahapatra et al., 2008; Riala et al., 2014). These barriers appear to stem from a gap in available education, empirical quantitative literature and knowledge transfer, which in turn impedes industry in gaining knowledge and understanding of mass timber systems; hence its adoption (Lehmann, 2012b; Smyth, 2018). In particular, it appears that this gap is the availability of measurable quantitative research on mass timber on-site productivity and process (Forsythe et al., 2019b).

Therefore, the study is oriented to on-site industrialised mass timber in multi-storey construction. The main aim of its research is to address this current gap to improve its take up and industry's overall productivity. The study also aims to assist the industry in a deeper understanding of the on-site process and factors to promote mass timber's improved productivity potential. The thesis uses a case study approach, in an Australian context. It focuses on on-site productivity and significant related factors from three multi-storey CLT cellular framed mass timber structures over six months in 2016.

The main question for this thesis is:
If and how on-site productivity baseline rates can be developed in a reliable way to assist predictable installation expectations for mass timber panels.

The finalised propositions are:

Proposition 1. Equipment, not labour, is the primary and leading on-site productivity input resource for the installation of mass timber systems. (section 2.2.5).

Proposition 2. A differential in floor level height above ground will not cause significant variance in productivity rates. (section 2.5 and 3.6.2).

Proposition 3. Increase in panel size will cause significantly positive upturn in productivity rates. (section 2.2.5).

Proposition 4. a) Wind inclement weather negatively affects the on-site installation productivity of prefabricated timber panels.
b) Rain adversely affects the on-site installation productivity of timber panels. (section 2.5).

Proposition 5. An equation, inclusive of the above predictors found in propositions 1-3, can be formulated to predict CLT panel daily productivity. (section 2.4.1).

The next chapter presents the research methodology to test the propositions.

Chapter 4 Methodology

The previous chapter presented several propositions concerning the development of productivity rates for CLT panel installation. This chapter presents a research methodology to address these propositions. It begins with the philosophical position of the research (section 4.1), followed by an examination of the pilot study conducted to test various methods of data gathering (section 4.2). It then provides a detailed methodology on all aspects of this empirical stage of the research, including the adopted data gathering, sample selection and analysis. This is illustrated in the research procedure flow chart framework below, Figure 4.1.

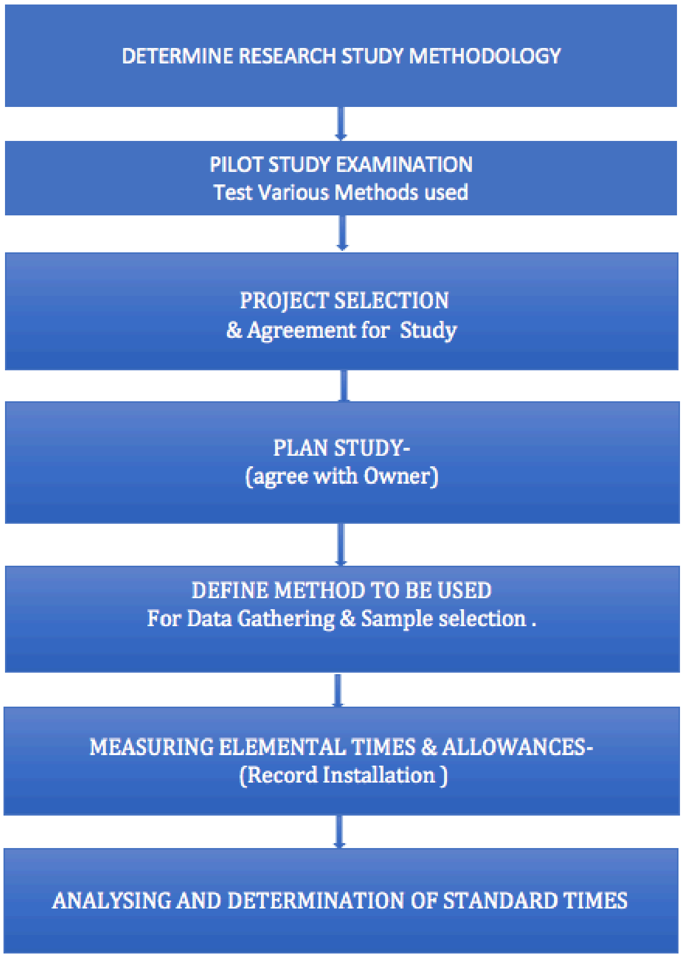

Figure 4.1 Research Procedure Framework

4.1 Philosophical position of the research

Research involves discovering new theories or testing existing ones by inductive creation or deductive testing (Runeson and Skitmore, 2006). The objective of scientific inquiry is to collect data, build theories to explain the data, and then test these theories against further data (Punch, 2005). A theory is a statement of a rule that generally consists of a set of interconnecting propositions that have the same form as laws but are more, as they make predictions to tell us why things occur, and can be empirically testable (Runeson et al., 2006; Singleton and Straits, 2010).

A theory's propositions are at a higher level of abstraction than specific facts or empirical data. Together they make sense of the facts and data, by description and explanation of the phenomenon studied, by deduction or induction reasoning (Punch, 2005). An explanatory theory provides a deeper and more accurate understanding of the phenomena by both describing and explaining its underlying causes (Punch, 2005; Schmenner et al., 1998). Therefore, explanatory evidence provides a higher value to the research propositions.

Adding to this, scientific enquiry is based on empiricism, and empirical research is the primary type of research adopted in science (Runeson et al., 2006). Empiricism is a way of knowing or understanding the world that relies directly or indirectly on what we experience through our senses, i.e. that can be observed or sensed under specified conditions (Singleton et al., 2010). The critical concept is observable information or direct experience, and the term used in research is data. Empirical research uses this data as a way of answering questions (Runeson et al., 2006). Empirical data is subdivided into two main types which are quantitative data, in the form of numbers or measurements, and qualitative data, which is not in numbers but generally in words (Punch, 2005).

Qualitative research uses the construction of categories and concepts in non-numerical data to develop patterns from which relationships are established. Whereas, quantitative research refers to a whole way of thinking using a deductive approach, which involves a collection of methods using data in a numerical form (Punch, 2005). Quantitative methods target representative populations that enable findings to be generalised for large populations. Qualitative methods use an inductive approach to formulate a new theory or to expand that theory. Quantitative methods use a deductive strategy to test and verify the existing theory by extrapolative means (Runeson et al., 2006; Singleton et al., 2010). These two types of data are fundamental to the research approach used.

The selected research topic suits a quantitative approach because the research focuses on measurable productivity and objective identification of factors influencing it. The data was collected and measure in numerical units and not descriptive units.

4.1.1 Methodological approach

Science is about theories, is explicitly a set of rules for how to formulate, test and verify theories and how they should be used (Runeson et al., 2006). In the case of a methodological approach, a theory's hierarchical inquiry paradigm defines its philosophical position, using frameworks of ontology, epistemology or methodology inquiry. It arrives at its philosophical position by a set of propositions, which describe and explain the phenomenon studied as well as the connection between methods and the underlying issues (Punch, 2005).

The formulation of a scientific theory is based on empirical research, which involves the creation of the research method, the collection of data, analysis of the theory and its hypothesis (Runeson et al., 2006). Generally, the quantitative paradigm uses the researched literature as a framework for the derived research question and propositions (Punch, 2005). The methodological implications from this chosen research topic and consequential propositions imply a quantitative, rather than a qualitative approach. The study was on measurable outcomes and of objective identification of factors influencing it (Punch, 2005). The data collected and measured were in numerical units, not descriptive units, using a methodology approach.

Important questions when planning research are "what is the role of theory in this study?" and "what substantial and original contribution to knowledge will this study make?" in terms of its contribution to substantive theory (Punch, 2005). The theories of interest were the production management theory of swift, even flow (Schmenner et al., 1998) and “transformation, flow and value” theory in construction (Koskela, 2000). The research approach was the verification and potential extension to these production management theories in the application of industrialised building systems, as outlined in chapter two.

As the research was a theory verification, that is “theory-first”, as opposed to a theory generation, it commenced with the theory. It then deduced hypotheses, or in this case propositions, from it and a study was designed to test those hypotheses (Punch, 2005). A pragmatic applied and professional approach was adopted in developing the research question and relevant propositions (Punch, 2005). Using a “top-down” deductive process, the research area was identified (industrialised building systems) and a comprehensive literature review was undertaken. A gap in theory was identified with a general question, in the form of a primary proposition, relating to productivity improvement.

A primary proposition and subsequent propositions were developed, working deductively by way of literature review, from general to finite issues, within that area and topic. This approach was contrary to the inductive, theory after, process: beginning with a specific question and working back to more general questions (Punch, 2005). The literature review established the theoretical and practical relevance of the research question and its propositions (Singleton et al., 2010).

4.1.2. Case Study Approach to gather quantitative data

There are four principle scientific research methodological strategies, which are experimental, survey, field study and available data research, i.e. archival analysis and history (Singleton et al., 2010). Each study tailors its basic approach to which methodology would provide a distinct advantage, compared to the others, for the research question (Yin, 2014). As CLT installation is on-site, in an outdoor environment, an experimental methodology was not suitable. At the time of undertaking the study, CLT projects were still uncommon in Australia. Consequently, there was insufficient existing quantitative data available for the archival and historical data research methodologies. As the survey strategy would not provide detailed empirical insight into CLT installation to address the question (Yin, 2014), the field study methodological strategy was adopted to gather quantitative data. The research field study provides has distinct advantages over the other methods. The field study gains first-hand knowledge of the naturally occurring situation. Field researchers endeavour to comprehend the world as their subjects, observe it and collect information, without unduly influencing its shape or content (Singleton et al., 2010). The first of the four strategies for adopting case studies is to follow theoretical propositions, which is the direction of this study (Yin, 2014) and to identify in meaning of their findings as they relate to existing theoretical frameworks (Singleton et al., 2010).

A standard method of the field study is by way of a case study (Singleton et al., 2010). Of note, the case study methodology promotes investigation of a current phenomenon that is positioned within real-world context rather than contrived for research purposes, such as an experiment (Flyvbjerg, 2006). Although there may be a misconception of bias, the case study has been found to contain no more significant researcher bias toward verification than other methods of inquiry. It includes a more considerable bias toward falsification of preconceived notions rather than a verification bias (Flyvbjerg, 2006). Case studies have been a standard research method in science, by enabling researchers to focus on a "case" and retain a holistic and real-world perspective, such as studying individual cycles, organisational and managerial processes (Yin, 2014).

A case study can be conducted by way of a single holistic case, single case embedded, holistic multi-cases or multi-case embedded study. It can be limited to quantitative evidence and a method for carrying out an evaluation (Yin, 2014). Three multi-storey apartment tower case buildings are chosen for this study. The three were located on a relatively large single project, where the same resources, i.e., management, labour and equipment, were common. Thus, allowing an internal comparison between the three tower findings. As the three buildings were different in height, floor area and design, the case study selection was limited to either a single case embedded study or holistic multiple case studies. The decision was determined by analyses as discussed later in this chapter and detailed in "Findings", chapter 5.

To commence the investigation, a method of collecting data had to be developed. A pilot study was determined as the most suitable approach to achieve this.

4.2 Pilot study.

A detailed pilot study process was undertaken to develop a suitably accurate, verifiable, replicable and reliable means to implement the above research methodology. The data collection method needed to address the following:

- how to measure the input units of labour, plant and equipment each cycle/day/week (i.e., the number of hours).
- how to measure the corresponding output produced each cycle/day/week, i.e. how many m^2 installed.
- the identification of site variables/factors that may cause variations in inputs or outputs.

The purpose of the pilot study was to trial different methods of data collection to arrive at the most reliable, verifiable and accurate collection approach. A variety of methods were tested in the field on a series of active building sites (pilot cases), as detailed in Table 4.1 below (detailed further in Appendix 1) using a time and motion study approach. Productivity input and output data were collected and correlated with building design documents provided by the contractor. The table's sequence of sites also reflects the progressive process of testing and improvement upon the methods used.

Table 4.1 Pilot study-sample sites

Project No. / Building type	Prefabricated assemblies measured	Method	Finding
1. Single 4-Storey Apartment building	Surrogate project (traditional construction)	Gather worker hours from the project manager's site diary and site records. Weekly inspection by the author to verify data and measure completed work area using material delivery dockets, design documentation to measure.	Inaccuracies and mistakes common when comparing on-site observations and design documents to site staff's records. Data collection by a third party found unreliable.
2. 2 x 2-storey townhouse.	Timber floor cassettes	Full-time researcher recording site activities, input hours and completed output work	Infeasible due cost and time of resources used. Also, the risk of human error.
3. 12x 2-storey townhouse complex.	Timber floor cassettes; pre-clad framed walls	Gathering data using time-lapse photography version 1 -Trialled on-site using camera semi-permanently installed to a high local structure.	The camera provides a reliable means of accurately capturing data within a defined work area—this method used building design documents to measure work areas and provide construction details.
4. 5 X 3-storey apartment buildings.	Timber floor cassettes.	Gathering data using time-lapse photography version 2 -Trialled on-site initially using site staff to set up and start camera for timber activity. Method changed for a researcher to set up and activate the camera.	As above but the unreliability of site staff to daily set up camera resulted initially, in a loss of capture, so an on-site researcher subsequently actioned the camera set up.
5. 1 x 2.5-storey large single dwelling.	CLT wall and floor panels, engineered beams	Gathering data using time-lapse photography version 3 - Trialled on panelised site using a camera in a fixed location with the pre-set program.	As project 3, but also included the ability to measure panel area in every crane lift, as the crew used installation sequence schedule, to provide a high granularity of detail in knowing how many m^2 placed in every crane cycle.
6. Single 3-storey apartment building.	Timber floor and roof cassettes	Gathering data using time-lapse photography version 4 -Trialled on-site using Webcam providing real-time on-site capture to researcher off-site	As above but Webcam provided the ability to change camera positioning, focus and timing efficiently to avoid capture loss.

In addition to the findings in Table 4.1, trials 3, 4, 5 and 6 focused progressively on positioning the camera in the most appropriate and practical location to provide the best possible perspective of the whole site area relative to the activities. The selected camera positioning and location was reliant on the availability of the contractor's resources, site facilities and surrounding structures. The selection of the type of camera and its set up had to consider the need for a waterproof housing, access for battery and memory chip replacement, avoiding rain on the lens and the effects of site plant vibration.

Semi-structured interviews were carried out as part of the trial to gather contextual information about variables impacting on productivity from the project team members[2]. A series of semi-open questions were trialled. These were tested for flow, understanding and quality of response in providing a template of questions for the case study. Where a question was identified that did not give a reasonable response, it was deleted, and others were rearranged for improved flow. The interviews enabled a collection of additional information for cross-referencing events observed from the video.

Overall pilot study findings and recommendations include:

1. Use of a time-lapse digital recording camera to accurately capture all panel installation activities.
2. To undertake an initial site meeting with the project management team to determine access, practical features about using a time-lapse camera and information transfer between the two parties.
3. Location of the camera: The camera needed to be in a precise observational location with full sight of the work area to capture all the productivity data information required. Important capture locations included delivery and unloading locations, the crane locations, crane to panel hook up spot, slewing[3] pathway, installation location and the crews' activities.

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[2] Ethical agreements between parties were obtained before interviews and any recording to capture personnel involved in labour activities by the camera (Appendix 2)

[3] In crane movement terms, slewing refers to the crane action to lift its load, suspend that load in mid-air, and then rotate it, via a boom rotating mechanism, to the destination location.

4. Camera installation: The camera needs to be semi-permanently[4] installed to reliably capture the necessary installation data. Temporary and daily camera installation was found unreliable and often resulted in mediocre viewing placement.
5. Time-lapse settings: The camera's frame to frame setting needs to be selected at less than 30 seconds/frame for accurate activity capture, i.e. to measure each crane cycle accurately.
6. Metadata[5] stills: The use of a time-lapse camera provides an advantage of digitally recording metadata of the actual recorded date and time measured in hours, minutes and seconds on each frame.
7. Verification of factors: The camera provided the ability to replay and observe activities at a later date. By repeatedly replaying the recordings, it enabled validation of the times per cycle, the breakdown work elements, productive and non-productive periods of work, etc.
8. Accuracy of the video recordings: During the study, the author recorded three sample days activities, which were later compared to video camera recording, collecting the same timber installation data. The camera's digital recording was found to be superior to that of the on-site observer.
9. Webcam: A webcam has the advantage of providing a technology to view in "real-time" to regularly observe and check the camera's recording and, if necessary, change the camera location and settings. Real-time access avoids collecting days of unusable video footage and consequential lost data collection by quickly facilitating requests for beneficial changes to the camera location and settings.

The above findings were used in the chosen methodology, which focused on the above-mentioned time-lapse approach.

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[4] The camera is fixed in one selected location for the duration of recording the selected activities with the ability to move later as construction proceeds to gain an improved view.

[5] Metadata is defined as the data providing information about one or more aspects of the data; it is used to summarise basic information about data, which can make tracking specific data easier, such as time and date of creation.

4.3 Case study approach.

As briefly discussed, the case study approach has several advantages, which were instrumental in its selection. A case study can "close-in" in real-life situations and test views directly in relation to phenomena as they unfold in practice (Flyvbjerg, 2006). Rather than set in a contrived reality as in an experiment, the case study investigates current phenomena positioned within a real-world context (Flyvbjerg, 2006). By way of proximity to reality, more discoveries, stemming from the type of intense observation, have been made possible utilising case studies than from statistics applied to large groups (Flyvbjerg, 2006). One can generalise based on a single case study, and the case study may be central to scientific development via generalisation as a supplement or alternative to other methods (Flyvbjerg, 2006).

4.4 Data collection methodology

General issues, regarding the case study, are how to select the appropriate setting, how to gain access, what to observe and record, when and how to record one's observations, and handling, organising and analysing the details (Singleton et al., 2010)? Many of these topics were trialled in the pilot study. Within this, the understanding that believability is significantly increased by replicability and rigour was paramount, as all are essential aids to certainty (Runeson et al., 2006).

Sampling Method

As stated previously, a case study methodology was used for several reasons, including:

- the ability to capture observed unbiased data from real-world activity (Flyvbjerg, 2006),
- enabling identification of influencing factors attributed to on-site CLT process as they unfold in practice,
- allowing the study of individual cycles, organisational and managerial processes (Yin, 2014),
- empowering the researchers to comprehend the world as their subject, observe it and collect information, without unduly influencing its shape or content (Singleton et al., 2010).

Yin (2014) found that the case study has been a standard research method in science. It enabled researchers to focus on a “case” and retain a holistic and real-world perspective, such as studying individual cycles, organisational and managerial processes. He offered several strategies and based on this, and the specific propositions, a reliable descriptive strategy with direct observation was adopted in this research. The approach was supported by design documents and semi-structured interviews and time series analysis.

4.4.1 Overview of the project study

The project ultimately selected for this study’s data gathering was located in a suburb of south-west Sydney, New South Wales, Australia. The project consisted of three multi-storey apartment buildings constructed in mass timber, primarily in CLT, on a shared reinforced concrete podium slab as shown on the plan of the development in Figure 4.2 below. The podium slab, which was cast over an underground, reinforced concrete, shared car park, enclosed the majority of the site. For simplicity, in this study the three tower buildings are referred as Tower A, the first to be constructed, followed sequentially by Tower B and Tower C. Tower A consisted of six stories of mass timber structure, Tower B contained seven stories, and Tower C had an eight-storey timber structure. The first level of each timber structure commenced at the ground floor podium level.

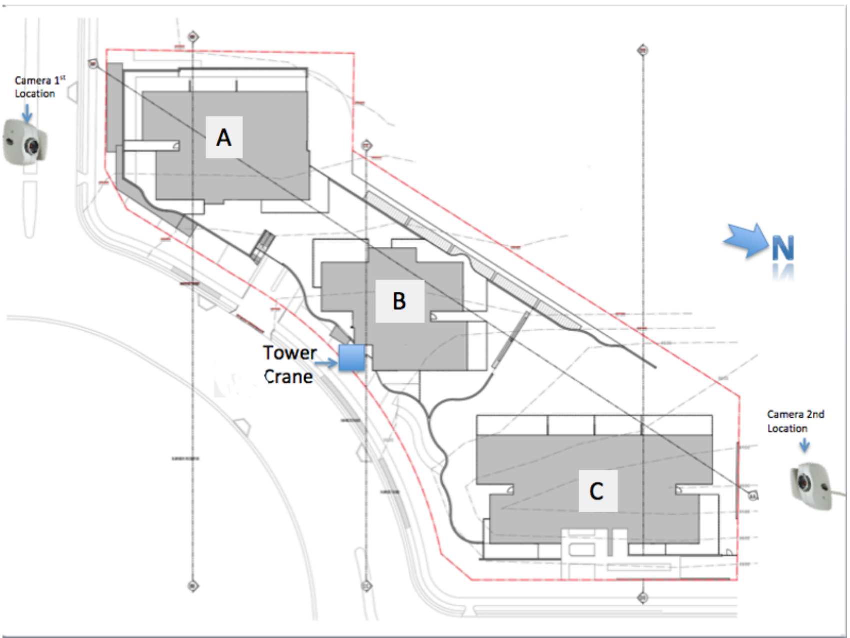

Figure 4.2 Site plan of case study project with camera locations

Each of the three buildings was designed with different floor areas and wall layouts. Each floor of Tower A comprised of 382 m^2 in area, Tower B's floor level area was 310 $m^{2,}$ and Tower C had the largest footprint of 515 m^2. These differences in dimensions, wall and floor layouts and heights resulted in a different selection of panel sizes to accommodate each tower's individual design. In 2016, a total of 24 weeks (140 days) of mass timber activities were captured live on video. Across the three towers 19,020 m^2 of CLT was installed from which 11,341 m2 of installed CLT data was captured. This data comprised of 1,994 value-added[6] crane cycles for 1,631 panels, across 16 different floor levels from the three buildings.

As illustrated in Figure 4.2 above, the site layout was bounded on one longitudinal and two lateral sides by a road. An occupied block of land and a car park extended over the remaining longitudinal side. Although roads on three sides appear advantageous for deliveries, the three buildings were designed adjacent to each other, which resulted in limited circulation and access area between them and an inherent restriction of site storage space.

A static hammerhead tower crane, Terex Model 331-16 tonne maximum capacity, was erected between Tower B and the footpath adjacent to the road, as indicated in Figure 4.2. This location provided the tower crane with a central position to the three buildings with its 55-metre reach. Even though the crane could reach all of Towers A and B, it was unable to reach Tower C's furthest corner by 12 metres and a mobile crane was consequently engaged as a supplementary resource.

4.4.2 Data collection

The pilot study's recommendations were implemented, as appropriate, for capture and measurement of data from the three case buildings. One of the first studies to adopt a time-lapse video recorder to capture construction productivity data was Drewin (1982). In his book *Construction Productivity* (1982), he outlined "time and motion" data collection and analysis methodology using time-lapse video photography. Summarised in Figure 4.3. below, is a framework for the research

[6] Refer "Key definitions" p xii

data collection methodology broadly based on Drewin's film analysis methodology. For clarity, the framework's headings attributed to Drewin's method are identified in capital letters.

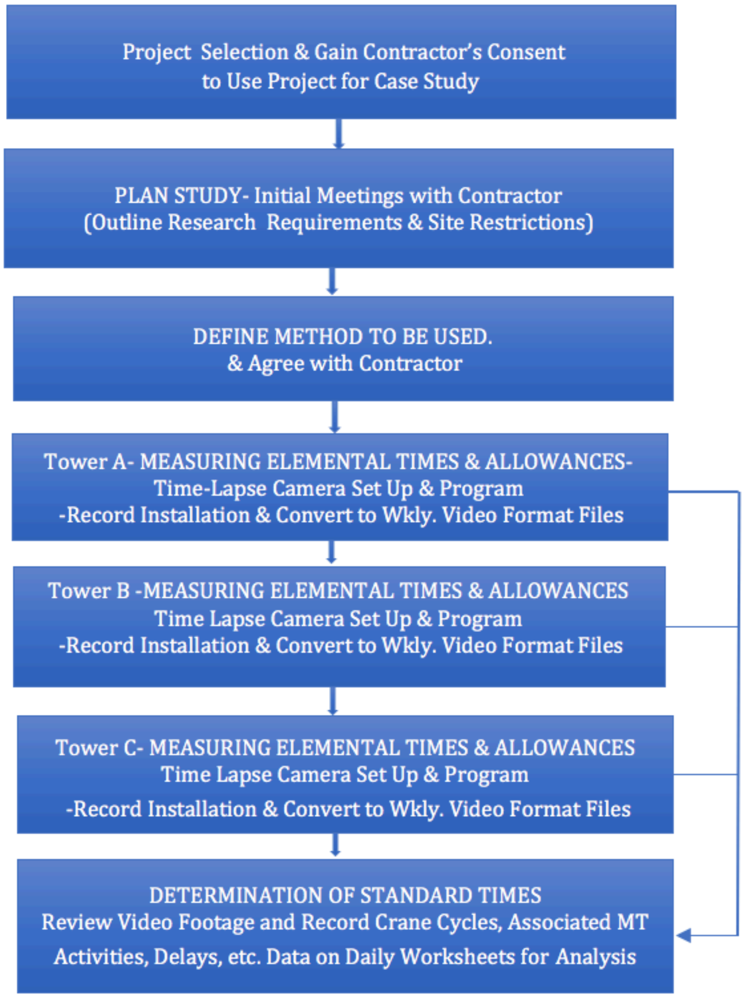

Figure 4.3 Case study data collection methodology framework

Although the data collection methodology was focused on determining the productivity of panel installation, the method of capture utilised photography of site activities with personnel present. Therefore, an ethical information sheet (sample in Appendix 2) including the ethics approval number was issued to each party, prior to recording. A verbal agreement was also obtained to record by camera personnel involved in labour activities.

An initial site meeting for data collection

Once the project was selected, and the contractor consented to the research study, the next step, as per the methodology framework, Figure 4.3, was to arrange an initial meeting. The meeting was organised at a convenient stage in the project's construction schedule prior to the mass timber installation. The purpose of the meeting was to outline the intricacies of the on-site data collection process for the research study with the project's site team and their directors. This meeting also enabled the project's supervisory team to understand the purpose of the study, as well as the study's aims and requirements. The beneficial outcome of the meeting was that both parties arrived at a mutually agreed data collection methodology for its implementation.

At this initial meeting, the project management personnel advised that they had pre-planned to install the mass timber implementing "just in time", lean construction, principles. Using this approach, the contractor had prearranged and scheduled for truck delivery to site of only those CLT panels and glulam elements that were required for each day's installation and to coincide with their installation time. The contractor had planned for mass timber delivery trucks to be pre-loaded with the panels in sequence. This process was planned to facilitate the panels being unloaded from the truck in the required order and be installed directly into position on site. In so doing, reduce the boundary between panel delivery and panel installation, resulting in minimising double handling and non-added value activities.

Time-lapse video camera set up

The next step in the methodology framework, Figure 4.3, was under the heading "measuring elemental times and allowances". The first subsection was to ascertain the set-up, locations and the programming of the video camera. For this part the pilot study recommendations were generally implemented.

Webcam. The time-lapse camera was connected, via a secured internet, to function as a webcam. This provided the off-site author with an observation of the site activities in real-time. Access was continuously available, via Webcam, except for a few infrequent circumstances where service was unavailable, due to connection difficulties. During these episodes, observation of the mass timber activities was unable to be recorded.

Programming. The time-lapse camera was programmed to be activated each day, over a standard period, to endeavour to capture all the mass timber site activities. Regular site hours on the project were from 7 am to 3.30 pm over a six-day working week. The camera was programmed to commence recording at approximately 6 am with cessation at 5 pm, to ensure that it captured the majority of any mass timber activity outside standard site hours. Although the project was open six days a week, the timber installation crew predominantly worked a half-day or a maximum of a four-hour shift on Saturdays. Consequently, the mass timber installation generally consisted of a five and a half-day working week.

Frame-to-frame time: The video capture method used the pilot study findings for detailed guidance and applied Drewin's video approach (Drewin, 1982) as a broad framework. The time-lapse camera was set to record photographs at 15 seconds intervals being somewhat faster than the pilot study's recommendation, to obtain greater granularity. The time-lapse camera used, in this study, captured actual time within each picture, which was digitally recorded and displayed the exact time in seconds. This provided an accurate start and finish-recorded time of the on-site mass timber activities. The activities captured included installation and associated tasks, such as delivery, storage and double handling as well as other trade activities (non-mass timber works). The video recordings were compiled in twenty-four weekly video files, each being 2.5–5 Gb in size. This method of data collection, by a time-lapse digital video camera, provided detailed and accurate quantitative data for the study.

Location selection of time-lapse camera

The time-lapse camera was installed in selected semi-permanent locations, as illustrated in Figure 4.2 above, to capture the majority of the mass timber installation process. The specific areas for the capture of these activities are discussed below.

Tower A

During the construction of Tower A, the time-lapse camera was in a fixed location in "1st Location" as illustrated in Figure 4.2. This location was on the roof of an adjacent apartment building facing Tower A, approximately two-floor levels above Tower A's roof level, on the opposite side of the road. It was a strategic observational location, which endeavoured to provide a clear view to observe all the mass timber installation activities to Tower A and the majority of the whole site area. The roof panels and remaining few wall and beam panels were captured from the second camera location. In total, 90.67% was captured from the total tower's installed CLT.

Tower B

Prior to the conclusion of the mass timber installation to Tower A, the camera was repositioned to the diagonally opposite rear corner of the site to capture the commencement of mass timber activities of both Towers B and C. The decision to relocate the camera was because the newly constructed Tower A's structure blocked the camera's view to the area for Tower B's mass timber activities, which commenced before Tower A's completion.

As there were no tall structures in close vicinity to this second location, the camera was installed on the roof of the only structure in the area, which was the site office building, as indicated in Figure 4.2. The location was also adjacent to the rear of the proposed Tower C's structure. Alternative options were neither feasible nor practical. For instance, a specific tall camera pole or the camera mounted on the crane would have both moved and incurred camera vibration during recording.

Tower B's camera location was relatively a similar distance away to that for A. However, at a low level, the camera's view was relatively horizontal for the lower floors and at an angle looking up to the higher ones, as opposed to looking down in the case for Tower A. This limitation, partially impacted on the detailed level of observation for Tower B's upper floor levels, six and seven. At these higher floor levels, especially the far side of the floors, previously installed wall panels, scaffold or shade-cloth occasionally obscured the view of CLT installation. Even with the above limitation, 76.11% of the total installed CLT was captured for the tower.

Tower C

For Tower C, the camera location was again at 2nd location (Figure 4.2), as for Tower B. The camera was closer to Tower C, approximately 10 metres to its rear wall, than was experienced for both Towers B and A. This provided advantages compared to the other towers facilitating more installation and panel detail. However, the camera was at a low level, which eliminated the ability to observe the higher floor levels' activities once the CLT installation reached its fourth level (Level 3). Even so, over 2,840 m^2 of CLT installation was captured, which represents over 32% of total CLT installed for Tower C.

4.4.3 Preparation for analysis Part 1

The next steps in the data collection process were to record the installation, convert the recordings to weekly format files, review the collected video footage and prepare the data for analysis. Before this process could commence, the criteria had to be finalised for the measurement of productivity and associated activities. Adrian and Boyle's work provided reasoning and guidance in the method to be adopted for on-site productivity measurement, as earlier discussed, that need to identify the production cycle, a leading input resource and the production unit (Adrian et al., 1976).

The production cycle measurement

The installation of the prefabricated timber elements was observed, in the pilot study, to be a relatively repetitive process, which confirmed the assumption in chapter 2. This aligned with Adrian and Boyer's earlier discussed reasoning that highly visual and repetitive and predictable processes need to be identified for the measurement of productivity and crane cycle and crane time suited these criteria (Adrian et al., 1976; Forsythe et al., 2019b). The point of separation in this repetitive process was the actual time of each prefabricated panel's crane cycle. To provide a more precise understanding, each crane cycle was found to comprise of five sub-activities as illustrated in Figure 4.4 below.[7]

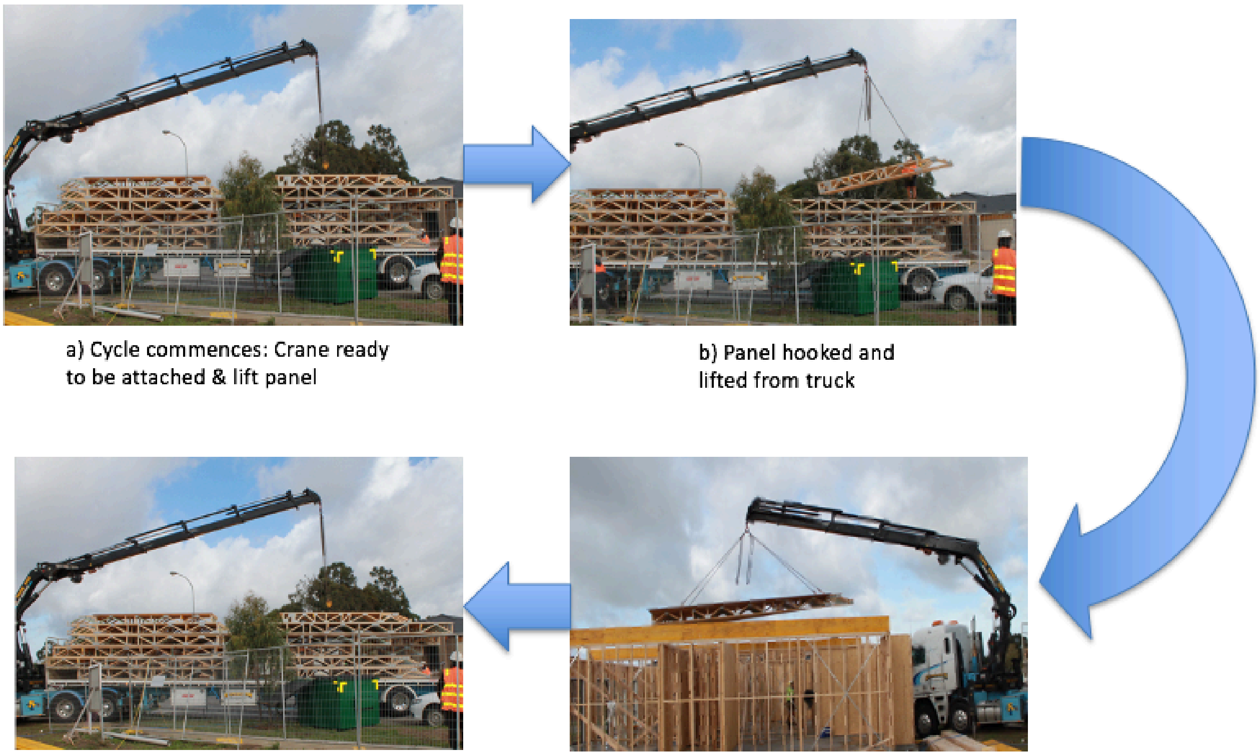

Figure 4.4 Crane cycle sub-activities

These sub-activities, in sequence, are as follows:

(a) the crane jib over and ready to be attached (hooked) to the panel,

(b) the panel hooked and lifted from the truck or pack,

(c) the crane slewed (jib moved) to the installation location,

(d) the panel installed in its designed position,

(e) the crane chains were then disconnected, and the crane jib slewed back to the original position ready for the next lift.

[7] Photos were taken during the pilot study of a timber cassette panel installation

Figure 4.5 Installation of wall panel

Figure 4.5 above captures the moment in the middle of a crane cycle when the crane crew was installing and back propping a wall panel still attach the crane's lifting chains. The crane cycle for a panel was defined as the time recorded (hour: minutes: seconds) from the moment the crane's jib was over the selected panel, ready to lift (photo "a" Figure 4.4) until the return of the crane's jib to the original location (truck or storage area), ready to lift next panel (photo "e" Figure 4.4).

The defined crane cycle needed to provide a standardised input unit measurement, irrespective of the type of crane is used, for example, tower crane or mobile. It was, therefore, decided to exclude any mobile crane set up and dismantle time. By containing the input resource measurement within defined boundaries, the data and findings of timber-prefabricated elements were aligned to the other currently known studies on the same subject (Forsythe et al., 2016; Forsythe et al., 2019a; Kasbar, 2017). These productivity inputs can then be applied for comparing productivity rates with other projects, thus allowing for logically objective comparison and benchmarking purposes (Forsythe et al., 2019b). The crane cycle time was the repetitive process separator and nominated as the production cycle and therefore, the main focus for the input data collection process.

Leading resource

The panel installation and associated activities were dependent on the availability of the crane and its work cycles. The crane was also the costliest resource on-site and the crane cycle time represented a measurement of a crucial input resource for the mass timber installation and related activities. As the cycle by the crane was the input unit of focus, the crane became a leading input resource for attention in the installation process.

Using cranage time reverses the usual productivity focus on labour and ignores capital inputs (Forsythe et al., 2019b). Labour, however, is considered to be a necessary input resource, assisting the crane in the CLT installation process. So that proposition one could be tested, the labour time (hours) for both the installation crew and the crane team was observed and recorded. Crane team labour hours included the crane driver as well as dogmen (riggers). Both the crane and the installation crews were measured in:

- Crew-hours, defined as the hours the whole crew worked per day on the installation of CLT or other defined activity,
- Labour hours, defined as crew hours x number of workers in the crew per day on the installation of CLT or other defined activity.

Both the crane and labour times for the installation process of each mass timber element were recorded, to determine the leading input resource. Labour hours for project management, site management, scaffolding, safety activities, and the like, were not included, in line with other studies (Forsythe et al., 2016; Forsythe et al., 2019a). These activities were considered necessary for the whole project and not for the individual mass timber installation activity.

Output: production unit measurement

The project's walls, floors, beams and columns panels were generally manufactured in cross-laminated timber (CLT). Therefore, it was decided to measure the surface element, length by width, of each panel (m^2). This provided a mechanism for comparison of each panel type measured. Each CLT panel was delivered to site with an identification number (ID), which was stamped, glued or stapled on it, by the manufacturer before being shipped from the factory, as in Figure 4.6 below. The ID tag assisted the installation crew in identifying the required panel at the workface.

Figure 4.6 Panel ID labels attached to CLT

The designated location for each panel was identified by the ID number on its respective floor plan within the CLT shop drawings. It was noted, however, that each of the three towers used the same identification number sequences. This replication may have contributed to occasional confusion and delay in the storage area in identifying the correct panel for installation.

To enable determination of each production unit's cycle, and therefore calculate each cycle's productivity, each panel and its ID was identified from the video recording by way of the supplemental architectural documentation provided by the contractor. Additional documentation provided, included delivery and installation schedules, panel floor and wall installation layouts, shop drawings and details of individual prefabricated elements with their particular shape, dimension and ID#. This facilitated cross checking and verification of the correct panel ID during the installation process.

The wall and floor panel data consisted of a wide range of sizes with wall panels ranging in area from 2.50 to 28.44 m^2 and floor panels ranging from 3.65 to 13.75 m^2. Applying Adrian & Boyer's reasoning (1976) that the chosen production unit should not be too broad or too small, the range in size needed to be rationalised. As the surface area of the panel was a significant component of the resultant productivity, these large ranges were subdivided into three functional sized groups for objective baseline analysis. Therefore, a standard division of panel size was chosen that would be practical and logical for application within the construction industry. The two area size division points chosen were 5 and 10 m^2 as these provided an approximately similar number of panels in each of the three groups, for both wall and floor panels. As the division points were defined as whole number values (5 and 10), it was anticipated that this would significantly improve acceptance and adoption by the construction industry. The selected sizes were: Small, less than 5 m^2; Medium (Intermediate) 5 m^2 to 9.99 m^2; and Large ≥10 m^2 as illustrated in **Table** 4.2 below.

Table 4.2 Panel size categories

Panel size category	Minimum size (m^2)	Maximum size (m^2)
Large	10.00	28.44
Medium	5.00	9.99
Small	0.3	4.99

Coincidently, all beam and column panels were within the small size, which corresponded to the small-sized wall and floor panels. Both floor and wall panel types consisted of all three size categories of panels: large, medium and small. The alternative option to the above chosen divisional point selection was to divide the total of each panel type into three sample sets, each with an exactly equal number of samples, for each category (i.e., Large, Medium and Small). This alternative option, by dividing each sample set into three equal sizes, would have provided abstract divisional values, e.g., 4.8738 m^2, each different for each category set of the four individual panel types and each tower. Simplistically, each panel category's area range would differ across each panel type and each of the buildings. The difference in each panel category size ranges would have resulted in the inability to make comparisons between the panel categories, towers or future studies. Consequently, the nominated 5 m^2 and 10 m^2 panel size criteria in Table 4.2 were used for this study.

Productivity capture

A panel's crane cycle was a clear demarcation of the time taken for the panel's installation process. Its resultant productivity could be measured using this cycle time (input units of labour or crane) and the output area of the individual installed panel. The capture process used to calculate the productivity for each panel installed is illustrated in Figure 4.7.

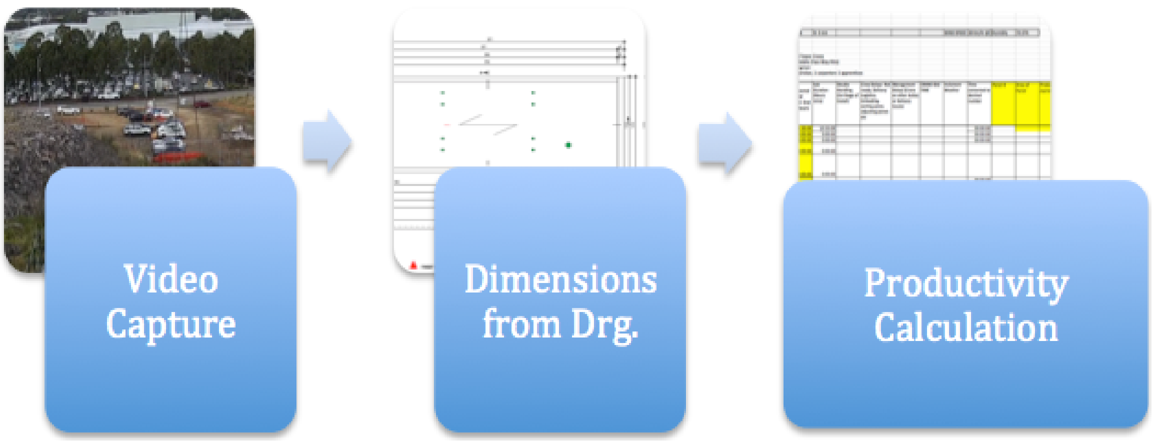

Figure 4.7 Flow chart of capture process for productivity

The crane cycles were captured and recorded via video camera in hours, minutes and seconds on a daily worksheet for the installation of each panel or element, as shown in Figure 4.9, section 4.4.4.a below. The output was the installation of the corresponding floor, wall, beam or column identified by video, measured in m^2, obtained from the contractor's supplied documentation and, also, recorded on the daily worksheet. These two records provided the relevant data to calculate the productivity (m^2/hr) value by dividing "Output" by "Input" in m^2/hr as per

Equation (1) from Chapter 2. Examples of the calculation are illustrated in Table 4.3 below.

Table 4.3 Example of productivity calculations for daily worksheets

Panel ID	Input: Time in hours	Output: Area of panel (m^2)	Productivity outcome (m^2/hour)
F300	0.48	19.99	19.99/0.48 = 41.65
F301	0.05	13.35	13.35/0.05 = 267

Recording of associated mass timber activities

Associated activities such as non-value-add activity data collected, including any delays observed in mass timber installation, were recorded against the respective crane cycle on the daily worksheet. These non-value-add activities included items such as delivery delays, delays due to trucks loaded by the factory with unscheduled panels or not loaded in sequence to facilitate just in time installation, double handling and mobile crane set up and dismantling time. Notations were also made on the daily worksheets of any additional unusual events or anomalies with relevant duration or crane cycle times.

Where there was more than one crane on-site, the identity and type of crane involved in the CLT activities was notated against the individual crane cycle on the daily worksheet. When a crane was interrupted from its CLT activities, for example by other trades, these crane cycle times were also recorded. Although the crane cycles for other trades and non-value-add tasks were logged, they were excluded from the calculation of the mass timber productivity as these cycles were attributed to management cause and effect. The purpose of the research study was to determine an unaffected on-site productivity baseline for the various panel categories.

Summary of required collected data

Outlined in Table 4.4 below are the detailed observed data collected from the daily video film recordings, which was used for analysis.

Table 4.4 Summary of required collected data

Item	Captured Information	Description
1	Mass timber installation cycle times	Including one and 2-stage crane cycles
2	Crane cycle times	Productive value-add cycles separated from non-productive usage (non-value-add)
3	Delivery logistic crane cycles	Unloading, storage, double handling, etc.
4	Crew sizes	Labour numbers for each cycle
5	Labour hours for CLT install activities/day	Install crew and crane crew
6	Output (Area (m^2) of panel per cycle and total m^2/per day)	Identification of each installed panel and surface area for each cycle/lift)
7	Wastage (non-productivity)	Input resources
8	Delays and non-productive work	Caused by other trades' activities, management decisions, changes, delivery logistics, safety, maintenance etc.
9	Miscellaneous crane usage/ movements	Not associated with the installation of mass timber elements (e.g. crane cycles for other trades' materials or equipment)
10	Identification of building storey level	For each set of productivity data
11	Weather conditions and inclement weather	°C, wind, rain, humidity and effects on installation process (where relevant or possible)
12	Crane type	Either tower crane or mobile crane

4.4.4 Capture, document and prepare data for analysis

The 24 calendar weeks of mass timber activities data recorded by the time-lapse camera was converted to a video format for review. The review process of each day's video file was similar to the pilot studies by using Drewin's film analysis methodology (Drewin, 1982). Before documenting each day's collected data, the full day's video recording was viewed at fast forward speed. This initial observation enabled the identification of its sequence of events, including any abnormalities and variable factors that could affect the overall daily outcome.

Observation and capture

Once there was an understanding of the overall day's events, from fast forward viewing, each day's video was replayed at normal or a slower time using the VLC

2.2.6 media player. The VLC 2.26 player could vary the playback speed between a range of “faster” to “very slow”, as can be observed in the drop-down box and “arrowed” in the screenshot, in Figure 4.8 below, of the VLC video recording.

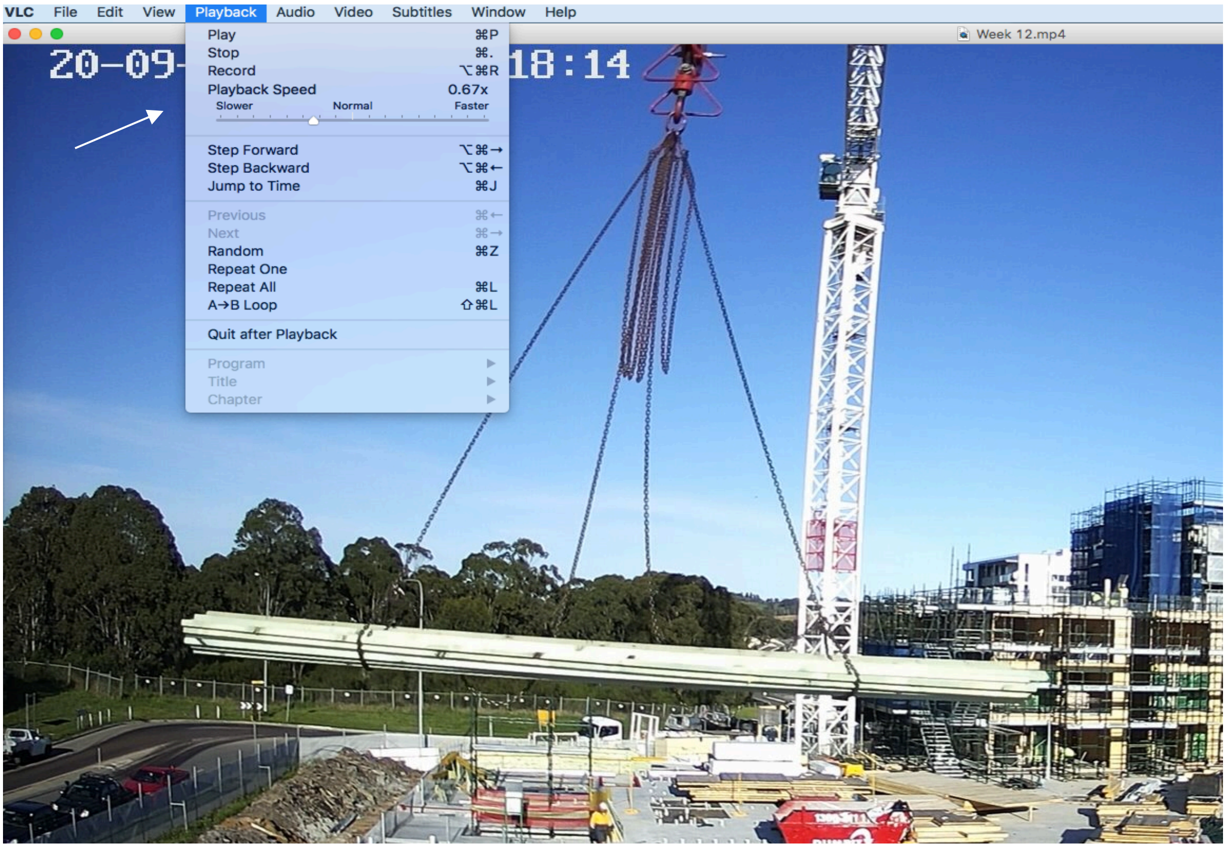

Figure 4.8 Screenshot of VLC playback speed adjustment bar

This process allowed a replay of any unclear, unusual event, action or activity, at a slower replay time, to gain clarity of the occurrences by obtaining details that were not apparent at normal speed. Generally, each crane cycle was replayed several times to enable the cycle times to be accurately logged to the second (unit of time) and to identify and verify the actual installed panel.

The observed activities, for each day, were broken down and documented on individually identified and dated daily worksheets. The crane cycle times, panel IDs and corresponding areas were recorded on these worksheets, and an example extract is shown in Figure 4.9 below. Each crane cycle comprised of five sub-activities, which were discussed earlier in this section, and illustrated in Figure 4.4.

The worksheets were similar to those trialled in the pilot study but were revised to suit the research study.

DATE:-	21/10/16													
WEEK #	16.00													
DAY #	92.00													
WEATHER		RAIN Y/N	N- 0 mm					WIND SPEED	28 Km/Hr @ 1	Humidity	73-27%			
Project: NSW														
TOWER #	C													
FLOOR	GF/Lv 1													
CRANE 1 (T)	Hammer Head Fixed Tower Crane													
CRANE 2-(M)	55 Tonne Liebherr Mobile (Two Way Hire)													
LOADING CREW SIZE	1 crane driver + 2 Dogman													
INSTALLATION CREW SIZI	2.5	0.5 supervisor, 1 carpenters 1 apprentices												
	Start Time (Hours: mins)	Panel manouvered into final position- End Time (Hours: mins)	Sub Duration (Hours: mins)	Double Handling (1st Stage of Install)	Crew Delays- Not ready, Delivery Logistics, Unloading, sorting panel, adjusting panels etc	Management Delays (Crane on other duties or Delivery issues)	CRANE IDLE TIME	Inclement Weather	Time converted to decimal number	Panel #	Area of Panel	Productivity /panel	CRANE TYPE (TOWER = T, MOBILE= M)	Notes
Video Capture	5:57:00	16:30:09	10:33:09						00:00:00					
Truck Arrives/leaves	0:00:00	0:00:00	0:00:00						00:00:00					
Truck Arrives/leaves	0:00:00	0:00:00	0:00:00						00:00:00					
Mobile Crane Set Up Ready	0:00:00	0:00:00	0:00:00											
Total site prep prior to crane cycles Preparation Activities incl. Set up	0:00:00	0:00:00	0:00:00											Crane commence moving
Tower Crane Moving before CLT work commences	5:57:00	5:57:00				0:00:00			00:00:00					
CLT INSTALL CREW ON SITE/ DECK	5:57:00	14:29:29							8:32:29	8.54				
Crane cycles measured:														
1	5:57:00	6:11:15	0:14:15						0.24	369W	20.74	87.33	M	Pick up Wall Panel from Side of GF/road and install (obscurs half of building of Lv 1)
2	6:11:15	6:31:32	0:20:17						0.34	361W	21.58	63.84	M	Pick up Wall Panel from Side of GF/road and install
3	6:31:32	6:48:03	0:16:31						0.28	Wall Panel 3	17.57	63.83	M	Pick up Wall Panel from Side of GF/road and install? (View obscured by Crane Job)

Figure 4.9 Extract from case study daily worksheet

Each crane cycle was generally, logged with the two critical time elements, as noted in Figure 4.9, which were:

- Commencement time: when the crane was ready to hook and lift the panel (first photograph (a) in Figure 4.4 and Photo 4.1).
- Completion time: when the crane's jib had returned to the starting point, ready to lift the next panel or to commence the next task or activity after installation (last photograph (e) in Figure 4.4 above).
- Additional times were recorded at positions of "b" (panel hooked and lifted), and "c" (slewed to installation location) in earlier Figure 4.4, where required.

One and two-stage crane cycles

Although a "just in time" approach was planned, the production unit's installation process was at times performed in two crane cycle stages. A single crane lift cycle was when the panel was lifted from the site storage location (or delivery truck) and installed directly in the one lift. This is illustrated in the right-hand illustration in Figure 4.10 below.

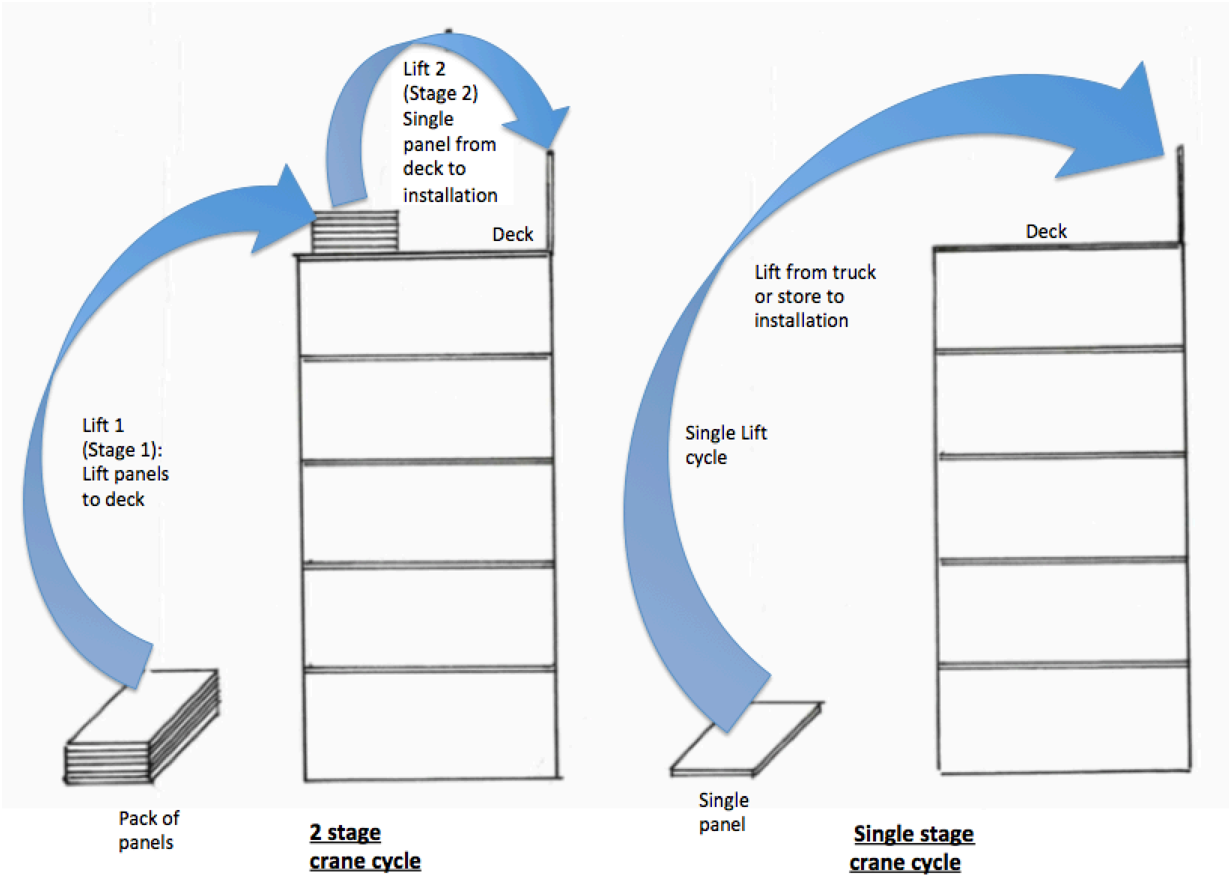

Figure 4.10 Single-stage and 2-stage crane cycle

The left-hand portion of Figure 4.10 illustrates the two crane lifts in a two-stage cycle. In the majority of cases, this comprised of a pack of panels, which was first hoisted from the ground floor store, or truck, to be temporarily stored on the installation deck (Stage 1). In other cases, this first lift comprised of only one selected panel lifted to and stored on the installation deck. To complete the two-stage cycle, a second crane lift (Stage 2) was required to hoist the required single panel from the pack, or the deck, to the designated location and installed.

Table 4.5 Example single and two-stage crane cycle calculation

Panel ID	Stage 1 crane time	Stage 2 crane time	Total installation (crane cycle) time for panel (T)
A-1 (single lift)	-	a	T=a
A-2 (2-stage with a pack of 6 panels)	b	c	T=b/6+c
A-3 (2-stage with single panel)	d	e	T=d+e

In the two-stage crane cycle process, both stages 1 and 2 crane lift times were measured and combined to arrive at a complete installation (cycle) time. This process ensured that both the single-stage and two-stage crane cycle installation processes were comparable and is illustrated in Table 4.5 above.

As an example, a pack of panels, "A-2" Table 4.5, are first lifted to the installation deck (Stage 1). From that pack, an individual panel is selected and installed by a second crane lift (Stage 2). To determine the time allocated to the respective panel for Stage 1, the time for the whole pack (b) is divided by the number of panels in the pack, in this case, six (b/6). The sum of the resultant number (b/6) and Stage 2 installation crane time (c) determines the total installation cycle time (T). The outcome provides the two-stage installation with an equivalent and comparable overall cycle time that of a single-stage installation.

A sample worksheet illustrating the method used for the combination of Stages 1 and 2, where panels were installed in two stages is shown in Table 4.6 below. The Stage 1 time displayed in the worksheet is that calculated for the first lift of an individual panel in a two-stage cycle. Its second stage of the two-stage process or where a panel was installed in one lift, it was logged in the "Stage 2" column.

Table 4.6 Example crane cycle stage 1 and 2 combination worksheet.

St. 2 | St. 1 | Total Time (Hr: Min: Sec) | Total Time (Hrs.)

TOWER B	LEVEL 1								
		FLOORS							
LOCATION TOWER/ FLR	DATE	CRANE STG 2 CYCLE TIME (h:m:sec)	AVE CRANE STG 1 CYCLE TIME (h:m:sec)	TOTAL CRANE CYCLE TIME	CRANE CYCLE TIME (hrs)	PANEL #	PANEL TYPE	AREA	PRODUCTIVITY (M2/HR
B/LV 1	3-Sep	0:11:46	0:00:00	0:11:46	0.1961	130	F (GF)	9.16	46.708
B/LV 1	3-Sep	0:09:46	0:00:00	0:09:46	0.1628	132	F (GF)	9.16	56.2730
B/LV 1	3-Sep	0:11:00	0:00:00	0:11:00	0.1833	133	F (GF)	9.16	49.9636
B/LV 1	3-Sep	0:06:01	0:00:00	0:06:01	0.1003	134	F (GF)	9.16	91.3463
B/LV 1	3-Sep	0:07:15	0:00:00	0:07:15	0.1208	135	F (GF)	8.26	68.3586
B/LV 1	3-Sep	0:08:01	0:02:54	0:10:55	0.1819	100	F (Deck)	4.68	25.7221
B/LV 1	3-Sep	0:04:45	0:02:54	0:07:39	0.1275	101	F (Deck)	4.68	36.7059
B/LV 1	3-Sep	0:03:45	0:02:54	0:06:39	0.1108	102	F (Deck)	4.68	42.2256
B/LV 1	3-Sep	0:04:01	0:02:54	0:06:55	0.1153	103	F (Deck)	4.68	40.5976
B/LV 1	3-Sep	0:03:15	0:02:54	0:06:09	0.1025	104	F (Deck)	4.68	45.6585
B/LV 1	3-Sep	0:04:00	0:02:54	0:06:54	0.1150	105	F (Deck)	4.29	37.3043
B/LV 1	3-Sep	0:03:30	0:02:54	0:06:24	0.1067	118	F (Deck)	4.51	42.2813
B/LV 1	3-Sep	0:02:45	0:02:54	0:05:39	0.0942	119	F (Deck)	4.51	47.8938
B/LV 1	6-Sep	0:06:30	0:00:00	0:06:30	0.1083	112	F (GF)	9.25	85.3846
B/LV 1	6-Sep	0:04:15	0:00:00	0:04:15	0.0708	113	F (GF)	9.25	130.5882

Recording observations

In addition to logging the hours worked by the crane and the installation and crane crews, other variables that may have affected the input and output of productivity were also notated on the daily worksheets. These variable items included items such as:

a. non-value-add crane waiting or idle time,
b. environment (i.e., inclement weather of wind and rain, temperature, humidity obtained from the Australian Bureau of Meteorology at a location within 2 km of the site),
c. abnormal stoppages,
d. the floor level of installation,
e. crane type used,
f. crane servicing other trades and obstructions.

Any delays observed in sub-activities of the crane cycle, such as double movements or waiting time were also documented, with notations made alongside each relevant panel cycle.

Where cycle times were identified, either during video viewing or analysis, to be significantly long or short in time, the possible assignable causes[8] of the outlier were examined. The video recording of the selected cycle was repeatedly replayed to identify the causation and factor(s) that contributed to abnormal time. Any identified outliers were highlighted and with the reason(s) observed noted, on the panel cycle and productivity summary worksheet. A worksheet example of this is illustrated in Table 4.7 below.

Table 4.7 Example of outlier identification on the summary worksheet

TOWER C	LEVEL 1					
		FLOORS				
LOCATION TOWER/ FLR	DATE	CRANE CYCLE TIME (h:m:sec)	CRANE CYCLE TIME (hrs)	PANEL #	PANEL TYPE	AREA
B/LV 1	27-Sep	0:11:27	0.1908	218	F (GF)*1	13.76
B/LV 1	27-Sep	0:04:31	0.0753	219	F (GF)	13.76
B/LV 1	27-Sep	0:07:01	0.1169	223	F (GF)	12.66
B/LV 1	27-Sep	0:11:45	0.1958	237	F (GF)*2	9.25
B/LV 1	27-Sep	0:04:30	0.0750	238	F (GF)	9.25
B/LV 1	28-Sep	0:06:31	0.1086	216	F (GF)	9.31
B/LV 1	30-Sep	0:12:01	0.2003	248	F (Deck)*8	4.17
B/LV 1	30-Sep	0:02:00	0.0333	247	F (Deck)	4.53
B/LV 1	30-Sep	0:04:00	0.0667	244	F (Deck)	4.53
B/LV 1	30-Sep	0:02:30	0.0417	243	F (Deck)	4.53
B/LV 1	30-Sep	0:14:16	0.2378	249	F (Deck)*3	6.95
B/LV 1	30-Sep	0:03:00	0.0500	206	F (Deck)	9.18
B/LV 1	30-Sep	0:04:15	0.0708	207	F (Deck)	9.18
B/LV 1	18-Oct	0:04:01	0.0669	254	F (Deck)	15.66
B/LV 1	21-Oct	0:21:16	0.3544	211?	F (GF)*4	8.45
B/LV 1	21-Oct	0:15:22	0.2561	253?	F (GF)*4	12.79
B/LV 1	8-Nov	0:06:45	0.1125	233	F (Deck)	4.53
B/LV 1	8-Nov	0:03:01	0.0503	234	F (Deck)	4.53
B/LV 1	8-Nov	0:03:30	0.0583	230	F (Deck)	4.53
B/LV 1	8-Nov	0:09:31	0.1586	229	F (Deck)*5	9.06
B/LV 1	8-Nov	0:05:15	0.0875	205	F (Deck)	12.66
B/LV 1	8-Nov	0:04:45	0.0792	201	F (Deck)	13.76
B/LV 1	9-Nov	0:22:01	0.3669	252?	F (Deck)*6	15.66
B/LV 1	14-Nov	0:11:30	0.1917	236	F (GF)*7	6.88
	AVE TIME	0:06:35	0.1096		AVE SIZE	9.37
F (GF)*4- View on slab obscured by Crane Jib and other installed Wall panels	F (GF)*1 Only 2 CLT crew and took time setting out this first Floor panel to be set out point	F (GF)*2- crew took 7+ mins to select and sling panel before lifting		F (Deck)*3 Panel picked up but view obscured by jib and had trouble installing not 100% sure if installed	F (Deck)*5 installed out of view of camera installation hidden behide structure so could not identify if there was an issue or moving others	F (GF)*6 View obscured by structure but partly view panel pick up from Lvl 1 and installed but with a number of attempts and adjustments (Slings not released)

The data of crane cycle times, productivity outputs, panel size, floor level, etc. determined from worksheets, as above, were entered into the relevant factor categories in SPSS Statistics analytical program for analysis.

[8] Assignable cause is defined pp 41-42, section 2.4.2.b, Chapter 2.

Crane cycle classifications

The categorical terminology concerning crane time is summarised and placed into context to provide clarity for the next chapters, in Table 4.8 below. Each crane cycle category consists of several activities, outlined in inclusions (i)–(iv); the summation of these equates to the overall categorical terminology.

For clarification, category "Crane Idle (Waiting) time" in Table 4.8 below, occurred when it could not be ascertained which trade was responsible for the delay. This meant that it could not be attributed to either CLT or another trade activity. As an example of this, the crane was working for the concreting trade, was idle and then later commenced with the CLT trade. It was concluded that "Crane Idle" time was a management issue.

Table 4.8 Summary of crane cycle classification

Categorical Crane Cycle Terminology (=i+ii+iii+iv)	**Inclusion (i)**	**Inclusion (ii)**	**Inclusion (iii)**	**Inclusion (iv)**
1. CLT Value Added (VA) <u>**(Net CLT Crane time)**</u>	**Single Lift Crane Cycle**: Lift panel from GF store or delivery truck and Install	**Stage 1 Crane Cycle**: Lift panel or pack from GF storage area or delivery truck to installation deck.	**Stage 2 Crane Cycle:** Lift panel from the deck and install.	
2. (CLT) Non-Value Added crane cycles	**Double handling:** includes identifying, rearranging and moving panels in the storage area but excludes Stage 1 crane cycle	**Unloading:** Unloading panels from delivery trucks	**Rework.** Alterations to panels or removal of panels installed incorrectly	
3. Non-CLT (Not-CLT Related) Non-Value-Added crane cycles	**Crane working for or servicing other trades**	**Crane Idle (Waiting) time**	**Stoppage due to others:** Safety issues, another crane or equipment working adjacent to CLT work area, etc.	**Stoppage due to Crane Maintenance**
4. Other Disruptions to work or observation	**Meal Breaks**	**Inclement weather (wind and rain)**	**Loss of video recording**	**Obstruction of view:** Inability to record an activity

Categorical Crane Cycle Terminology (=i+ii+iii+iv)	**Inclusion (i)**	**Inclusion (ii)**	**Inclusion (iii)**	**Inclusion (iv)**
5. Gross CLT Crane Time	**1. (CLT) Value Added**	**2. (CLT) Non-Value Added**		
6. Gross Crane Time	**1. (CLT) Value Added**	**2. (CLT) Non-Value Added**	**3. Non-CLT Non-Value-Added**	

The subcategory "Obstruction of view" occurred where there was an inability to record any activity. This was caused by several issues including previously installed panels obstructing observation (to capture the installation activities), the crane jib blocking the view, sun shining into the camera lens and shade cloth attached to the scaffold.

4.5 "High" and "intermediate" level analysis.

An initial "high-level" CLT productivity (HLP), metre^2/hour, review at a project level was undertaken for each tower (T) building, (T_X HLP). This was achieved by dividing the total area of panels of the selected tower (T_X A) by the entire site workdays during its installation and multiplied by 7.5 hours (per day) as per the Equation 2 below.

$$\text{Equation (2): } T_X \text{ HLP} = (T_X\, A/(\frac{CD-SD}{7})5.5*7.5). \qquad (2)$$

Where:

CD = completion date

SD = start date

Workdays were estimated to be at seven and half hours per day for a five-and half-day week. Each tower's site workdays were calculated from the commencement of the CLT installation to the date of completion of its timber structure. The duration period included non-value-add activities, delays, days of nil CLT activities, inclement weather and non-workdays, for example, shutdowns and union holidays.

From the information collected on the daily worksheets, an intermediate level analysis for each tower was undertaken of the individual workday's input and output values. Each contained a basic calculation of the average daily productivity (m^2/hr) per panel type. The analysis included a comparison of both productivity and cycle times for the various panel types across the three towers. The intermediate level analysis quantified each tower's overall gross CLT crane time (the summation of both Categories 1 and 2 inclusions from Table 4.8) and net CLT crane time (the summation of Category 1's inclusions, Table 4.8). In addition, it provided a breakdown, displayed in a pie-chart format, of non-value-add activities (Category 3), stoppages, waiting time and inclement weather.

4.6 Activity level analyses methodology

For an activity level analyses, the data captured on the daily worksheets was compiled into separate sample sets of panel types, i.e., floors, walls, beams and columns, for each tower. The process of compilation sample sets is addressed below.

4.6.1 Determination of case study design

It initially had to be established whether the total project's recorded data for the three buildings could be analysed as a single-case or a multi-case study design, that is, separated into three tower building case studies. To resolve this decision, the crane cycle times of the CLT panels were tested for homogeneity of variance using One-way ANOVA in SPSS. One-way ANOVA is a statistical method commonly used to check whether there are differences among at least three groups of data with the same independent variable (University of California and Statistical Consulting Group, 2019). Therefore, ANOVA was an appropriate analyses application as the data sets consisted of three categorical, independent groups, namely Towers A, B and C. Each had the same independent variables, i.e. panel types and same dependent variables crane cycles and productivity.

ANOVA tested the combined CLT crane cycle time data across the three towers. As the sample set number (n) in each building was different, the One-way ANOVA test incorporated Brown–Forsythe and Welch robust test of equality of means tests, with Scheffe post hoc multiple comparison test, to observe the mean differences.

If the ANOVA test found that the data was not significantly different across the three Towers, p-value>0.05, it would prove the Null hypothesis that the CLT crane cycle (installation) time data was heterogeneous. Therefore, the data could be combined and analysed as one case study. If the ANOVA findings indicated that there was a statistically significant difference between each tower's set of data ($p<0.05$), then the three buildings would need to be tested separately, that is analysed as a multi-case study. By using discussed ANOVA analysis approach, it was resolved that the three buildings needed to be treated as a multi-case study. The analyses findings are outlined in chapter 6.

4.6.2 Determination of baseline data

4.6.2.1. Normal distribution analyses

Once the decision was made whether or not to divide the data into three case studies, the panel data was separated into the four-panel type sample sets (floor, wall, beams and column). Each sample set was required to be normally distributed before detailed analyses could be undertaken to avoid type 1 errors[9] and obtain accurate results.

Reliability and repeatability are essential factors in the determination of the prefabricated panel cycle time and productivity (Thomas, H. R. et al., 1986; Yi et al., 2014). The importance of normal distribution and statistical control was raised by Shewhart (1931) and later Deming (1982), both of whom pioneered Total Quality Control (TQC) in the 1950s. They introduced TQC initially into Japan's post World War 2 industry with the focus of achieving a controlled manufacturing process, which would reliably and repeatedly produce quality products conforming to set specifications. Deming later assisted Western Electric in the United States in the

[9] Type 1 errors occur when one rejects the "null" hypothesis even though it is true. This could occur if the sample set was not a true representation of the "population" as the case with a skewed or non-normal distributed sample set.

introduction of the controlled manufacturing process and TQC into their plants to improve their manufacturing processes. Armand Feigenbaum, one of the originators of TQC, outlined the philosophy of TQC in his book (Feigenbaum, 1983). Feigenbaum outlined the importance of Shewhart's control charts to test processes for normal distribution and statistical control.

Nelson (1984, 1985) used his work experience at Nashua Corp and the detection rules from Western Electric's Statistical Quality Control Handbook 1956 to compile and propose a set of rules which are now known as Nelson Rules. He applied these rules to Shewhart control charts to determine if sample sets from a factory's productivity data were "out of control" or in non-random condition. The Nelson rules proposed nine rules for Total Quality Control of a factory's manufacturing process. These rules determined whether the manufacturing equipment and its operation was in statistical control or out of control and could be improved. However, compliance to all of Nelson's nine rules (1984, 1985) was found time-consuming with conflicting results. Nelson's first rule is: a single point outside three sigma limits is interpreted as a signal of a substantial process shift. Nelson's rule 2 is: a run beyond the two sigma of nine in a row is interpreted as a shift in underlying process. Wheeler and Stauffer (2017) argued that by adopting just rules 1 and 2 together for detection (for control charts to determine the uniform distribution and whether data was in or out of control), it would provide the same normality finding.

In this study, the installation time was a crucial factor in productivity measurement. The crane cycle time for each panel type was determined as the dependent variable to test to establish normal distribution using the above process. Normality analysis of each panel type sample set was by Shewhart's control charts with Wheeler's application of Nelson's rules 1 and 4 (Nelson, 1984, 1985; Shewhart, 1931; Wheeler et al., 2017).

The original data sample sets, for each of the four-panel types, were plotted in a scatterplot. Superimposing the mean and plus and minus one, two and three standard deviation lines produced a statistical control chart to test each of the four or 12 sample sets (dependent on single or multi-case design). During this process, outliers were removed if found to fall outside the control limits of +/- three standard deviations (Gulezian et al., 2003a, b). Causation of any identified outlier was determined, where possible, by replaying a video recording of the relevant cycle.

Once the first set of outliers were removed, using the remaining data, new mean and standard deviations were calculated, and a new control chart was plotted for each sample set. This process was repeated until no data fell outside of the control limits. With each new control chart, box plots, quartile–quartile and histograms were also produced to help identify any outliers and whether the subsequent data provided a normally distributed Bell chart. The box plots compared the mean and median values of the sample sets. Where these two values converged, it provided confidence the data set had a general characteristic of symmetrical distribution, and the process was normally distributed (Guarnieri, 2015).

Once a sample set appeared close to normality, a normality analysis was carried out by testing the data sets using Shapiro Wilk W-test in SPSS, a formal normality test. If the p-value > 0.05, then this verified that the sample set had a 95% confidence of being normally distributed (Guarnieri, 2015) p226. The Shapiro Wilk W-test also provided the skewness and kurtosis z values to ascertain if the sample set values were within the acceptable range of -1.96 and +1.96.

Where the Shapiro Wilk W-test findings determined that the sample set was not normally distributed then the control chart process was repeated. Outliers were identified and removed until Shapiro Wilk's test confirmed a normal distribution and contained data not affected by assignable causation. The Shapiro Wilk W-tests were carried out on each panel type sample set, across the towers, until the tests confirmed the obtainment of normally distributed final sample sets. This delivered reliability and repeatability attributes for the research baseline results. It determined that the sample sets would provide robust ANOVA tests to assess significance (Field, 2017).

To clearly identify all outliers and analyse for the similarity of causation, each original panel type data sample set was plotted in individual control charts. The charts were superimposed with the value of the final set's normally distributed mean value and last standard deviation values. The Upper and Lower Control lines were plus/minus 2 x standard deviations, (not 3 x standard deviations) were used to provide a more unambiguous indication of the original data set's range from the final control lines from the last trimmed[10] sample set's values.

4.6.2.2 Panel type similarity analysis

The next step was to determine whether there was a significant difference between the four-panel type sample sets. For this analysis, the four-panel types, i.e. floor, wall, beam and column, were tested for both crane cycle times and productivity (m^2/hr). If the results found that there was a statistically significant difference across the four-panel types, then each type would be tested separately to determine their baseline rates across the buildings or for each building for a multi-case design. If there was not a significant difference, then the four-panel type sample sets could be combined for one baseline analysis for the single case study or in the case if multi-case for each building, i.e., three sample sets.

For the ANOVA analysis, the independent variable should consist of three or more categorical groups. T-tests are commonly used for two independent groups (Field, 2017). Analysis by One-way ANOVA was selected for the collected data sets, as there were four types of CLT panel to review.

Tests of homogeneity of variance were carried out across the towers and where the sample sizes (n) were not the same Welch and Brown–Forsythe robust tests and Scheffe post hoc (Field, 2017) were applied. This test determined whether all panel types combined provided similar a) crane cycles times and b) productivity (m^2/hr) results. For the first analysis, the panel type was the independent factor with the crane cycle time as the dependent actor. The second ANOVA test was carried out with the productivity outcome as the dependent factor.

[10] "trimmed" term used to denote where assignable causations have been removed from sample set

4.6.2.3 Panel size category: similarity analyses

If a statistically significant difference was found between the four-panels (floor, wall, beam and column), in the preceding tests above, then the four types were separated and divided into the three size categories (small, medium and large) as illustrated in the first step of figure 4.11 below. As beams and columns were predominately less than five m^2 there would be eight categories (large floor and wall, medium floor and wall, small floor, wall, beam and column). The eight-panel categories would then be tested for homogeneity of variance using ANOVA.

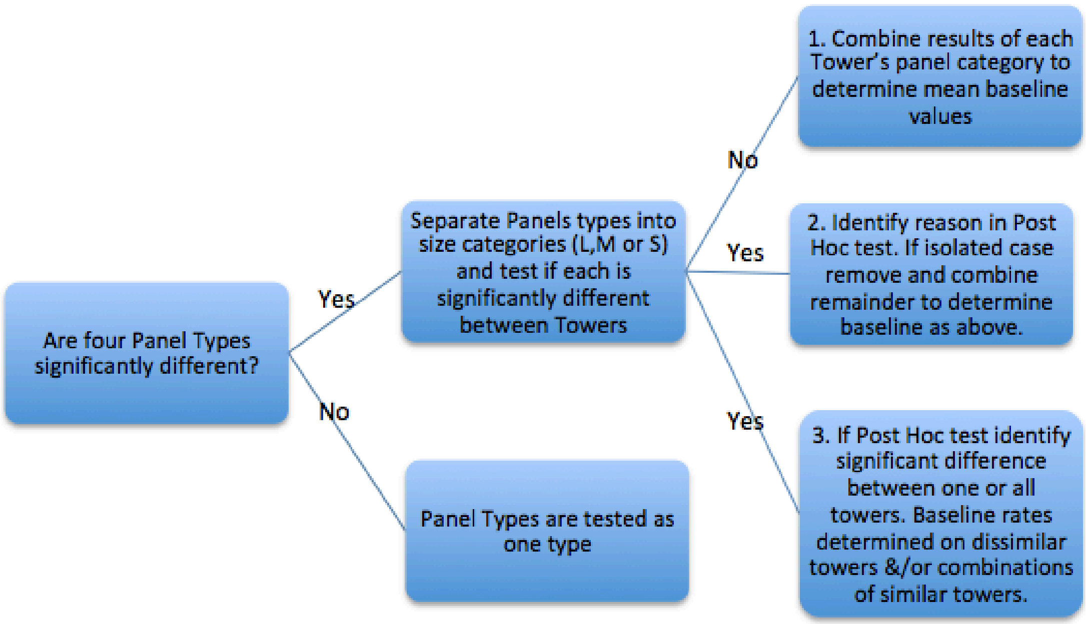

Figure 4.11 Flow chart of analyses steps for baseline findings

The floor panels and wall panels were each tested, first, to determine if there was a significant difference in findings across the three categories. Secondly, each panel size category was tested to determine any significant difference across the panel types. If at the onset of analyses, a multi-case study was determined, then the sample sets of each panel category within each tower would be tested, as above, for similarity. Should the panel categories be found to be significantly different within the panel type, then the sample sets of similar panel categories would be tested for similarity across the towers, using ANOVA. Should the findings determine that there was no significant difference for panel categories across the three buildings, then the sample sets of the predetermined metrics would be used for baseline analyses (#1 third step Figure 4.11).

Where there was a significant difference found for a particular panel category, post hoc tests were used to identify the reason for the finding. If that significant difference were an isolated case, then that anomaly would be removed. Should a significant difference in panel category findings be determined across the three towers, then the baseline analysis would be carried out on each tower separately (#3 third step Figure 4.11). If the tests determined that only one tower was significantly different, then the panel category sample sets from the two similar towers would be combined, and the significantly different tower would be analyses separately. Should the tests for each panel category find there was no significant difference in results across the towers, this would provide robustness in the production of CLT baseline productivity data rates for the study.

4.6.2.4 Determination of baseline data

Guzelian and Sumelian's baseline model (Gulezian et al., 2003a, b) provided a statistical approach to develop baseline productivity rates (m^2/hr) and crane cycle time data for the various CLT panel categories. The method uses a statistical application of control charts in which the means of statistically controlled selected time-period sample sets are analysed. The independent factors for this study's baseline method were the individual CLT panel types (floor, wall, beam and column*)*, size categories (Table 4.2) and, if a multi-case design or found to be significantly different, the towers. The dependent factors were productivity rates and crane cycle time.

Guzelian and Sumelian's metric for their method was the mean of the relevant sample sets calculated for repeated samples taken at corresponding determined "time-periods". The selected sample set's unit of time (X-axis) for this study was the specific days (time-period) of CLT installation (Hatfield and Vezza, 2016; Hayavadana, 2012). A week's duration was not chosen as a unit of time as it was deemed excessive, as in the majority of cases, the floor level installation was less than a week. The metric, therefore, used for this baseline methodology was the individual panel category's mean daily productivity (m²/hr.) and mean daily crane cycle time (hrs.) (Y-axis).

Gulezian and Sumelian's basic control chart is replicated below, in Figure 4.12, to illustrate the metric values: a) the mean productivity rates or crane cycle times) plotted on the vertical Y axis, b) the time periods (days) plotted on the horizontal X-axis, and c) the control lines (Gulezian et al., 2003a).

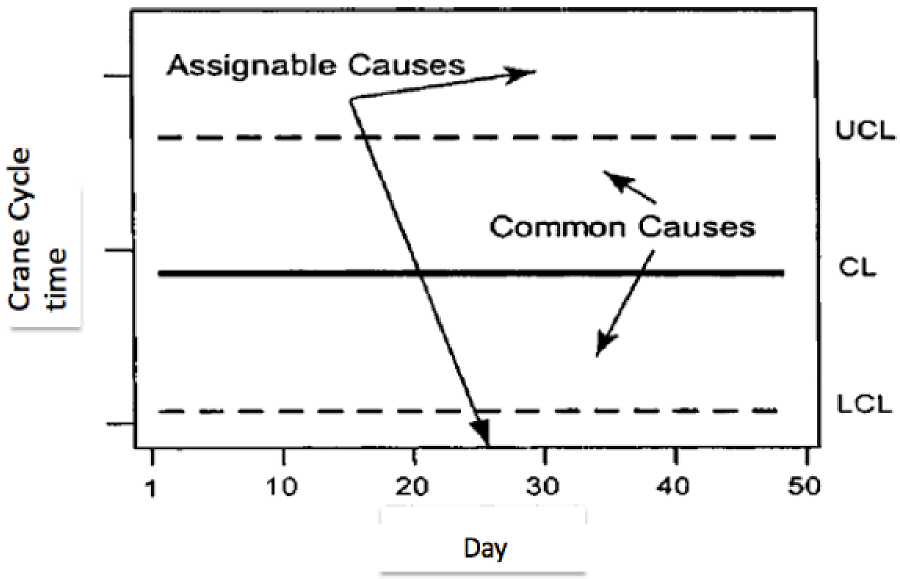

Figure 4.12 Basic control chart structure (adapted from Gulezian & Sumelian, 2003

The three horizontal control lines, in the above control chart, corresponding to:

- Centre Line (CL), which is the average of the mean values,
- Upper Control Line (UCL),
- Lower Control Line (LCL).

The control limits were plotted as plus and minus three standard deviations from the average mean, and the centre line (CL), which represented the average mean. As reiterated previously, values that fell within the control limits were deemed to be in statistical control and within a normal range of variation, with common causes contributing to the differences. Where any metric fell outside the control limits, they were deemed caused by assignable variations (outliers, i.e., ones that were not attributable to chance) as illustrated in Figure 4.12 above, and consequently removed. This was because they were unlikely to exist in a statistically controlled process or under normal operating conditions. When an outlier was identified and removed, the mean of the remaining sample sets and standard deviations were recalculated with the remaining data. The centre CL of each panel category's final control chart determined the overall average of the daily mean, i.e. baseline, for that category's productivity or cycle time sample set. The resulting baseline findings should reflect a contractor's typical operating performance.

Propositions 1-3 were tested, as appropriate, using one-way of homogeneity of variance by One-way, Two-way ANOVA or t-tests, Pearson coefficient, correlation tests, means plots and post hoc tests to analyse the data. Multivariate regression analysis tested Proposition 4 to determine the effect of inclement weather on CLT productivity. To determine Proposition 5, an algorithm for forecasting productivity was analysed by multivariate regression (Jang et al., 2011; Yi et al., 2014) using the analysis findings from the previous propositions.

4.6.3 Analysis of qualitative data

The data measured was qualitatively supported by information gathered during semi-structured interviews with the project manager and the contractor's directors after the mass timber installation had been completed (see Appendix 5 questionnaire). The interview with the project manager was recorded and a transcript produced. It provided an opportunity to discuss and clarify specific observations noted during the video replays, for example, delays/stoppages, weather interruptions with possible effects on productivity, craneage details, unusual unproductive times (crane or/and installation crew) and panel delivery logistics. The interviews also provided a forum to discuss the contractor's project experience with this new industrialised system. It was also an opportunity to gain their views of the activities and suggestions for improvement in mass timber prefabricated systems.

4.7 Summary

This chapter discussed the pilot study and the different methods used, its recommendations and those implemented in the research study. A methodology framework was proposed in Figure 4.3 p. 98, which formed an outline of the method used to conduct the research study. An overview of the selected project, the initial site meeting was discussed as well as the installation and set-up of the recording camera. It explained how the case study followed the stages for analysis in the framework, the data collection process and the analysis approach adopted for the research propositions. The following chapter discusses the analysis testing, the resultant outcomes and findings.

Chapter 5 Results and findings (Part 1): High and intermediate analysis.

This chapter presents quantitative results and findings in three levels of detail. A high-level analysis, at the project level, provides a global perspective, considering the total rate of panel installation for each building. At an intermediate level, it reviews floor-by-floor productivity by encapsulating gross CLT time and identifies observed non-value-added time. A micro-level analysis, focused at an activity level, analyses single panel crane cycle times and productivity rates to test the nominated propositions.

5.1 High Level review

The video recordings of the mass timber activities were obtained in the 24 weeks commencing 4 July 2016 until 16 December 2016. The data was extracted from the video files and recorded using the methodology as outlined in Chapter 4.

Table 5.1, below, provides a "high level" project-level summary of the total number of panels designated for the three towers (A, B and C). It includes the total quantity and percentages of installed and observed panels for each tower, together with their areas at each floor level. For the three buildings, a total of 19,020 m^2 of CLT was installed compared to 11,341 m^2 observed and captured on video over 140 workdays. The data captured comprised of 3,289 crane cycles for 1,631 CLT panels, across 16 different floor levels from the three buildings. Of those captured, 634 panels were on Tower A, 632 on Tower B and 365 CLT panels were from Tower C as outlined in Table 5.1 below.

The total CLT area captured was 90.67% for Tower A, 76.11% for Tower B and 32.14% for Tower C (80.12% of first three floor levels). In the case of Tower C, the panel areas not captured, above the floor panels at Level 3, are notated in red.

Table 5.1 Panel quantity and area measured per tower

Tower	Floor	Actual no. of panels	Recorded no. of panels	Total panel area installed (m^2)	Total panel area recorded (m^2)
TOWER A	GF	103	52	496.22	439.71
	LV 1	146	103	892.95	869.9
	LV 2	144	105	896.08	858.78
	LV 3	143	102	895.03	805.05
	LV 4	143	102	899.4	836.22
	LV 5	237	167	987.8	794.96
	ROOF	7	3	44.93	30.68
A	**TOTAL**	**923**	**634**	**5112.41**	**4635.3**
TOWER A % CAPTURE			**Panels= 68.69%**		**Area= 90.67%**
TOWER B	GF	111	78	433.13	377.34
	LV 1	149	107	748.35	663.68
	LV 2	150	100	754.2	679.2
	LV 3	149	63	748.43	472.84
	LV 4	149	98	752.23	628.31
	LV 5	147	69	743.77	481.71
	LV 6	213	117	832.38	545.48
	ROOF	4	0	44.27	0
B	**TOTAL**	**1072**	**632**	**5056.76**	**3848.56**
TOWER B % CAPTURE			**Panels= 58.96%**		**- Area=76.11%**
TOWER C	GF	148	77	657.26	550.98
	LV 1	206	160	1185.27	1075.49
	LV 2	206	96	1194.22	930.84
	LV 3 (Floor only)	55	32	513.75	287.41
	LV 3 (Vertical panels)	143	0	686.95	0
	LV 4	193	0	1199.99	0
	LV 5	191	0	1187.99	0
	LV 6	241	0	1216.79	0
	LV 7	229	0	1009	0
C	**TOTAL (Levels 4-7 in red not observed)**	**1,612**	**365**	**8,851.22**	**2844.72**
TOWER C % CAPTURE			**Panels= 22.26%**		**Area= 32.14%**

The initial high-level review, summarised in Table 5.2 below, indicates that the floor-to-floor cycle of Towers A and B were similar, at an averaged 7.73 workdays. Tower C was significantly different, having an average floor cycle of 21.17 workdays over the first three floors. The extended time of floor cycle for Tower C was partly due to the inefficient sequence of work, discussed in Section 5.2 below.

Table 5.2 High-level: Towers A, B and C

	Recorded	**Tower A**	**Tower B**	**Tower C**
1.	Commencement date	4/6/16	29/8/16	20/09/16
2.	Completion date	31/08/16	4/11/16	9/12/16
3.	"Input" – Gross Crane Time – Total No. Workdays per timber structure (Based on 5.5 days/wk.)	46	54.5	63.5
4.	Total No. Floor Levels Recorded	6	7	3
5.	Total m^2 panels installed on captured Floor Levels (delivered)	5,112.41	5,056.76	3,580.19
6.	Total No. panels on captured Floor Levels (delivered)	923	1072	615
7.	Ave. Days/ Floor	7.67	7.79	21.17
8.	Gross CLT Productivity (m^2/workday) (Equation 1 Productivity= Output (item 5)/ Input (item 3)	111.14	92.78	56.38
9.	Gross CLT Productivity (m^2/hr.) (Equation 1: Productivity = Output (item 5)/ Input (item 3)/7.5 hrs	14.82	12.37	7.52
10.	Ave. No. Value-Added CLT panel cycles/day (Divide Item 6 by item 3)	20.07	19.60	11.94
11	Average Crew Size	5	5	2.5

Note: Above based on 7.5hr./ day & 5.5 days/ week

At a (high level) project-level perspective, applying Equation (2) (page 118), the overall average gross CLT productivity rates (m^2/hr.), item 9 Table 5.2, were less productive than those observed in the pilot study. The average productivity for Towers A, B and C were 14.8, 12.4 and 7.5 m^2/hr respectively appeared low compared to the average found in the pilot study's CLT project of 43.66 m^2/(crane) hour for untrimmed mean floor, wall and beam[11] panel sample sets. This anomaly raised a point of interest for further investigation, which is discussed later in this chapter.

5.2 Sequence of work

There is a need to clarify the difference in terms of productivity rates, floor cycle times and types of cranes employed across the tower buildings, as indicated in Table 5.2. These aspects are discussed below, from an installation sequence, together with a program schedule of floor level activities for comparison (Figure 5.1).

Tower A

Tower A's mass timber structure was installed solely with the use of a single static Terex CTT 331-16 hammer-head tower crane. The CLT installation for the first two floor levels adopted a “just in time” approach, installing panels directly from the delivery truck. This approach ceased, following completion of the second level, as at this point the delivery logistics sequencing faltered. It did not comply to, nor deliver panels in the planned and agreed order. Instead, the deliveries arrived out of sequence and consequently were stored on-site. Panels were later selected from the store and hoisted to the appropriate installation floor deck location. The out of sequence timber delivery continued throughout the remaining towers.

Tower B

The majority of Tower B's structure was installed with the use of the single Terex tower crane, similar to Tower A. However, a Lebhierr 55 tonne mobile crane was hired and used for the early commencement of the first two floors of Tower B's structure. Tower B commenced prior to Tower A's CLT installation completion. The requirement for an extra crane for Tower B was, in part, due to the tower crane fully occupied, installing the remaining CLT on Tower A and its following trades, such as external cladding, roofing and internal finishes.

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[11] beam area calculated on estimated average height 300mm.

Tower C

Similar to Tower B, a mobile crane was initially employed to progress the project program schedule by commencing the first three lower floor levels of Tower C before the completion of Tower B. The mobile crane was required because the tower crane resource was occupied with Tower B's CLT structure, as well as servicing other following trades on both Towers A and B.

Although the mobile crane was engaged to progress the installation, video footage observation showed that the mobile crane could only reach approximately 50% of Tower C's floor area (the northern half). Consequently, this delayed Tower C's structure until the tower crane resource had completed the CLT on Tower B. Once CLT on Tower B was complete, the tower crane was available to complete the remaining portion of Tower C's lower three floors. The tower crane then completed the remaining CLT structure. For the floors captured the crew size averaged only 2.5 workers as opposed to an average of 5 workers for the other two towers.

5.2.1 The program schedule of towers' CLT installation

The points discussed above, are illustrated in the program schedule of the actual sequence of installation in Figure 5.1 below.

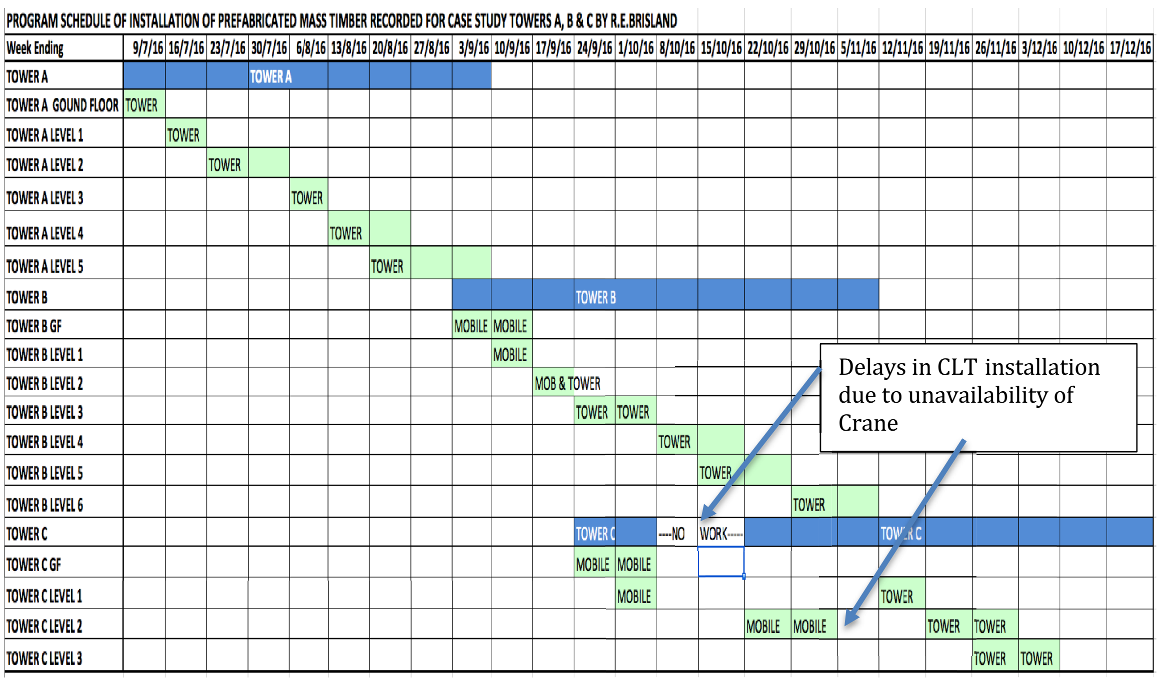


Figure 5.1 Program schedule of timber installation and crane types used

The program schedule includes continuous single blue shaded time-line bars for each of the three towers. These blue bars represent each tower's total duration for the installation of the prefabricated CLT structure observed. Plotted below the single blue time-line bar are the individual floor level time-line bars of each tower, shaded in green. The type of crane (tower or mobile) engaged for CLT installation varied on both Towers B and C. The respective crane is notated in the corresponding green shaded floor time-line bars for the weeks that it was the installation resource. Within the program schedule, Figure 5.1, the notation identifies the two stoppage periods to the CLT installation work process to Tower C. These were due, as discussed, by the unavailability of the tower crane and the inability of the mobile crane to reach the northern half of the building. The issues contributed to Tower C's ambiguous productivity outcome at a high-level review, Table 5.2.

5.3 Intermediate level review

Table 5.3 Summary of statistics for three case study towers

Description of items identified and logged	Tower A	Tower B	Tower C
FLOOR AREA PER LEVEL (m^2)	382	310	515
NUMBER OF FLOOR LEVELS IN TOTAL (#)	6	7	8
NUMBER OF FLOOR LEVELS OBSERVED (#)	6	6	3
NUMBER OF PANELS IN TOTAL (#) (FOR FLOORS OBSERVED)	923	1072	615
NUMBER OF PANELS OBSERVED INSTALLED (#)	634	636	365
TOTAL AREA CLT OBSERVED INSTALLED (m^2)	4633.77	3892.91	2816.48
CLT WORKDAYS OBSERVED (#)	45	47	28
AVAILABLE WORKDAYS (#)	51	54	42
O/A CLT NET CRANE HRS (STG 1 & 2) (HRS)	113.86	115.03	62.44
AVE. O/A *PRODUCTIVITY* (m2/HR.) (Σ (*Productivity* per day)/No. of CLT installation Days)	40.7	35.7	45.1
GROSS CRANE TIME (HRS)	305.31	342.81	189.09
GROSS CLT CREW TIME (HRS)	293.37	329.92	165.7
GROSS CLT CREW LABOUR TIME (HRS)	1240	1337	589
AVE. INSTALLATION CREW SIZE (#)	4.32	4.0	3.5
AVE. CRANE CREW SIZXE (#)	3	3	3
TOTAL CRANE DELIVERY LOGISTICS (HRS)	48.9	70.59	35.22
a) Storage Double Handling	*22.49*	*42.31*	*26.44*
b) Unloading	*23.18*	*23.32*	*3.75***

Description of items identified and logged	Tower A	Tower B	Tower C
c) Rework	*3.23*	*4.96*	*5.04*
CRANE IDLE (Waiting for trades) TIME (HRS)	15.11	45.04	23.05
CRANE STOPPAGES (Maintenance, stoppages, etc.) (HRS)	8.75	5.42	6.57
CRANE USED FOR OTHER TRADES (HRS)	106.56	112.15	59.81
VIDEO RECORDING OUTAGES (HRS)	17.31	30.8	8.84
OBSERVATIONAL VIEW OBSTRUCTED (HRS)	1.74	39.42	36.58
INCLEMENT WEATHER DELAY- RAIN (HRS)	30.2	22.47	7.08
INCLEMENT WEATHER DELAY- WIND (HRS)	24.9	4.27	5.13

** Unloading not observed as the view to the road blocked by constructed tower structures.

The intermediate level analysis focused on the productivity of panel types at each floor level. Each of the three tower's intermediate level worksheets are in Appendix 4. Table 5.3, above, summarises the relevant content from the tables for the three case towers.

A summary of the intermediate level productivity output analysis is tabulated in Table 5.4 below. It provides a breakdown for each tower, separating the data of the four types of CLT panels, floor, wall, beam and column, to each floor level.

The hours ("HRS (VA)") notated in Table 5.4, are the total net CLT crane cycle times, which excludes non-productive time, in accordance with the definition provided Table 4.4. The highest standard deviation values are in asterisk and highlighted in green for expedient identification. In general, these high values occur at the first two floor levels for each tower, with the exception to Tower B's columns.

Table 5.4 Intermediate level productivity analysis for the three towers

R. Brisland																				
	WALLS					FLOORS					BEAMS					COLUMNS				
BUILDING/ FLOOR	NO OF PANELS	AREA	HRS (VA)	PRODUCT'Y AVE m2/ hr	Standard Deviation	NO OF PANELS	AREA	HRS (VA)	PRODUCT'Y AVE m2/ hr	Standard Deviation	NO OF PANELS	AREA	HRS (VA)	PRODUCT'Y AVE m2/ hr	Standard Deviation	NO OF PANELS	AREA	HRS (VA)	PRODUCT'Y AVE m2/ hr	Standard Deviation
TOWER A																				
GF	35	408.99	6.039	80.28	47.93						11	19.2	1.791	13.140	9.51	5	7.19	0.698	13.470	11.76
LV 1	35	435.66	5.633	64.18	40.33	44	380	5.12	63.17	26.05	19	33.42	3.892	9.420	4.65	3	7.83	0.505	15.110	7.62
LV 2	40	453.05	6.913	56.50	33.15	43	381.29	7.34	67.82	29.96	12	25.43	1.91	11.790	3.21	6	9.34	0.927	12.170	4.61
LV 3	39	417.27	6.175	60.50	40.04	43	381.89	5.53	92.47	36.9	12	27.24	2.714	9.580	5.61	4	7.5	0.798	13.740	11.07
LV 4	31	397.86	7.111	67.38	38.77	43	381.89	6.32	64.04	27.8	13	25.59	3.186	7.670	3.52	13	25.63	1.813	16.830	11.03
LV 5*	110	397.61	20.434	24.23	8.2	37	316.89	5.03	80.17	31.9	13	72	5.726	12.574		7	8.06	1.31	6.153	
ROOF***				0.00		3	30.68	1.47	20.87											
TOTAL/AVE	**290**	**2510.44**	**52.305**	**58.33**	**40.2**	**213**	**1872.64**	**30.81**	**73.53**	**32.28**	**80**	**202.88**	**19.219**	**10.140**	**5.68**	**38**	**65.55**	**6.051**	**10.833**	**9.46**
TOWER B																				
GF	54	315.49	7.523	65.34	44.82						20	29.3	3.61	8.410	6.13	12	17.86	2.53	12.090	9.16
LV 1	24	297.15	6.997	78.82	40.61	40	301.49	7.78	62.04	37.75	25	33.3	6.75	6.420	3.1	12	21.46	1.84	9.600	6.46
LV 2	29	318.3	7.57	65.08	42.81	41	307.92	4.786	79.80	41.51	15	25.05	3.54	7.500	4.2	13	24.75	2.86	10.180	6.25
LV 3	24	237.17	6.53	60.51	32.82	25	213.22	3.68	78.97	36.61	7	13.32	1.75	8.160	3.76	7	9.13	1.15	11.440	11.36
LV 4	27	298.88	6.82	63.51	42.16	38	286.58	6.29	56.05	18.61	14	24.91	3.1	9.700	7.09	17	25.97	2.49	10.710	7.56
LV 5**	9	158.93	4.092	38.98		38	285.91	4.77	78.11	34.53	9	18.68	1.608	11.617		11	16.61	1.14	14.570	
LV 6**	55	194.82	7.45	26.15		39	293.19	7	41.88		16	43.17	5.46	7.907		7	14.3	0.69	20.725	
ROOF***						4	44.27	1.11	39.88											
TOTAL/AVE	**222**	**1820.74**	**46.982**	**41.12**	**41.12**	**225**	**1732.58**	**35.416**	**70.47**	**35.8**	**106**	**187.73**	**25.818**	**8.060**	**5.32**	**79**	**130.08**	**12.7**	**10.980**	**8.06**
TOWER C																				
GF	38	474.476	8.98	71.98	41.56						22	31.83	3.84	10.100	6.36	12	24.554	1.74	17.560	11.479
LV 1	52	523.272	13.381	48.28	30.85	48	449.53	6.74	81.25	47.83	25	35.818	3.669	9.270	7.52	30	46.6	4.45	9.960	7.02
L2	32	396.996	7.045	73.97	34.17	55	513.75	7.75	101.18	49.08	2	1.744	0.196	6.470	1.98	7	6.89	0.359	14.090	5.48
LV 3						32	287.41	4.58	79.41	37.96										
TOTAL/AVE	**122**	**1394.744**	**29.406**	**64.74**	**37.43**	**135**	**1250.69**	**19.07**	**88.61**	**46.79**	**49**	**69.392**	**7.705**	**9.530**	**6.83**	**49**	**78.044**	**6.549**	**12.960**	**8.87**
*- Wall Panel size< 5m2 & Col & Beam view obscured ** view mainly obscured to accurately determine time and panel type *** Roof Panels- view part obscured																				

Of note, the wall panels to Tower A's Level 5, sixth storey, were less than 5 m^2 in area, alien to the other floors and is highlighted in yellow and in red font in the above table. Consequently, its productivity was considerably lower than other decks. Also, it is noted that roof panels to Towers A and B, Tower A's level 5 beams and columns, Tower B's level 5 and 6 walls, columns and beams and level 6 floor panels are highlighted in yellow and typed in red. These data were not considered in the analysis, in Table 5.5 below, because the installation observation was partly obscured. Therefore, the crane cycle time and panel identification could not be confidently verified.

Table 5.5 Intermediate to high-level productivity comparison across three tower cases

Tower	High level average productivity (m^2/hr)	Intermediate level daily average productivity (m^2/hr)
A	14.82	49.98 (St. Dev. 26.91)
B	12.27	34.60 (St. Dev. 22.27)
C	7.52	45.90 (St. Dev. 25.13)

The productivity as summarised in Table 5.5 above, showed that from the intermediate level analysis, the overall outcome had considerably higher value from the high-level review findings. The average daily CLT productivity, at an intermediate level, was 34.6 to 45.9 m^2/hr., compared to 7.52 to 14.82 m^2/hr., at the high-level review. This finding implies that a project level perspective does not provide an accurate indication of the productivity of an individual activity. This is because general project stoppages, non-working days and non-productive activities are not identified nor discounted at that macro level.

5.4 Intermediate level analysis of value-added and non-value-added time

The number of workdays where mass timber activities were observed and logged was:

- 44 workdays recorded for Tower A,
- 48 workdays recorded for Tower B,
- 27 workdays recorded for Tower C.

Table 5.6 below shows there were many full normal workdays and partial regular workdays (1 to 6 hours) where no mass timber activities occurred due to various causes. This lost day calculation did not include the half-day portion not generally worked on a Saturday.

Table 5.6 Summary of workdays lost

No mass timber activity: Cause	Tower A: days affected	Tower B: days affected	Tower C: days affected
Inclement weather	3 full days and 13 partial days	2 full days and 4 partial days	1 full and 4 partial days
Public holidays	0	1	1
Union non-workdays (Lock Down or Long Weekends)	0	2	2
Recording/Observation loss	11 partial days	1 full day and 30 partial days	4 full days and 13 partial days
Management issues	1 full day and 28 partial days	4 full days and 36 partial days	20 full days and 21 partial days
Crane working for other trades	45 partial days	40 partial days	26 partial days
TOTAL	4 full days and 97 partial days	10 full days and 110 partial days	28 full days and 64 partial days

As identified in Table 5.6 above, several non-productive (non-value-added[12]) days or partial days were observed where the crew or the installation was delayed under the heading "management issues". Such issues included incorrect delivery or delayed delivery of the next scheduled panels required to be installed, the CLT crew waiting for scaffold or working on non-critical activities and the crane resource not available (sometimes allocated to an adjacent building). All these were classified as non-value-added activities.

The findings in Table 5.6, indicates that Tower A, which comprised of six-floor levels, experienced the least number of four full lost workdays. Tower B experienced the highest “recording and observation” lost time, partly due to the low-level location of the camera and sun glare. Tower C was the most affected by lost CLT workdays across the three buildings, with a total of 28 full days over only three-floor levels. Twenty of those 28 days were due to unavailability of the crane, as earlier discussed, and 21 partial days due to non-value activities (management

[12] value-added & non-value-added crane cycles defined in Table 4.7

issues). A break-up of the total number CLT crane cycles recorded, between value-add and non-value-add sequences, related to each tower, is outlined in Table 5.7 below.

Table 5.7 CLT crane cycles logged for Towers A, B and C

Description	Tower A	Tower B	Tower C	Total
Number of CLT Value-Added Crane Cycles[13]	764 (63.6%)	780 (58%)	450 (61%)	1,994 (60.6%)
Number of CLT Non-Value - Added Crane Cycles[14]	438 (36.4%)	564 42%)	293 (39%)	1,295 (39.4%)
Total Number of Gross CLT Crane Cycles recorded[15]	**1,202**	**1,344**	**743**	**3,289**

From Table 5.7, it is noted that out of a total of 3,289 gross CLT crane cycles, 1,295 (39.4%) were for non-value-added activities. The 3,289 gross CLT cycles consisted of 472 CLT crane hours and 789 CLT crew hours. The difference in hours between the crane and the crew was due to the crane frequently leaving the CLT activity to service other trades. This action by the crane incurred lost or non-value-added crew time, waiting for the crane to return or working on non-critical activities, e.g. moving material.

The recorded data allowed a categorical breakdown of the crane activities for each tower building. The gross crane time, from the two cranes, were divided and allocated, in hours and percentages, into the various categories of observed value-add and non-value-added activities. The results of this analysis are illustrated in the separate tower pie charts, in Figure 5.2 below.

[13] Definition refer to Table 4.8 p 112

[14] Definition refer to Table 4.8 p 112

[15] Definition refer to Table 4.8 p 112

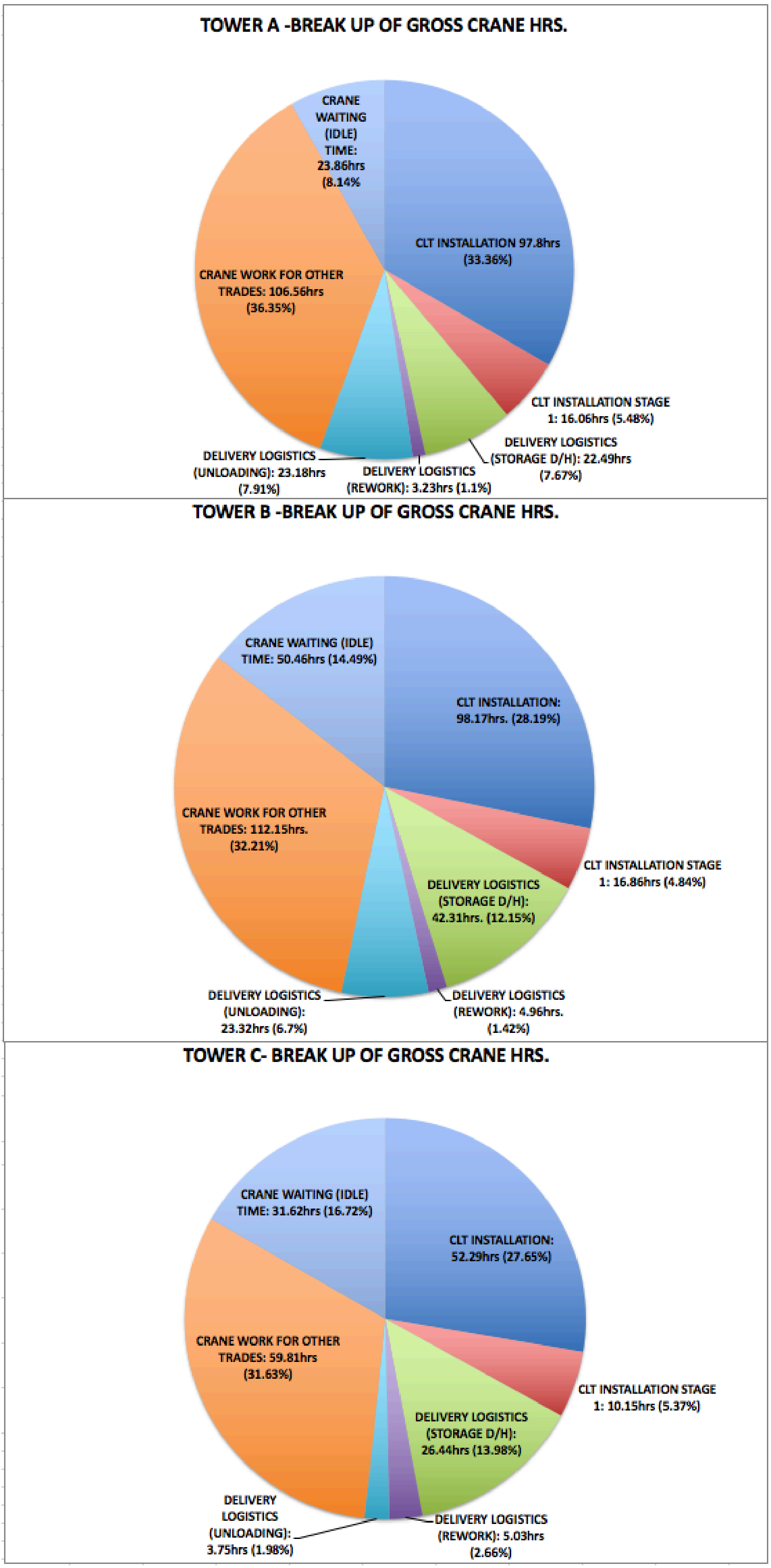


Figure 5.2 Pie charts of the logged activity break up for Towers A, B and C

Each pie chart, in Figure 5.2, is divided into the following categories:

a) CLT installation: Stage 2 of two-stage plus single-stage installation crane cycles,
b) CLT Stage 1: crane cycle from a store (or truck) to store on deck prior to installing. *Note: "a" + "b" = CLT Value-Added (Net CLT Crane Time),*
c) Delivery logistics (Non-Value-Added CLT Crane Time which include Storage Double handling, Unloading and Rework[16]),
d) Crane used for other trades,
e) Waiting (Idle) time.

Note: Gross CLT crane time equates to the total time for items a, b and c above, Gross crane time equates to the Grand Total of a, b, c, d and e.

The pie charts, Figure 5.2, indicate that between 44.49% and 48.35% of total crane allocated time was to either other trade activities (average 33.4%) or idle time (average 13.1%). Idle time could not be attributed to either CLT or other trades as it occurred between servicing other subcontractors and servicing CLT (or vice-versa).

Of note, Figure 5.2 identifies that over 39% of the remaining gross CLT crane cycle time was attributed to non-added value CLT crane cycles. This result equates to those outlined in Table 5.7; both are based on different units of measure. Figure 5.2 calculations are in time (hrs.), and Table 5.7 values are crane cycle numbers, which provides robustness to the finding.

Therefore, almost half of the project's crane time, during the CLT period, was allocated to non-CLT related activities. Value-add (Stages 1 and 2) CLT activities accounted for only 38.8% of the total crane time on Tower A, 33% on Tower B and 33% on Tower C.

[16] Delivery logistics category included rework, and this included panels installed in incorrect location then removed. This was often observed to be due to missing or illegible ID tags. Rework also included rectifying damaged panels or incorrect manufacture by adjusting incorrect panel dimensions.

5.5 Summary

This chapter discussed the study's findings on the three tower buildings from two levels: a high-level project review and an intermediate level (floor level) review. The multi- case field study captured 3,289 crane cycles for 1,631 CLT panels, across 16 different floor levels across the three case towers. The high-level (project level) analysis, which applied the time, in calendar days, to install the total panel area for each project found that the project's mass timber productivity was in a relatively low range of 7.52 to 14.82 m^2/hr. However, the intermediate level (floor level) analysis found that the CLT productivity, which excluded delays and interruptions, was found to be within a higher range: between 35 to 50 m^2/hr. across the three-tower cases (Table 5.5).

The findings implied that the project level, macro, perspective did not provide an accurate indication of the individual activity's productivity. This can be attributed to the fact that general project stoppages, non-working days and non-productive activities are generally not identified nor discounted at a macro level.

The analysis of value-added activities across the three case towers determined from the pie charts (Figure 5.2), identified that on average 65 % of the crane time was allocated to non-value-added activities. It was that found that between 44.49% and 48.08% gross crane time was allocated to activities not related to CLT installation: 33.4% was for other trade activities and 13.1% crane idle time.

Only 35% was on value-added CLT work, which coincidently corresponds to previous studies, as mentioned in the literature review on total project time directly related to value-add work (Girmscheid, 2010; Koskela, 2000; Levy, 1990). It was also determined that on average 39.4% of CLT related crane cycles were performed on non-value-added tasks.

The above findings provided clarity to the poor productivity findings at a project (high) level perspective when the CLT activity is isolated from the other project activities and delays. At the intermediate (activity) level (floor by floor) perspective it determined that the activity achieved a higher overall average daily productivity.

The above high and intermediate level analysis of CLT installation provides background information for the more detailed micro-level analysis of the collected productivity data, which is now addressed.

Chapter 6 Results and findings (Part 2): Activity (micro) level baseline findings

A primary focus of this research study was on the question if and how on-site installation productivity baseline rates could be developed reliably to assist predictable on-site expectation for mass timber. In addition to this, the focus was on assessing whether the secondary propositions had statistical support.

However, it first had to be determined whether the study would use a single case study or a multi-case study approach. Secondly, an outline of the analyses that were carried out with their findings, including formulating normally distributed sample sets, are presented. These findings determined whether the case study data could establish baseline rates. This is followed by a review of the analysis findings for the baseline analyses and development of a baseline matrix. The findings for propositions one to five are outlined in "Part 3" (Chapter 7).

6.1 Determine single or a multi-case study approach

For the one-way analysis of variance (ANOVA) test, the CLT crane cycle time data for the three towers were combined. The Null hypothesis was that there was no difference in crane cycle times between the three buildings. The statistics from this ANOVA test showed that the CLT crane cycles time data (N=1,212), and the CLT productivity data from each tower were heterogeneous. This was determined by the p-value= <0.001 (crane cycle) and 0.024 (productivity), as illustrated below in Tables 6.1 and 6.2.

Table 6.1 ANOVA test for crane cycle times between three towers

Tower	Mean (hrs)	σ/SD (hrs)	p	n
A	0.2559	0.6462	<0.001	503
B	0.1423	0.05756	<0.001	400
C	0.1408	0.06305	<0.001	309

The assumption of variance was tested for cycle time and found not tenable using ANOVA with results of $F=7.89$, $p<0.001$, $\eta 2=0.013$, Table 6.1. In other words, there was a significant difference found to reject the Null hypothesis, which concluded that there was a difference in crane cycle times between the three buildings.

Similar to crane cycle data, a One-way ANOVA analysis of variance was conducted on the productivity output observed, to evaluate the Null hypothesis that there was no significant difference in productivity outputs between the three towers.

Table 6.2 ANOVA test for productivity output between three towers

Tower	Mean (m^2/hr)	σ/SD (m^2/hr)	p	n
A	57.12	40.19	0.024	503
B	54.26	42.98	0.024	400
C	63.32	48.53	0.024	309

The assumption of variance for productivity was, again, tested and found not tenable using ANOVA with results of $F=3.901$, $p=0.024$, $\eta2=0.0064$, Table 6.2. In other words, a significant difference to conclude that there was a difference in productivity outputs between the three towers and reject the Null hypothesis.

Determination

Therefore, the three towers needed to be treated as three separate case studies and analysed separately, even though they were part of the same project. A multiple case study approach did create additional statistical analyses. It, consequently, provided the benefit of comparing crane cycle times and production outputs for non-similar floor layout designs and floor area sizes within the same environment, using the same resources, i.e. labour, equipment and management. Being three case studies was also conducive to ascertain if there were any differences in outcome for the various prefabricated CLT panel types across the different designed structures.

6.2 Panel sample sets' normality test findings

The majority of beams and columns in each of the three buildings were manufactured in CLT and so are classified for this study as panels. Each tower building had four main types of prefabricated panels: floors, walls, beams and columns Therefore, each panel type was independently tested to ascertain if each recorded panel sample set per tower was normally distributed.

As there were three case studies, twelve panel sample sets were tested for normality. To provide an interpretation of skewness and kurtosis findings from the Shapiro Wilk W-tests, a rule of thumb was applied for each test result (McNeese, 2016):

- where the skewness z value is between -0.5 and +0.5, the data is "fairly symmetrical".
- where the skewness z value is between -1 and -0.5 or between +0.5 and +1, the data is "moderately skewed".
- where the skewness z value is less than -1 or greater than 1, the data is "highly skewed".
- where the kurtosis value is close to 0, then normal distribution is assumed.
- where the kurtosis is less than 0, i.e., a minus value, then the distribution is light tails and is called a platykurtic distribution.
- where the kurtosis value is greater than 0, i.e., a positive value, then the distribution has heavier tails and is called a leptokurtic distribution.

The sample-set data used to test for normality was the crane cycle time, which was a prevalent measurable variable across all panel installations. The crane cycle sample sets were in units of hours. For a detailed understanding of the finding values, the control chart's control lines were plotted in hours, as per the tests, and are also reported, below, in minutes and seconds. Complementing the Shapiro Wilkes tests were the production and visual inspection of histograms, typical Q-Q plots and box plots. The results of the four-panel types are discussed separately, with each of the three towers' findings compared, commencing with floor panels.

6.2.1 Floor panels: normality test findings.

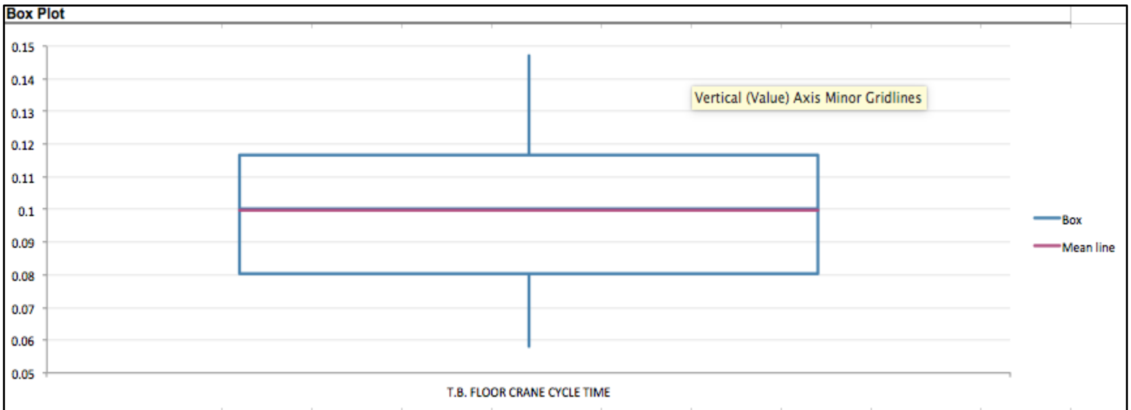
The Shapiro Wilk W-tests for normality for floor panels for each tower building all had $p>0.05$, A: ($p=0.189$), B: ($p=0.105$ and C: ($p=0.198$). The test determined that the trimmed floor panel cycle times for each of the three tower sample sets were normally distributed. The findings from the three towers are noted in Table 6.3 below.

Table 6.3 Floor panel cycle time normality test results per tower

Tower	p	Skewness z value	Standard Error (SE)	Kurtosis z value	Standard Error (SE)	Mean value of crane cycle time (mins: secs)	σ/SD (mins: secs)
A	0.189	0.013	0.204	-0.661	0.406	6:13	1:05
B	0.105	0.045	0.217	-0.811	0.430	5:40	1:09
C	0.198	0.108	0.243	-0.694	0.481	5:27	1:22

The skewness and kurtosis z-values for all towers were between the acceptable range of -1.96 and +1.96 (Kim, 2013). The skewness z value indicated that the trimmed sample sets for all three buildings were relatively symmetrical. Tower A was z-value -0.013 (SE=0.204), which indicates a very slight negative skewness, Tower B was 0.045 (SE=0.217), which and Tower C was 0.108 (SE=0.243), which shows slightly positive skewness. The kurtosis z values of the three towers were similar, which indicated that the trimmed sample set had a platykurtic distribution, that is light tails. Tower A was -0.661 (SE=0.406), Tower B's kurtosis z value of -0.811 (SE=0.430), and Tower C's z-value was -0.694 (SE=0.481).

As mentioned, histograms, standard Q-Q plots and box plots were also carried out on each panel set and visually inspected to verify normality. An example of the trimmed data box plot for Tower B is in Figure 6.1 below. This chart indicates that the sample set mean-line was symmetrical within the box with the whiskers being relatively similar lengths. No outliers are identified in the box plot.



Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
T.B. FLOOR CRANE CYCLE TIME	140	0.09971	0.0581	0.0581	0.08015	0.10015	0.11648	0.1469	0.1469
		0:05:59	0:03:29	0:03:29	0:04:49	0:06:01	0:06:59	0:08:49	0:08:49

TOWER B FLOOR CC TRIM 3A BOX-PLOT

Figure 6.1 Tower B- floor panel box plot

Floor panel normality control charts

The control charts for each tower are shown in Figures 6.2, 6.3 and 6.4 below. The outliers that were identified and removed to obtain a normally distributed crane cycle sample set are those plotted outside the final upper and lower control lines. To produce the control charts, the original panel data sample sets were plotted as a scatterplot. Superimposed on each plot is the final normally distributed trimmed data set's mean value, with plus/minus 1 and 2 standard deviation lines. The respective floor levels and cycle number are shown on the x-axis, and the extreme outliers are highlighted.

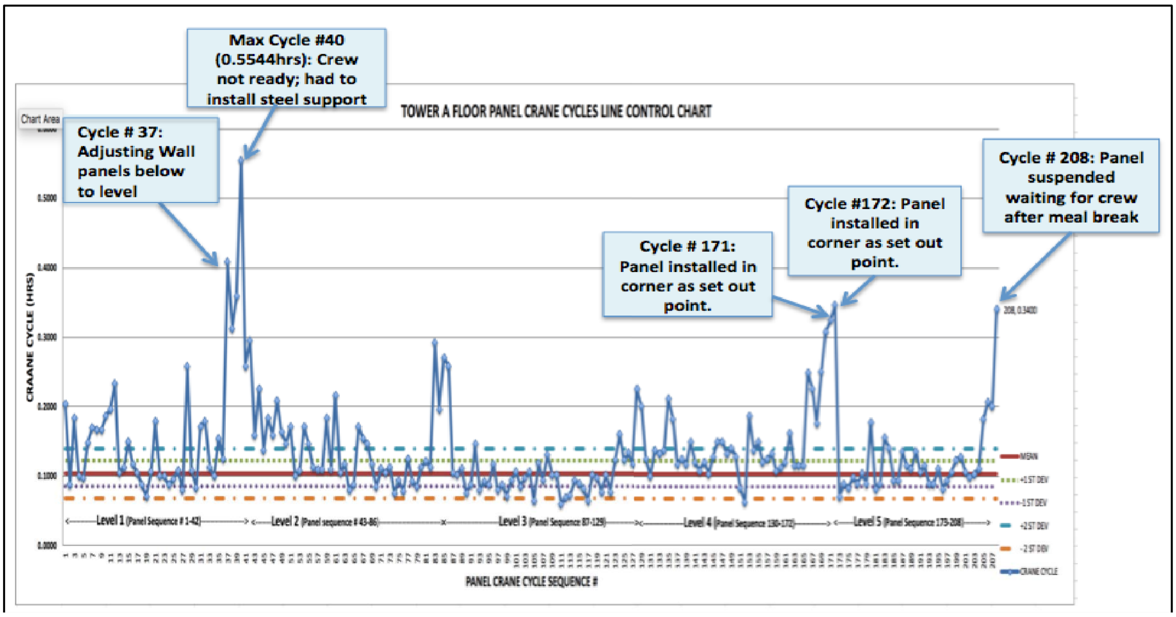


Figure 6.2 Tower A's control chart for floor panel cycle times

Tower A's upper control limit (UCL) (+2 x SD) (Figure 6.2) was 0.1399 hrs (8:23 mins), the lower control limit (LCL) (-2 x SD) was 0.0676 (4:03 mins) and the mean crane cycle was 0.1037 hrs (6:13 mins).

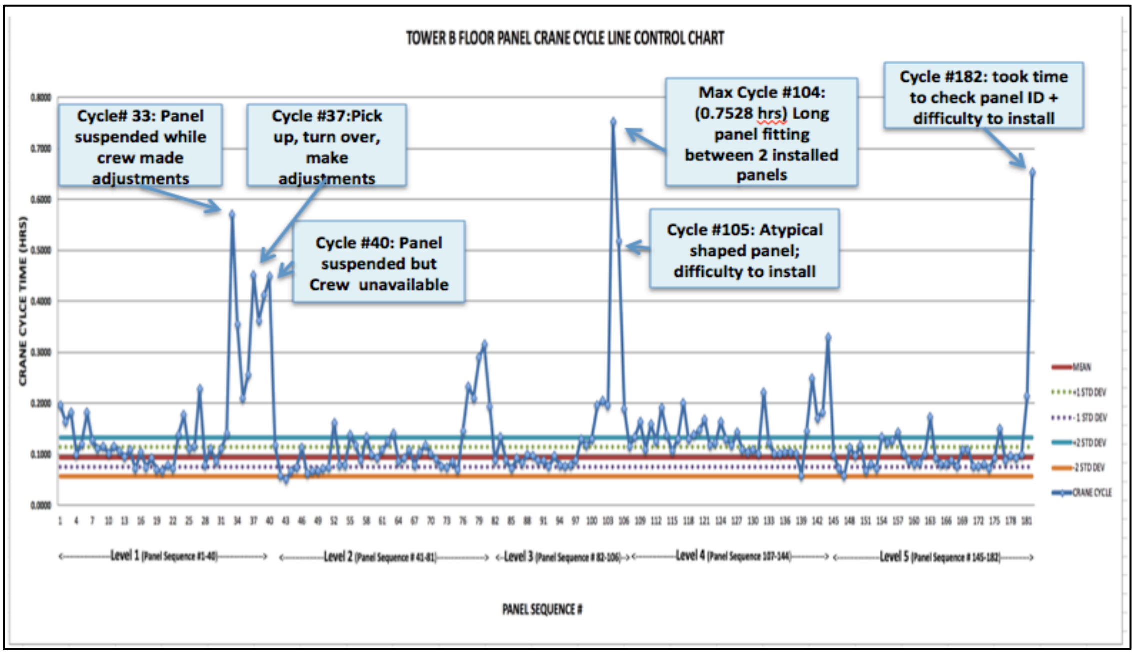


Figure 6.3 Tower B's control chart for floor panel cycle times

The UCL (+2xSD) for Tower B, in Figure 6.3 above, was 0.1328 hrs (7:58 mins), the LCL was 0.056 hrs (3:22 mins) and a mean crane cycle time of 0.0944 hrs (5:40 mins). The standard deviation was 0.0192 hrs (1:09 mins).

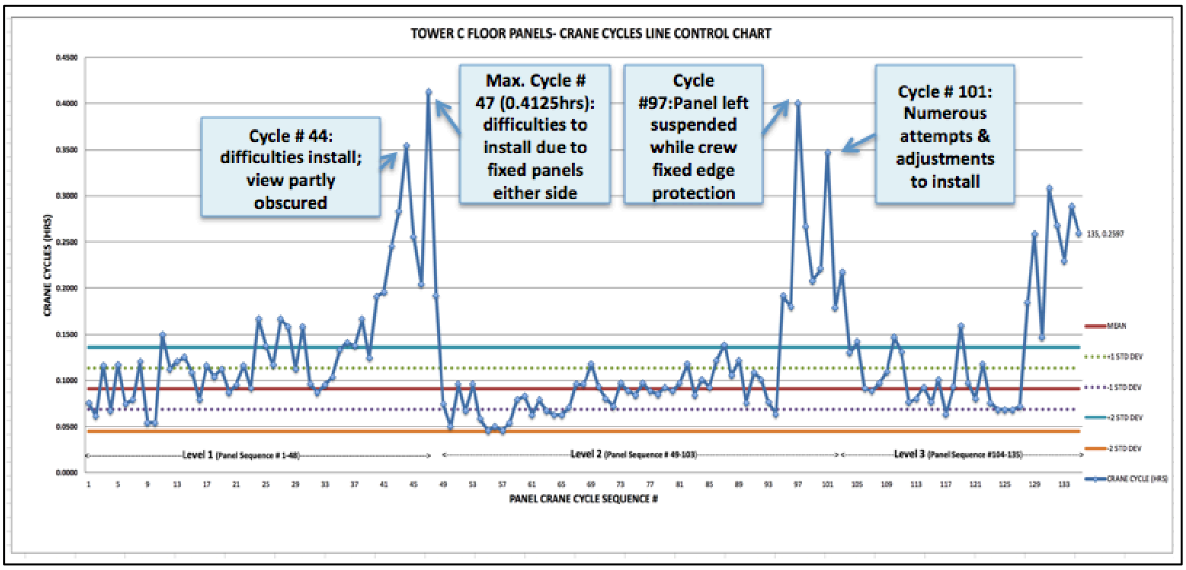


Figure 6.4 Tower C's control chart for floor panel cycle times

For Tower C the UCL (+2xSD) indicated in the control chart in Figure 6.4 was 0.1367 hrs (8:13 mins), the LCL was 0.0451 hrs (2:42 mins) and a mean crane cycle time of 0.0909 hrs (5:27 mins). The standard deviation was 0.0229 hrs (1:22 mins). Four outliers are identified in Tower C's control chart in Figure 6.4 above. From the above charts, across the three towers the mean values and standard deviation values of floor panel sample sets were relatively similar. The mean ranged between 5:27 to 6:13 mins, a difference of 46 seconds. The sample sets' standard deviation values fluctuated by only 17 seconds (1:05–1:22 mins).

Floor panel outliers

Tower A's maximum cycle time, as identified in Figure 6.2, was 33:16 mins (0.5544 hrs) for cycle 40, compared to the mean value of 6:13 minutes. The five extreme outliers identified were cycles 37, 40, 171, 172 and 208. Two of the outliers (cycles 40 and 208) were due to the install crew not being ready or available. Two of the panels were corner set out points (cycles 171 and 172), which required additional time to accurately position. The cause of one outlier crane cycle (37) was due to the supporting wall panels not being level, therefore, the wall panels had to be adjusted before the floor panel was installed.

As indicated in Figure 6.3 above, Tower B's maximum outlier identified was cycle 104 with a time of 0.7528 hrs (45:10 mins) compared to the set mean of 0.0944 hrs. (5:40 mins). Out of the six extreme outliers identified, two outliers (33 and 40) were due to the install crew not being available or working elsewhere while the panel was left suspended. The causation of three outliers (cycles 105, 104 and 182) was due to difficulty in fitting the panel into position: one (105) was due to being an atypical shape (similar to Figure 6.6 below) and one (104) because it was a long panel to close the opening between two previously installed. The crew’s substantiation of the panel's ID delayed cycle 182.

The maximum cycle time for Tower C was cycle 47, Figure 6.4, with a time of 0.4125 hrs (24:45 mins). Cycle 47’s observed causation was a difficulty in installing the floor panel to close an opening between two fixed panels, resulting in adjustments to them. Cycle 101 also experienced problems in installation with several attempts before fitting into the dedicated location. Cycle 44 also experienced problems in installation, but the crane partly obscured the view, so the exact issues could not be verified. In cycle 97 the panel was left suspended while the crew installed adjacent edge protection to ensure their safety.

Table 6.4 Number of floor-panel outliers via normality tests

	Tower A	Tower B	Tower C
Original total panel (cycles)	208	183	135
No. Outliers	67	58	36
%age reduction	32.2%	31.7%	26.6%

From table 6.4 above, the percentage of outlier removal was similar across the three buildings. A total of 161 outliers were found and deleted from a total of 526 crane cycles for the three-floor panel sample sets, which equated to an average reduction of 30.6%.

Typical floor panel outlier causation

Across all three tower buildings the, most prevalent floor panel outlier categories are:

1. The panel left suspended over the deck while the crew focused on other outstanding issues or because meal breaks were not synchronised with crane crew (e.g., the panel hooked and slewed to the location, but the crew was not ready to install).
2. Installing the floor panel on a corner or set out point (Photo 6.5 below) which required extra verification time by the crew to ensure accuracy of panel location.
3. Installation of an atypically shaped floor panel (Photo 6.6 below), a final floor panel or closing an opening required adjustment, while on the hook, to fit into the opening. Such panels often required multiple attempts to install before accomplishing the task.
4. The crane cycle for the first panel after a meal break or stoppage was delayed, with the crane or install crew not ready.

5. Before a floor panel was installed, whilst still attached to the crane, adjustments were required to the wall panels, on which the floor panel was to sit, in order for the panel to installed in the correct horizontal plane.
6. There was excessive time to verify ID and selection of panel (from store) before the panel was hooked and lifted to the installation location.
7. The panel initially slewed to an incorrect location then relocated to the correct position to be installed (without the crane releasing the panel).
8. The view of the crane cycle activity was partially obscured and could not verify exact cycle times.

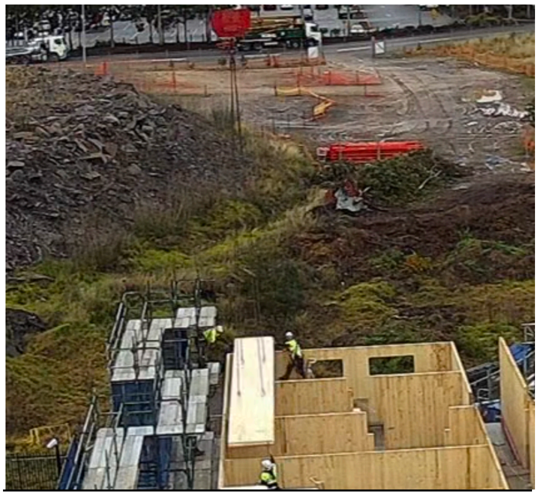


Figure 6.5 Set up point floor panel

Figure 6.6 Atypical shaped (floor) panel

6.2.2 Wall panel normality test findings

The Shapiro Wilk tests for the wall panels found each tower building to be normally distributed with p-value>0.05, as illustrated in Table 6.5 below: A (p=0.051, B (p=0.121 and C (p=0.278).

Table 6.5 Wall panel cycle time normality test results

Tower	p	Skewness z value	SE	Kurtosis z value	SE	Mean value of crane cycle time (mins: secs)	σ/SD (mins: secs)
A	0.051	0.009	0.117	-0.617	0.352	9:33	2:25
B	0.121	0.189	0.224	-0.543	0.444	8:31	2:26
C	0.278	0.062	0.245	-0.775	0.485	9:18	2:18

Table 6.5 indicated that for all three towers, both the skewness and kurtosis z values were between the acceptable range of -1.96 and +1.96. The skewness z value, for Tower A wall panels, was 0.009 (SE=0.117) and its kurtosis z value of -0.617 (SE=0.352). For Tower B the skewness z-value was 0.189 (SE=0.224) and its kurtosis z-value of -0.543 (SE=0.444). Tower C's skewness z-value was found to be 0.062 (SE=0.245), and the kurtosis z-value was -0.775 (SE=0.485). The skewness z values indicate that the trimmed sets were each relatively symmetrical, from their kurtosis z values the distributions having light tails and were platykurtic in the three cases.

Wall panel control charts

The three towers' normality control charts for wall panel crane cycles are shown in Figures 6.7, 6.8 and 6.9 below for Tower A, B and C, respectively. The production of the wall panel normality control charts was the same as described for floor panels. The outliers that were removed to obtain the final trimmed sample set are those above and below the control lines for Tower A's wall panels. Extreme outliers are identified on the charts and are discussed below.

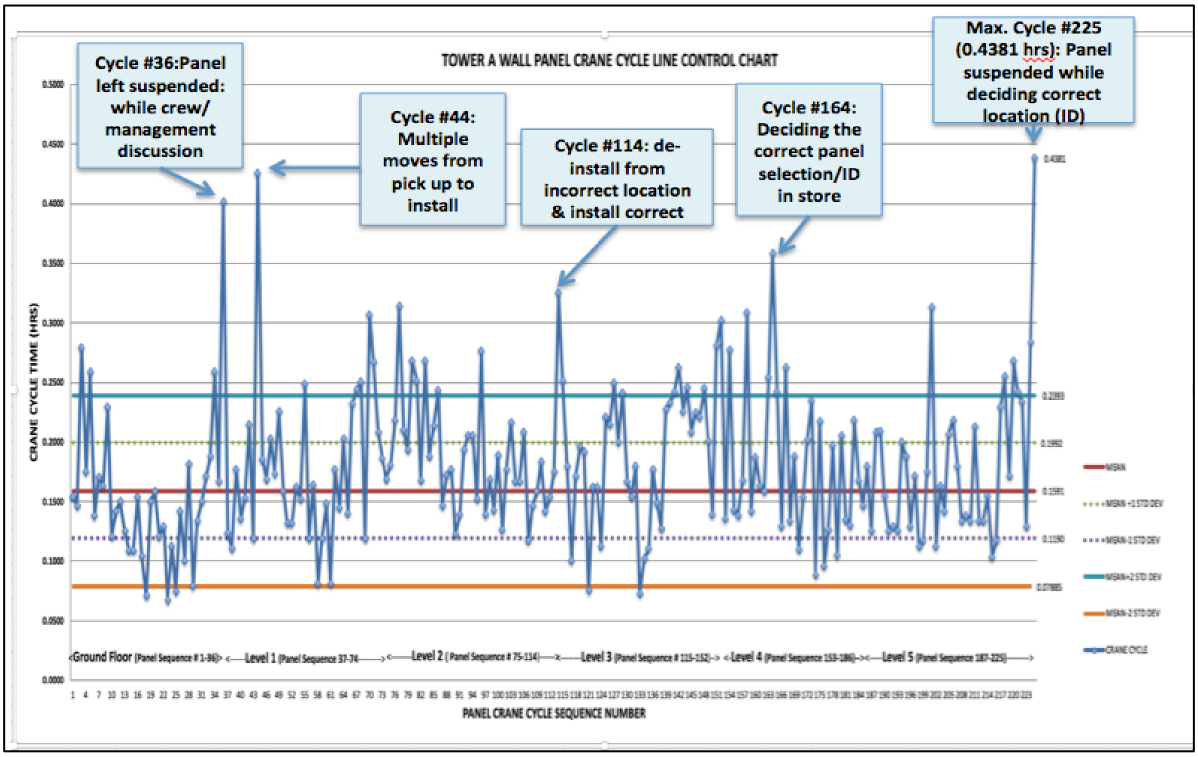


Figure 6.7 Tower A's control chart wall panels

Tower A's UCL (+2xSD) was 0.2395 hrs (14:22 mins) (Figure 6.5), the LCL was 0.0787 hrs (4:43 mins) and a mean crane cycle time of 0.1591 hrs (9:33 mins). The standard deviation was 0.0402 hrs (2:25 mins) and a total range between UCL and LCL of 9:39 mins.

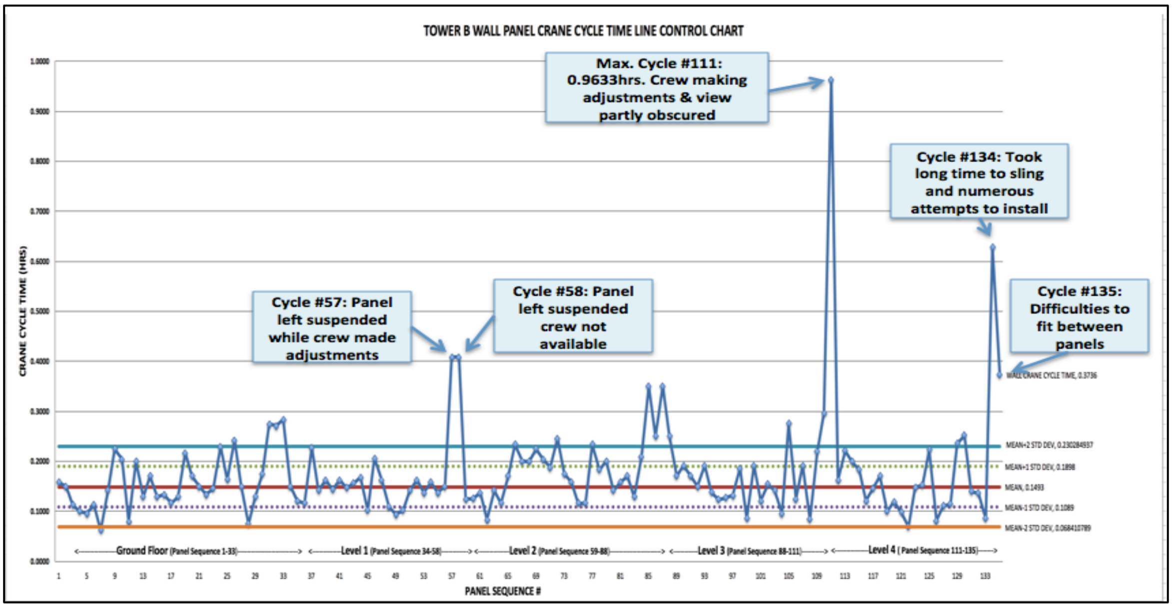


Figure 6.8 Tower B's control chart wall panels

Tower B's control chart, Figure 6.8, above, show UCL (+2xSD) value was 0.2231 hrs (13:23 mins) and LCL (2xSD) value of 0.0607 hrs (3:39 mins) with a mean cycle time of 0.1419 hrs (8:31 mins). The range between UCL and LCL was 9:44 mins.

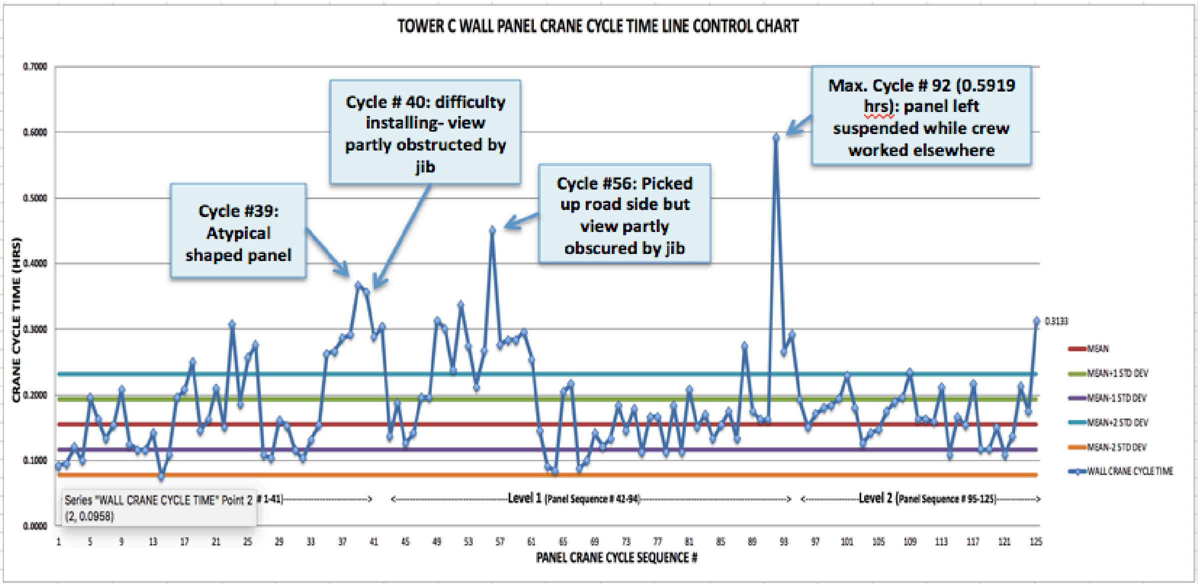


Figure 6.9 Tower C's control chart wall panels

In the control chart for Tower C, in Figure 6.9 above, the UCL (+2xSD) is 0.2319 hrs (13:55 mins), the LCL (-2xSD) is 0.0783 hrs (4:42 mins). There is a range of 9:13 mins, and the mean crane cycle time value plotted is 0.1551 hrs (9:18 mins).

The mean values and standard deviation values of the three wall panel sample sets, above, were relatively similar. The mean ranged from 8:31 to 9:33 mins, a difference of 62 seconds. Each of the sample sets' standard deviation values fluctuated by only 8 seconds (2:18 to 2:26 mins), the range from UCL to LCL differed by 31 seconds between the three cases.

Wall panel outliers

As indicated in Figure 6.7 above, Towers A maximum outlier was crane cycle #225 with a cycle time of 0.4381 hrs (26:17 mins). The causation of outliers, cycles 225 and 164, were issues concerning the identity of the panel, possibly due to the loss or illegibility of ID label. Outlier 36 was due to management requiring discussion with the installation crew while the panel was suspended above the install location. Cycle 114's excessive time was because the panel had been incorrect installed on Tower B and once removed was lifted to the correct position. The cycle 44 had more than two moves before it was fixed in its allocated place.

Five extreme outliers were identified in Tower B's control chart, in Figure 6.8 above. Cycle 111, at a time of 0.9633 hours, was found to take the maximum install time of all panel cycles in this study. During this cycle, the installation crew was observed making many adjustments and attempted to install the panel before completing the rectification, the causation could not be ascertained. Two outliers (cycles 57 and 58) were due to the crew leaving the panel suspended as they were not ready to install or were working on another activity. The lengthy time for one outlier (135) was due to difficulties installing the panel between two fixed panels (closing panel). Another outlier's causation (134) was due to the crane crew taking excessive time to sling and hook the panel, after which, the install crew experienced difficulties in installing the panel.

For Tower C, four wall panel crane cycles were identified with extreme time values, Figure 6.9. The maximum cycle was 92 at 0.519 hrs (31:08 mins). The causation was due to the panel left suspended above the deck, while the installation crew were unavailable working on another activity. Two extreme outliers (cycles 40 and 56) were due to difficulties installing the panel but, in both cases, the view was partially blocked by the crane jib. In cycle 39, the additional time was due to installing an atypical shape panel, as shown in Figure 6.6 above.

Table 6.6 Number of wall-panel outliers via normality tests

	Tower A	Tower B	Tower C
Original total panel (cycles)	225	135	125
No. Outliers	36	18	28
%age reduction	16%	13.33%	22.4%

Table 6.6 above indicates that the percentage reduction for wall panel was similar between Towers A and B, with a slight increase for Tower C. From a total of 485 crane cycles, 82 outliers were found and removed from the original sample sets.

This equated to a relatively low average reduction of 16.9% compared to an average of 30.6% for floor panels.

Typical outlier causation for wall panel

The most prevalent outlier categories of wall panel crane cycles observed were:

1. The crew was not ready to install after the panel was hooked and slewed to the installation position with the panel left suspended while they were working on other activities or because meal breaks were not synchronised with crane crew.
2. A panel was initially slewed to an incorrect location then relocated to the correct position be installed, possible ID tag issue.
3. The view was partially obstructed, and activity could not be observed clearly.
4. Difficulty in finding or verifying the selection of the required panel to be hooked before lifting the panel to the installation location.
5. Wind adversely affected the lifting time from the Ground Floor store to the installation deck.
6. An atypically shaped wall panel took longer to install.
7. Setting up the first wall panel after a break or the first panel to floor level took a long time.
8. Detaching a panel from an incorrectly installed location then installing it in the correct position took time, possible misreading ID tag or layout.

6.2.3 Beam panel normality test findings

The analyses found that p>0.05 for each of the three case final sets from the Shapiro Wilk tests for beam panels, which indicated that they were all normally distributed: Tower A p=0.250, B p=0.161 and C p=0.058. The findings from the tests on the three towers are noted in Table 6.7 below.

Table 6.7 Beam panel cycle time normality test findings

Tower	p	Skewness z value	SE	Kurtosis z value	SE	Mean value of crane cycle time (mins: secs)	σ/SD (mins: secs)
A	0.250	0.019	0.304	-0.441	0.599	11:14	3:36
B	0.161	0.039	0.316	-0.954	0.623	10:58	3:14
C	0.058	0.232	0.378	-1.176	0.741	8:10	2:35

Both skewness and kurtosis z values for all three buildings were within the acceptable range of -1.96 and +1.96. The skewness z values (A: 0.019 (SE=0.304), B: 0.039 (SE=0.316) and C: 0.232 (SE=0.378) determined that each of the sample sets were all relatively symmetrical. Each of the three sample sets was found to have light tails and a platykurtic distribution from the kurtosis z-value findings (A: -0.441 (SE=0.599), B: -0.954 (SE=0.623) and C: -1.176 (SE=0.741)).

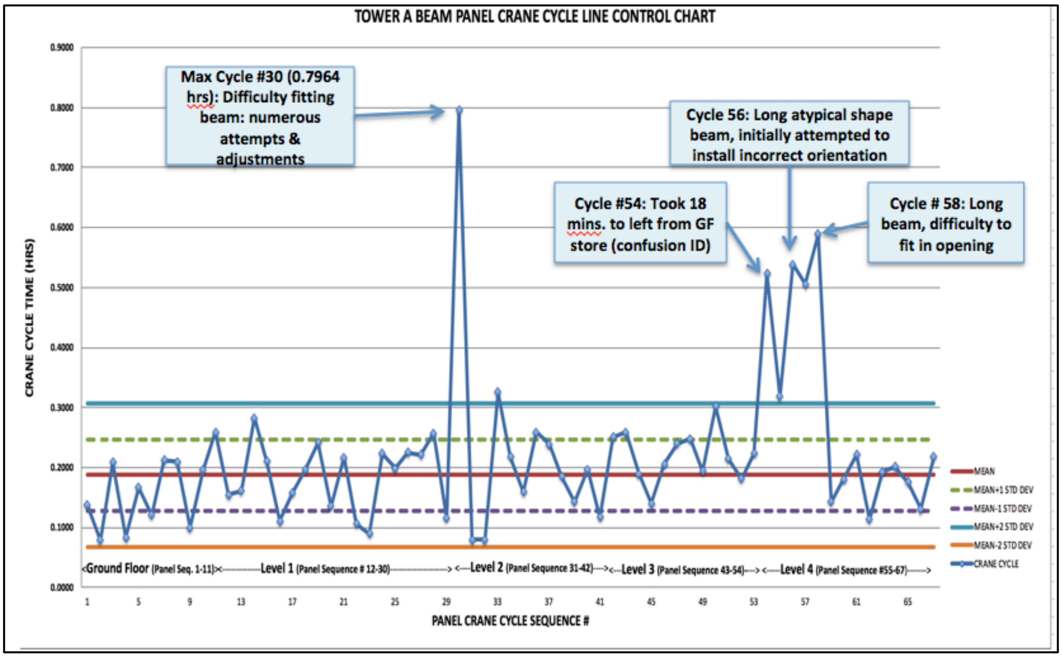


Figure 6.10 Tower A's control chart beam panels

The UCL (+2xSD) indicated on the above control chart for Tower A, Figure 6.10, is 0.3075 hrs (18:27 mins), the LCL (-2xSD) is 0.0671 hrs (4:02 mins) and the mean crane cycle time value plotted is 0.1873 hrs (11:14 mins). The trimmed sample set's standard deviation was 0.0601 hrs (3:36 mins).

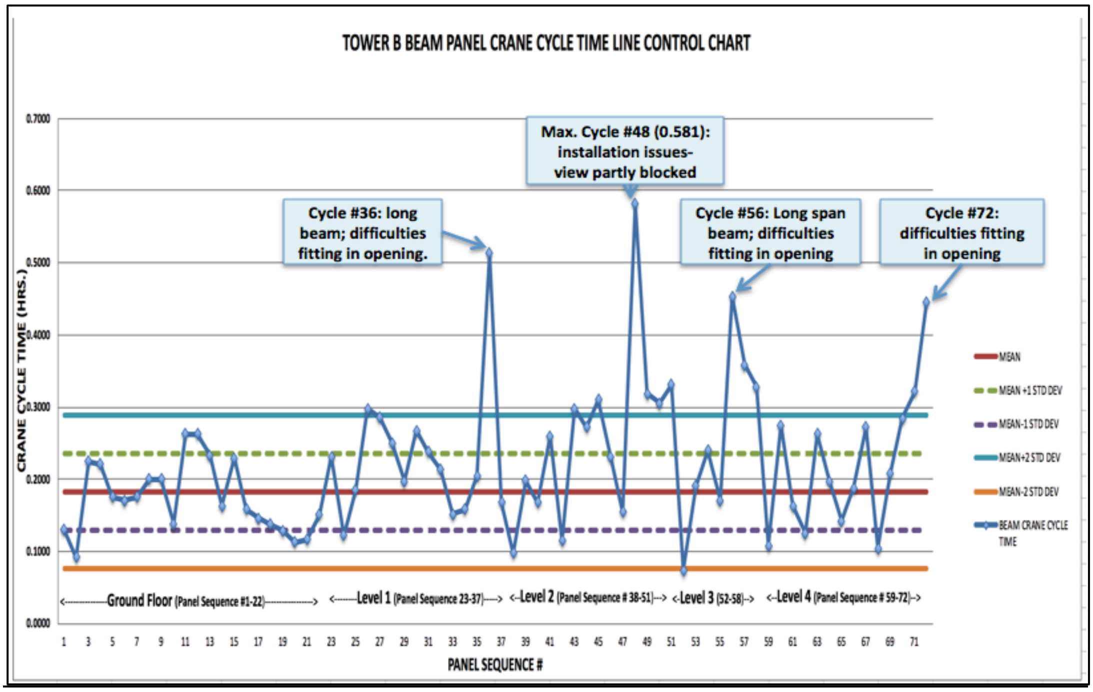


Figure 6.11 Tower B's control chart beam panels

The UCL (+2xSD) of Tower B's trimmed set, indicated on the above control chart in Figure 6.11 is 0.2905 hrs (17:26 mins), the LCL (-2xSD) is 0.0753 hrs (4:31 mins) and the mean crane cycle time value plotted is 0.1829 hrs (10:58 mins). The trimmed sample set's standard deviation was 0.0538 hrs (3:14 mins).

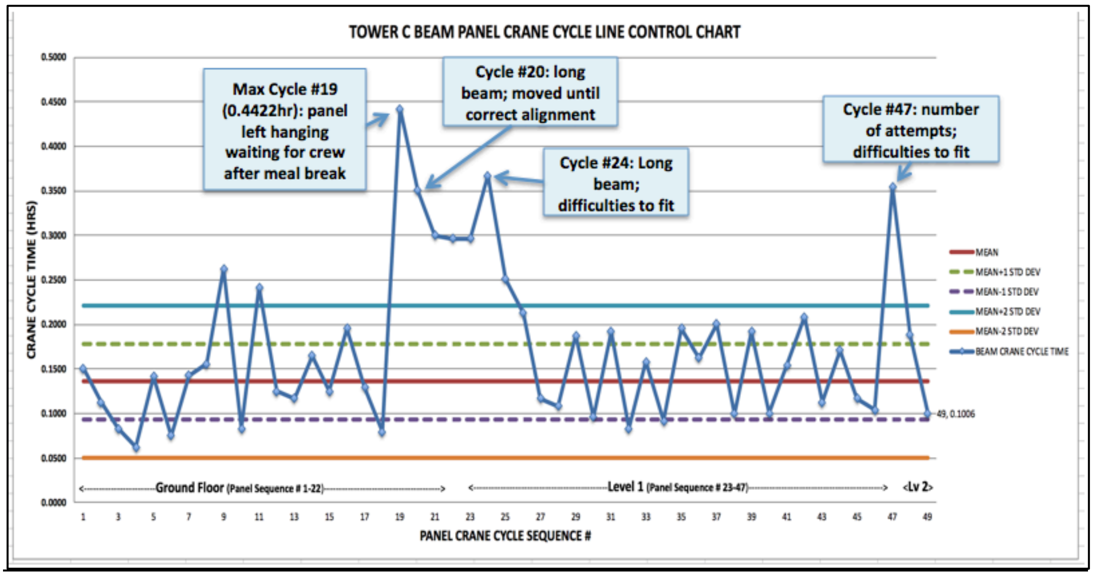


Figure 6.12 Tower C's control chart beam panels

Tower C's trimmed beam panel set's UCL (+2xSD) is 0.2222 hrs (13:20, mins) and the LCL (-2xSD) is 0.0498 hrs (2:59 mins), as indicated on the above control chart in Figure 6.12. The trimmed mean crane cycle time value plotted is 0.136 hrs (8:10 mins). The trimmed sample set's standard deviation was 0.0431 hrs (2:35 mins).

The mean crane cycle values for Tower A and B beam panel sample sets were reasonable similar with only 16 seconds difference (11:14 and 10:58 mins). However, there was a significant difference in the mean values of Towers A and C (Table 6.7) with the latter found to be 3:04 mins faster. The mean ranged from 11:14 to 8:10 mins. The difference between the highest and lowest standard deviation value was 1:01 mins (3:36–2.35 mins). The standard deviation values between Towers A and B beams were closer with only 22 seconds difference (Table 6.7).

Beam panel outliers

From Tower A's control chart, Figure 6.10 above, four outliers were identified, which has the four extreme cycle times. Cycle 30 had the maximum time of 0.7964 hrs (47:47 mins) and with cycle 58 had difficulties in installing its beam into the wall cut out. For outlier (cycle 56) the beam was an atypical shape, which again caused problems and additional time to install. In the case of cycle 54, for an unidentifiable reason, the time to identify and hook the panel before lifting was over 18 minutes.

From the four extreme outliers in Tower B's control chart in Figure 6.11, the sample set's maximum time was cycle 48 with 0.581 hrs (34:52 mins). The cycle had installation difficulties, which could not be identified as previously installed panels partially blocked the view. The other three highlighted outliers (cycles 36, 56 and 72) also had similar installation difficulties in fitting the beam panel into the installed wall panel openings.

The maximum outlier, for Tower C, Figure 6.12 above, was cycle 19 with a time of 0.4422 hrs (26:32 mins). The causation was due to the crane and install crew not synchronising their meal breaks. This resulted in the crane leaving the panel suspended until the install crew finished their meal break and returned to the deck. The other three outlier cycle times (20, 24 and 47) were due to difficulties, again, in fitting the beam panels in the wall openings. This difficulty was exacerbated for outlier #20 because it was also a long beam.

Table 6.8 below is a summary of the outliers identified and deleted from the original sample sets during the three case normality tests for beams.

Table 6.8 Number of beam-panel outliers via normality tests

	Tower A	Tower B	Tower C
Original total panel (cycles)	67	72	49
No. Outliers	5	15	10
%age reduction	7.5%	20.8%	20.4%

From the three cases, 30 outliers were found and deleted from a total number of 188 beam panel crane cycles. This equated to an average reduction of 15.95% for beam panels compared to a 17.52% reduction for wall panels and 30.6% for floor panels.

Typical beam outlier causation

The most prevalent outlier categories of beam panel crane cycles observed were because:

1. The beam required adjustment while on the hook to fit into pre-formed openings in wall panels, which often required multiple attempts before finally installing.
2. A long beam panel bearing on more than two columns generally required longer installation time than shorter beams.
3. The installation crew was not ready after a panel was hooked, slewed to installation position, and it was left suspended while they focused on other issues or because meal breaks were not synchronised with crane crew.
4. A panel was initially slewed to the incorrect location then relocated to the correct place and installed.

5. It took excessive time to verify selection and hook panel before lifting to the allocated location, possible ID issues.
6. The view obstructed, so the activity could not be observed clearly, or cycle time accurately identified.

6.2.4 Normality test findings for column panel type

The findings indicated that the column trimmed sample sets were all normally distributed. The column panel Shapiro Wilk W-tests found, in all three cases, that p-values> 0.05 with Tower A p=0.433, Tower B p=0.520 and C p=0.881 as shown in Table 6.9 below. Both the skewness and kurtosis z values for the three cases were within the acceptable parameters of -1.96 and +1.96.

Table 6.9 Column panel cycle time normality test results

Tower	p	Skewness z value	SE	Kurtosis z value	SE	Mean value of crane cycle time (mins: secs)	σ/SD (mins: secs)
A	0.433	0.195	0.464	-0.966	0.902	7:03	2:08
B	0.520	0.163	0.350	-0.481	0.688	7:46	1:52
C	0.881	0.045	0.409	-0.320	0.798	8:35	2:15

The skewness z values indicate that both Tower A (0.195 (SE=0.464)), and B (0.163 (SE=0.35)) trimmed sets were fairly symmetrical with Tower C set close to being precisely symmetrical at 0.045 (SE=0.409). The kurtosis z value of Tower B and C were -0.481 (SE=0.688) and -0.320 (SE=0.798) respectively, indicating that their distribution had light tails with a platykurtic distribution. Tower A's kurtosis z-value was -0.966 (SE=0.902), and although the value was not close to 0, the z-value determined the distribution had light tails with a platykurtic distribution.

Column panel normality control charts

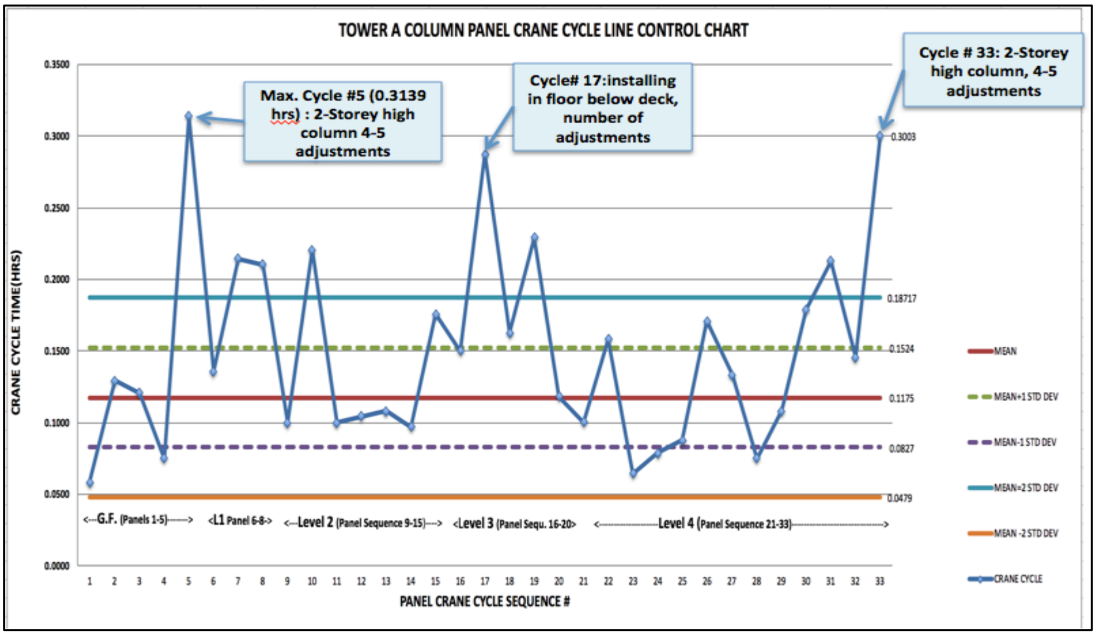


Figure 6.13 Tower A's control chart column panels

The UCL (+2xSD) of Tower A's trimmed column panel set was 0.1885 hrs (11:19 mins), and the LCL (-2xSD) was 0.0465 hrs (2:47 mins), as plotted in the above control chart Figure 6.13. The mean value crane cycle time plotted from the trimmed sample set was 0.1175 hrs (7:03 mins) The trimmed sample set's standard deviation was 0.0355 hrs (2:08 mins).

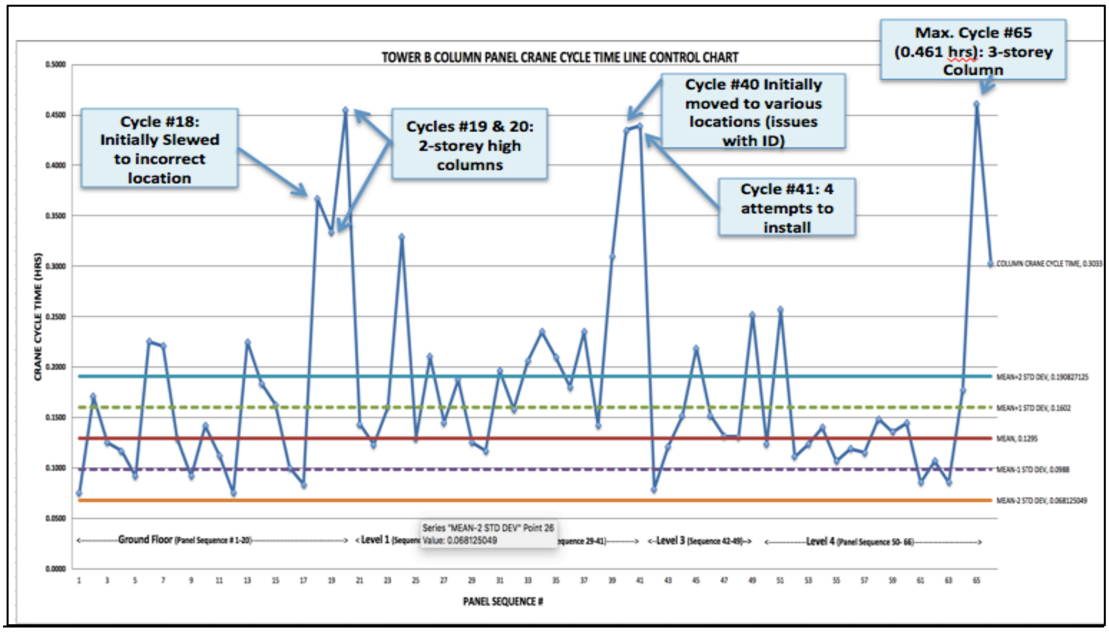


Figure 6.14 Tower B's control chart column panels

Tower B's trimmed column panel set UCL (+2 x SD) was 0.1915 hrs (11:29 mins) and the LCL (-2 x SD) was 0.0675 hrs (4:03 mins) as the control chart Figure 6.14. The trimmed set's mean crane cycle time value, as plotted, was 0.1295 hrs (7:46 mins). The trimmed sample set's standard deviation was 0.031 hrs (1:52 mins).

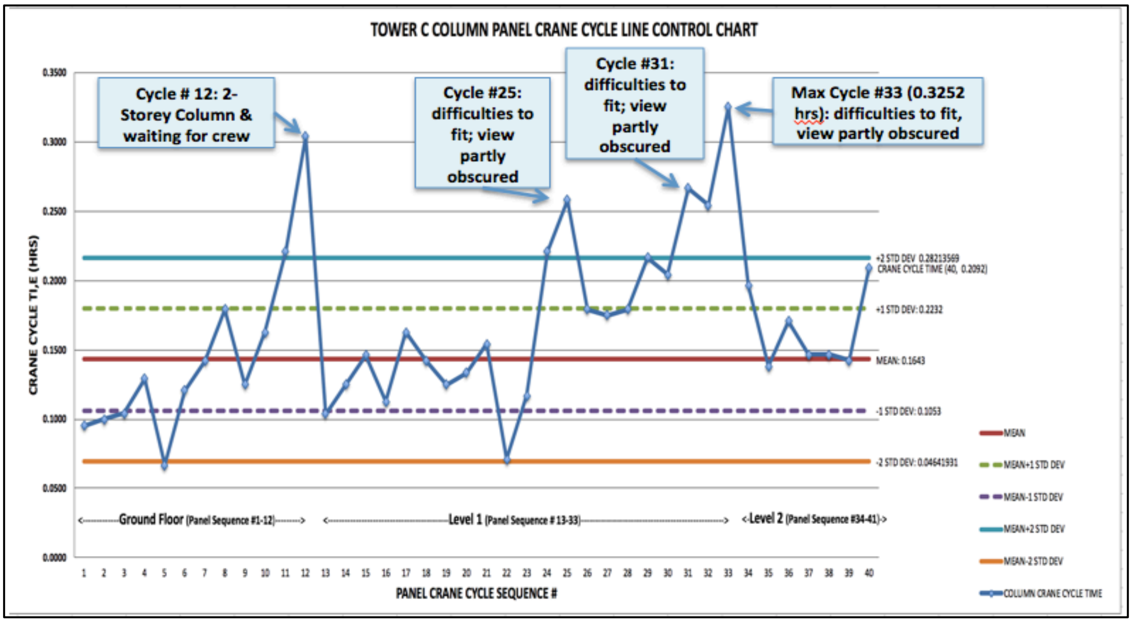


Figure 6.15 Tower C's control chart column panels

Tower C's control chart, Figure 6.15 above, has the trimmed column panel set's UCL (+2xSD) value of 0.2178 hrs (13:04 mins) and the LCL (-2xSD) value of 0.0682 hrs (4:05 mins) superimposed on the chart. The trimmed mean crane cycle time value plotted is 0.143 hrs (8:35 mins). The sample set's standard deviation was 0.0374 hrs (2:15 mins).

A comparison of the mean crane cycle values across the three towers for column panels indicated that there was a 1 minute 32-second difference between the highest and lowest values, for Tower C (8:35 mins) and Tower A (7:03 mins) respectively. Tower B's column sample set mean of 7:46 mins was almost equal distance between the other two towers. The three column sample sets' standard deviation values differed by 23 seconds between lowest to highest (1:52–2:15 mins). The standard deviation values between Towers A and C were closer, with only 7 seconds difference, Table 6.9 above. The difference in range between UCL and LCL among the three cases was 1:33 mins.

Column Panel Outliers

In Figure 6.13 above, the causation of Tower A's maximum outlier, identified as cycle 5, with a time of 18:50 mins., was partly due to the column being two stories high. Five attempts were taken to install this column and additional time was required to achieve final vertical alignment of the tall column accurately. Cycle 33's extended time was also due to the same causation. Outlier cycle 17's extended time was due to the column's out of sequence delivery, resulting in an out of sequence installation, one floor below the current installed deck.

In the above Tower B column control chart, Figure 6.14, six extreme outliers were identified. The maximum outlier was cycle 65, with a time of 0.461 hrs (27:40 mins). The causation of this outlier was because the column was three stories high. Due to this, there was a high degree of difficulty in installing the column, which required extra time to achieve vertical alignment accurately. The causation for outlier cycles 19 and 20 was the same as cycle 65, as both were 2-storey high columns. For outlier cycle 40, the install crew had issues in identifying the panel's correct location. The causation appeared to be due to an illegible or misplaced panel's ID tag, and it was consequently moved to various locations until the crew found the right position. Outlier cycle 18 was due to the column being initially lifted to an incorrect place, which was subsequently relocated to the correct position. Outlier cycle 41 had difficulties in installation with three failed attempts before the fourth was successful.

Four extreme outliers were noted in Tower C's control chart, Figure 6.15 above. The maximum outlier was cycle 33 with a time of 0.3252 hrs (19:31 mins). The causation of the outlier was due to difficulties in installing the panel to fit in the designed location. The exact causation was unclear because the view partially blocked by the crane jib. The causation for both outlier cycles 25 and 31 was for the same reason as cycle 33. Outlier cycle 12 time was due to the column being 2-

stories high, which required extra time to accurately achieve vertical alignment and its installation process consequently had a higher degree of difficulty.

Table 6.10 below is a summary of the column outliers identified and deleted from the original sample sets during the three case normality tests.

Table 6.10 Number of column-panel outliers via normality tests

	Tower A	Tower B	Tower C
Original total panel (cycles)	33	66	40
No. Outliers	8	20	7
%age reduction	24.2%	30.3%	17.5%

A total of 35 outliers were found and deleted from a total number of 139 crane cycles to produce the three trimmed sample sets. It equated to an average reduction of 25.18% for column panels compared to beam panels at 15.95%, wall panels at 17.52% and the greatest reduction was for floor panels at 30.6%.

Column outlier causation summary

The most prevalent outlier categories of column panel crane cycles observed were:

1. The crew was not ready to install after the panel was hooked and slewed to the installation location, and the panel was left suspended while they focused on other issues or because meal breaks were not synchronised with crane crew.
2. A panel was initially slewed to the incorrect location then relocated to the correct position to be installed, inaccurate reading of ID or drawing.
3. The view obstructed, and the activity could not be observed clearly.
4. An atypical 2 to 3-storey high column required additional installation time.
5. The crew took excessive time to verify the selection of the required panel to hook before lifting it to the installation location, possible issues with an ID tag.
6. Multiple attempts to install a column before finally fitting due to difficulties in the installation process.

6.2.5 Determination

It is generally accepted that sample sets need to be in normal distribution for robustness of ANOVA against violations. From the above analysis process, the twelve trimmed sample sets from the four panel-types across the three buildings, have now been verified as normally distributed. The trimmed sample sets' data consisted of the crane cycle data least affected by assignable causes and can now be analysed using ANOVA and regression without any fear of violation.

6.3 Cross case analysis: Similarity of panel type analyses findings

The next step, in the analysis process to determine baseline values, was to establish if the four types, i.e., floor, wall, beam and column, were statistically significantly different in crane cycle time and productivity output. If there was no significant difference between the panel types, their four sample sets could be combined into one panel type for further analysis. If there were a significant difference, then the four types would need to be tested separately for each case.

The findings of the initial One-way ANOVA tests are in Table 6.11, below, for crane cycle times and in Table 6.12 for productivity output. The findings determined that for each test: the p-value<0.001 (p>0.05) and F>1.00 for both cycle time and productivity. Therefore, there was a statistically significant difference between the four types of panels for both crane cycles and productivity in each of the three cases, rejecting the Null hypotheses of significant statistical similarity.

Table 6.11 One-way ANOVA: all panel crane cycle times

Tower	N	Mean mins: secs (hrs)	St Dev. mins: secs (hrs)	Range (mins: secs)	F	p-value	η^2
Tower A	417	8:32 (0.1421)	2:57 (0.0492)	(3:36–19:48)	(3,413) 92.484	<0.001	.402
Tower B	345	7:56 (0.1323)	2:54 (0.0483)	(3:00–16:48)	(3,341) 92.387	<0.001	.448
Tower C	268	7:38 (0.1271)	2:40 (0.0443)	(3:00–14:24)	(3,264) 62.057	<0.001	.414

Table 6.12 One-way ANOVA: all panel productivity rates (m^2/hr)

Tower	N	Mean (m^2/hr)	St Dev (m^2/hr)	Range (m^2/hr)	F	p-value	η^2
Tower A	417	58.69	42.02	0.23–213	(3,413) 82.126	<0.001	.374
Tower B	345	57.81	44.17	1.73–206.5	(3,341) 113.973	<0.001	.501
Tower C	268	66.79	51.02	2.84–246.2	(3,264) 87.334	<0.001	.498

The eta square (η^2) value from ANOVA tests, for both crane cycle times and productivity, indicated that panel type had a strong effect size, with values generally being between 0.37 to 0.5 (<0.06) (Zar, 2014).

Post hoc tests were carried out for cross-data examination of the findings in panel types, and these are shown in Tables 6.13 and 6.14 below. From the multiple comparison post hoc tests for crane cycles, Table 6.13 below, there was a statistically significant difference between the four panel types for the three towers. However, there was no statistically significant difference found in three out of 18 individual panel type cross-comparisons. These three comparisons were i) between the column and beam panels on Tower C p=0.808 (p>0.05), ii) column and wall panels on Tower C p=0.302 (p>0.05) and iii) column and floor panels on Tower A p=0.334 (p>0.05). In each of these three comparisons, the prevalent panel was the column.

Table 6.13 Post hoc test: multi comparison findings: crane cycles

Tower	Panel type (l)	Panel type (k)	Mean difference (l-k)	St Error	Sig.	95% Conf. Lower Bound	95% Conf. Upper Bound
Tower A	Floor	Wall	-.05533	.00425	0.00	-.0663	-.0444
		Beam	-.08368	.00582	0.00	-.0987	-.0687
		Column	-.01379	.00828	.334	-.0352	.0076
	Wall	Beam	-.02835	.00559	.000	-.0428	-.0139
		Column	.04153	.00812	.000	.0206	.0625
	Beam	Column	.06988	.0904	.000	.0466	.0932

Tower	Panel type (l)	Panel type (k)	Mean difference (l-k)	St Error	Sig.	95% Conf. Lower Bound	95% Conf. Upper Bound
Tower B	Floor	Wall	-0.05497	.00464	.000	-.0669	-.0430
		Beam	-0.8858	.00576	.000	-.1034	-.0736
		Column	-.03509	.00622	.000	-.0511	-.0190
	Wall	Beam	-.03355	.00582	.000	-.0486	-.0185
		Column	.01987	.00627	.009	.0037	.0361
	Beam	Column	.05342	.00714	.000	.0350	.0719
Tower C	Floor	Wall	-.06419	.00488	0.00	-.0768	-.0516
		Beam	-.04494	.00646	0.00	-.0616	-.0282
		Column	-.05217	.00686	0.00	-.0699	-.0344
	Wall	Beam	.01925	.00647	.017	.0025	.0360
		Column	.01202	.00688	.302	-.0058	.0298
	Beam	Column	-.00723	.00808	.808	-.0281	.0137

As determined by the multiple comparison post hoc productivity findings in Table 6.14 below, there was a statistically significant difference between all panel types for the three towers except for, again, the comparison findings of beams and columns. In respect of the post hoc comparison tests the findings between column and beam, i.e. the two small panel types were relatively similar: Tower A p=0.863; Tower B p=0.911 and Tower C p=0.972 (p>0.05).

Table 6.14 Post hoc test: multi comparison findings: productivity

Tower	Panel type (l)	Panel type (k)	Mean difference (l-k)	St Error	Sig.	95% Conf. Lower Bound	95% Conf. Upper Bound
Tower A	Floor	Wall	21.46905	3.71445	.000	11.8875	31.0506
		Beam	72.69522	5.08652	.000	59.5744	85.816
		Column	66.51255	7.24357	.000	47.8276	85.1975
	Wall	Beam	51.22617	4.88527	.000	38.6245	63.8278
		Column	45.04350	7.10369	.000	26.7194	63.3676
	Beam	Column	-6.18267	7.9081	.863	-26.5818	14.2164

Tower	Panel type (l)	Panel type (k)	Mean difference (l-k)	St Error	Sig.	95% Conf. Lower Bound	95% Conf. Upper Bound
Tower B	Floor	Wall	11.97224	4.03302	.017	1.56	22.3845
		Beam	74.90494	5.01088	.000	61.9681	87.8418
		Column	70.78316	5.40674	.000	56.8243	84.742
	Wall	Beam	62.93269	5.06425	.000	49.8581	76.0073
		Column	58.81091	5.45623	.000	44.7243	72.8975
	Beam	Column	-4.12178	6.21403	.911	-20.1648	11.9213
Tower C	Floor	Wall	33.8413	5.19129	.000	20.4194	47.2632
		Beam	92.62098	6.86975	.000	74.8595	110.3825
		Column	88.88062	7.30405	.000	69.9962	107.765
	Wall	Beam	58.77968	6.88973	.000	40.9665	76.9723
		Column	55.03932	7.32285	.000	36.1063	73.9723
	Beam	Column	-3.74037	8.59465	.972	-25.9616	18.4808

The findings from above tests of variance concluded that the difference in outcomes from the four panel types, 83% were statistically significantly different for both crane cycle times and productivity. As a consequence, the four panels types were required to be analysed separately.

6.4 Cross case analysis: Similarity of panel size categories

The next tests were to establish whether there was or was not a statistically significant difference in the eight-panel size categories for crane cycle time and productivity across the three case buildings as discussed in section 4.6.2c and shown in Figure 4.11.

Initial analyses found that panel size categories were found to be significantly different within the wall and floor panel types for each of the towers, which can be observed from the findings of the next test. Therefore, the sample sets of each panel category were tested for similarity across the towers, using ANOVA, to determine whether they could be combined across towers for baseline metrics.

6.4.1 Crane cycle time findings

The One-way ANOVA tests findings with cycle time are shown in Table 6.15 below with the Scheffe post hoc multiple comparison findings in Table 6.16.

Table 6.15 Crane cycle time One-way ANOVA test results

Tower	Panel type and size category	N	Mean mins: secs	St Dev. 'σ' mins: secs	Range mins: secs	F	P-value	η^2
A, B & C	Floor – Large	51	06:17	01:21	03:36–09:00	(2,50) 2.969	.371	.12
A, B & C	Floor – Medium	211	05:49	01:13	03:00–08:24	(2,208) 8.723	<0.001*	.0795
A, B & C	Floor – Small	104	05:38	01:18	03:00–07:48	(2,101) 5.675	.013*	0.1
A, B & C	Wall – Large	177	09:42	02:18	04:48–14:24	(2,174) 1.318	.266	0.016
A, B & C	Wall – Medium	126	08:56	02:23	03:36–13:48	(2,123) 2.241	.111	0.036
A, B & C	Wall – Small	96	09:04	02:31	04:12–14:24	(2,93) 0.785	.505	0.018
A, B & C	Beams	157	10:21	03:28	03:36–19:48	(2,154) 12.034	<0.001*	.1349
A, B & C	Columns	104	07:51	02:07	03:36–13:12	(2,101) 4.026	.037*	.0703

*Refer to Table 6.16 Crane cycle post hoc results

The ANOVA tests confirmed that three wall panel categories and the large floor panel were not statistically significantly different across the three towers (A, B and C) case studies ($p>0.05$). In three other categories, medium floor $F(2,208)=8.723$, $p<0.001$, small floor $F(92,101)=5.675$, $p=0.013$ and columns $F(2,101)=4.026$, $p=0.037$. although found to be statistically significantly different ($p<0.05$), η^2 was less than 0.10 in each of these three categories, so the difference was only of a small effect. Beams, however, were significantly different across the three towers, $F(2,154)=12.034$, $p<0.001$.

The post hoc crane cycle findings of the latter four categories are outlined in Table 6.16 below. From the post hoc test findings no significantly statistical difference was found in crane cycle times for three out of four panel categories tested among Towers A and B (small floor ($p=0.952$), beams ($p=0.939$) and columns ($p=0.377$, $p>0.05$)). There was a statistically significant difference in Tower C beam panel times compared to both Towers A and B ($p<0.05$).

Table 6.16 Crane cycle time post hoc multiple comparisons

Panel type	Tower	Mean (mins: secs)	Std Dev. 'σ' (mins: secs)	p-value	N
Floor – Medium	Tower B–Tower C	05:31	01:15	0.884	124
Floor – Medium	Tower A–Tower B	05:53	1:09	0.020	168
Floor – Small	Tower A–Tower B	05:52	01:03	0.952	75
Beams	Tower A–Tower B	11:04	03:25	0.939	118
Columns	Tower A–Tower B	07:25	01:59	0.377	71
Columns	Tower B–Tower C	08:10	02:03	0.226	79

For medium floor panel category, the post hoc tests found that there was no statistically significant difference between Towers B and C ($p=0.884$, $p>0.05$). However, there was a statistically significant difference found in this category across Towers A and B crane cycle findings ($p=0.020$), although the effect was weak, $\eta^2 = 0.0795$ ($\eta^2 < 0.1$). The crane cycle times between Towers A and B for seven out of the eight panel categories were found not significantly different, and in the eighth category, even though $p<0.5$, the effect was weak.

6.4.2 Productivity findings

The One-way ANOVA tests findings for productivity are tabulated in Table 6.17 below with the subsequent post hoc multiple comparison results in Table 6.18. The Null hypothesis ($p>0.05$), that there was no statically significant difference, was confirmed for six out of the eight panel categories across the three towers. These six panel types are large floor ($p=0.228$), large wall ($p=0.133$), medium wall ($p=0.074$), small wall ($p=0.139$), beams ($p=0.209$) and columns ($p=0.279$, $p>0.05$).

Table 6.17 ANOVA Productivity panel category findings for Towers A, B and C

Panel type and size category	N	Mean m^2/hr	St Dev. 'σ.' m^2/hr	Range m^2/hr	F	p-value (p>0.05)	η^2
Floor – Large	51	135.72	36.77	92.57–246.18	(2,48) 3.055	.228	.113
Floor – Medium	211	96.64	25.73	31.51–185.0	(2,208) 12.61	<0.001*	.108
Floor – Small	104	50.23	13.2	21.3–98.8	(2,101) 7.16	.013*	.124
Wall – Large	177	103.12	30.37	46.45–206.52	(2,174) 2.097	.133	.023
Wall – Medium	126	49.31	15.43	23.36–118.24	(2,123) 2.664	.074	.0415
Wall – Small	96	23.11	10.44	6.02–66.23	(2,93) 2.179	.139	.045
Beams	157	9.89	5.93	0.23–37.66	(2,154) 1.679	.209	.021
Columns	104	14.35	9.16	1.73–38.13	(2,101) 1.424	.279	.027

*Refer to Table 6.18 Productivity post hoc results

From the two categories found to be statistically different, medium floor panels were ($F(2,208)=12.61$, $p<0.001$) and small floor panels were ($F(2,101)=7.16$, $p=0.013$**)**. η2 was between 0.108 and 0.124, which indicated there was a medium effect. The findings of the post hoc tests on these two panels are tabulated in Table 6.18 below.

Table 6.18 Productivity post hoc multiple comparisons

Panel type	Tower	N	Mean m^2/hr	S Dev. 'σ.' m^2/hr	Productivity p-value (p>0.05)
Floor – Medium	Tower B – Tower C	124	104.31	26.6	0.538
Floor – Medium	Tower A – Tower B	168	94.28	23.32	0.001
Floor – Small	Tower A – Tower B	75	47.26	10.27	0.852

Across Towers A and B, the post hoc tests findings, Table 6.18, indicated that for productivity output, there was no statistically significant difference in small floor panels ($p=0.852$, $p>0.05$). However, there was a significant difference between Tower C and the other two towers ($p<0.05$).

The medium floor panel category's post hoc tests, also, found no significant difference across Towers B and C (p=0.538, p>0.05). However, across Towers A and B, there was a significant difference in results for the medium floor panel category (p=0.01, p>0.05). This finding corresponded to the crane cycle findings for the same (medium floor) panel category.

Determination

The ANOVA analysis for panel size categories' crane cycle times and productivity found that there was no statistically significant difference between Towers A and B except for medium floor panel category. There was, nevertheless, a significant difference from Tower C findings to that of both Towers A and B for most size categories.

As the above analysis, across Towers A and B, found only one, out of eight panel categories, that was statistically significantly different, a baseline table of rates was formulated using those seven categories. The medium size floor panel category was analysed separately for its baseline comparison. The number of floor levels, crew size and cranage captured on both Towers A and B was similar. The data from the both Tower A and B each consisted six-floor levels, i.e. same overall height, the installation was generally by a crew size of five workers using the tower crane, except for Tower B's Ground Floor and part of level one.

However, on Tower C the number of floor levels captured, frequency of mobile crane usage and the size of the installation crew size used was different from that of the other two buildings. Tower C's video capture consisted of three-floor levels with approximately 50% of the CLT installation by the mobile crane with an average installation crew of 2.5 workers and the remaining 50% by tower crane with a crew size of an average of five workers. Consequently, Tower C was separated from Towers A and B for the baseline analysis.

From the above similarity of panel type analyses findings, Towers A and B were selected as a representation to develop baseline rates, using the improved baseline model, for buildings up to six stories with a tower crane (input resource). It was resolved that Tower C be a representation to develop baseline rates for buildings up to three storey high, with input from both tower and mobile cranes for CLT installation baseline rates.

6.5 Baseline (multi-case) analysis for panel categories.

To establish the baseline rates for both productivity and crane cycle times of each panel size category Gulezian and Samelian's "Improved baseline model" was implemented. Crane cycle control charts, using each day's mean cycle time, were produced for each category (Gulezian et al., 2003a, b). Similarly, productivity control charts were generated for each panel type category using its daily mean productivity (m^2/hr). On the X-axis, the floor sample sets are represented by the respective date with the Tower ID, for example: Tower A on 7 July is described as A-7.09. The control line of each resulting charts represents the baseline value, being the average mean value, for each panel category.

The crane cycle time control charts for the six-storey buildings (Towers A and B) are first presented, followed by their productivity charts and their resulting baseline tables, in section 6.5.1. These are then followed, at section 6.5.2 by control charts and schedules for similar factors for Tower C, a representation of a three-storey building.

6.5.1 Towers A and B: 6-storey buildings

6.5.1.1 Crane cycle time baseline control charts

The crane cycle time control charts for each panel type category are presented below in Figures 6.16 to 6.24. The medium floor panel category, which was statistically significantly different across the three-tower cases, is analysed in separate individual control charts for the relevant tower building. The review of the outcomes of the 6-storey building charts are brought together in sections 6.5.1.c for crane cycle time and 6.5.1.d for productivity below.

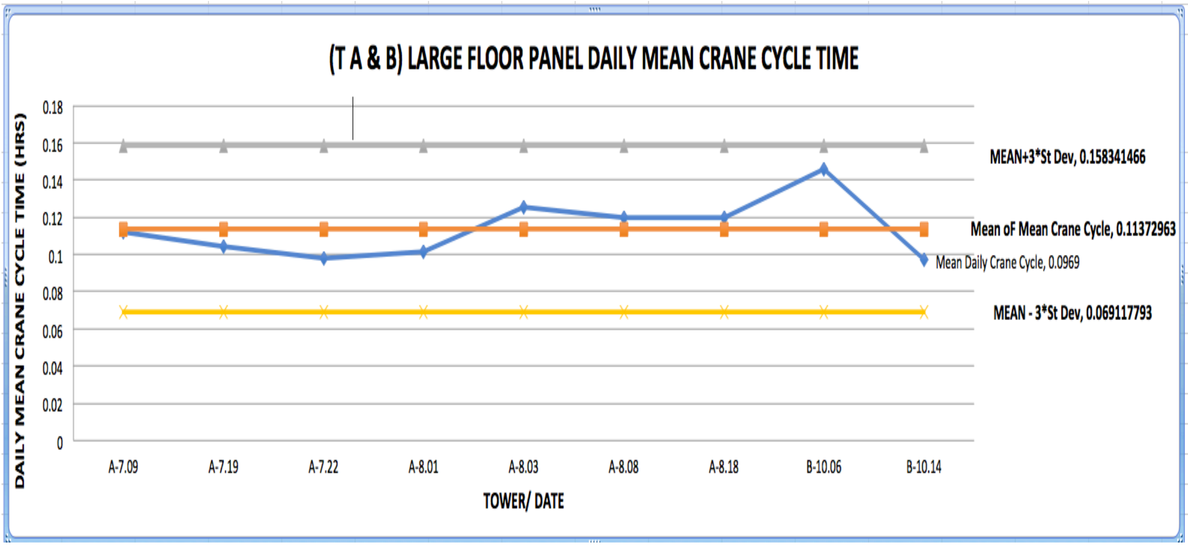


Figure 6.16 Towers A and B floor large panel crane cycle time baseline control chart

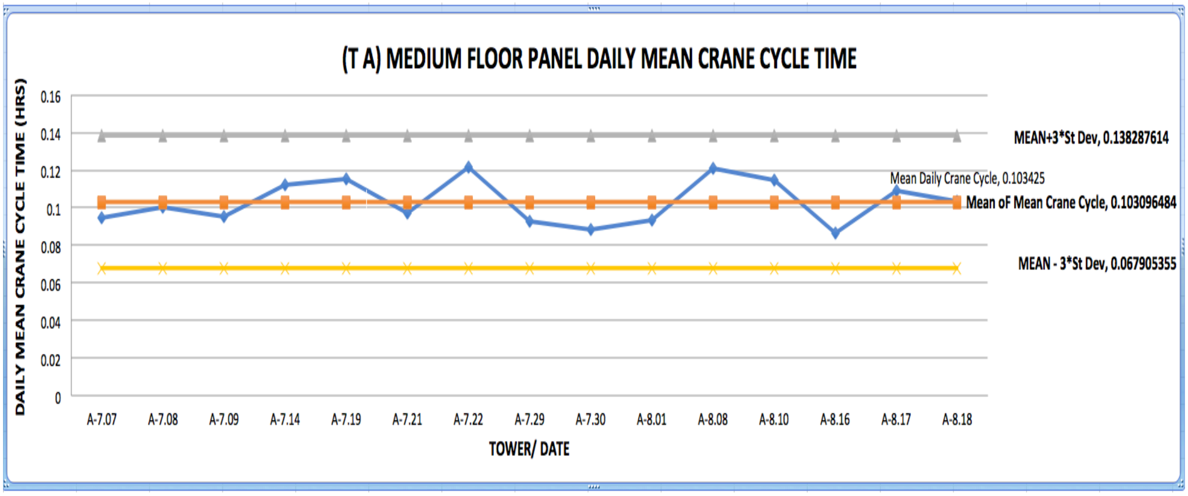


Figure 6.17 Tower A floor medium panel crane cycle time baseline control chart

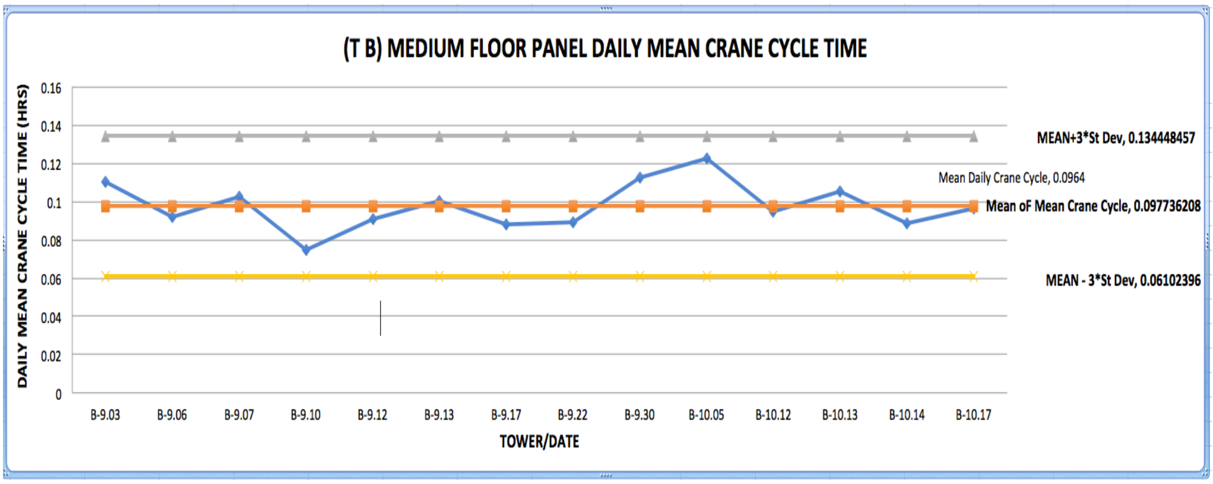


Figure 6.18 Tower B floor medium panel crane cycle time baseline control chart

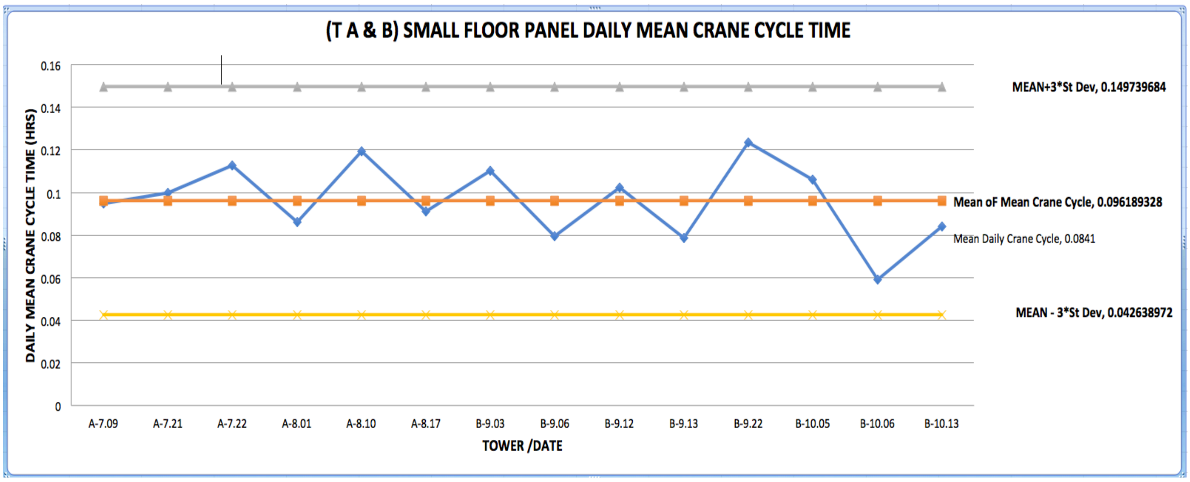


Figure 6.19 Towers A and B floor small panel crane cycle time baseline control chart

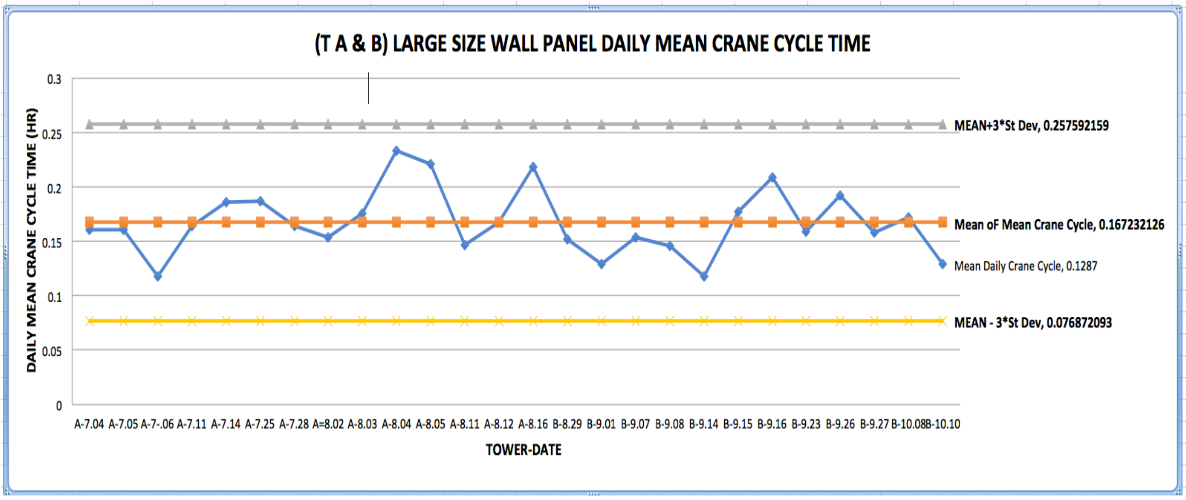


Figure 6.20 Towers A and B wall large panel crane cycle time baseline control chart

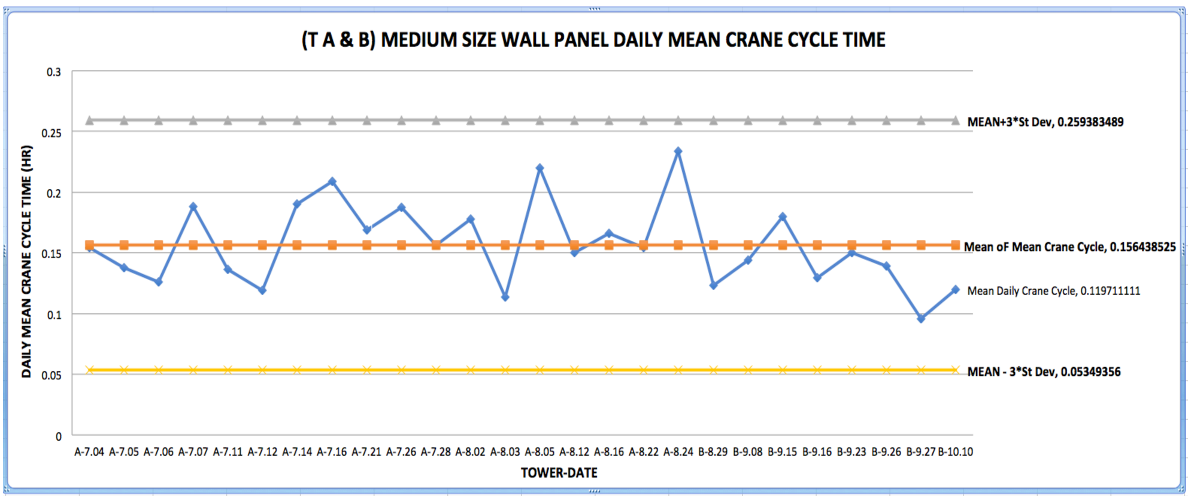


Figure 6.21 Towers A and B wall medium panel crane cycle time baseline control chart

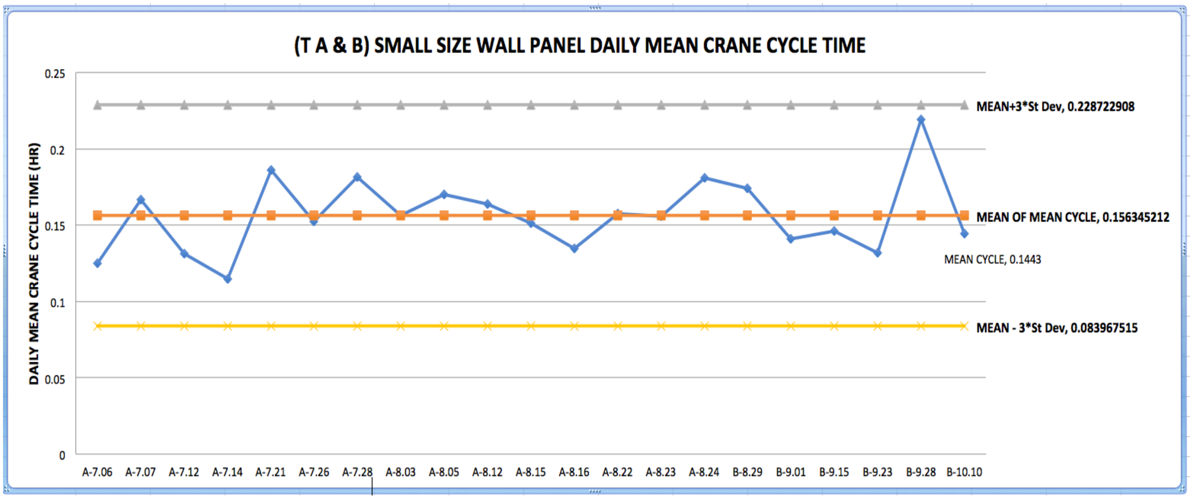


Figure 6.22 Towers A and B wall small panel crane cycle time baseline control chart

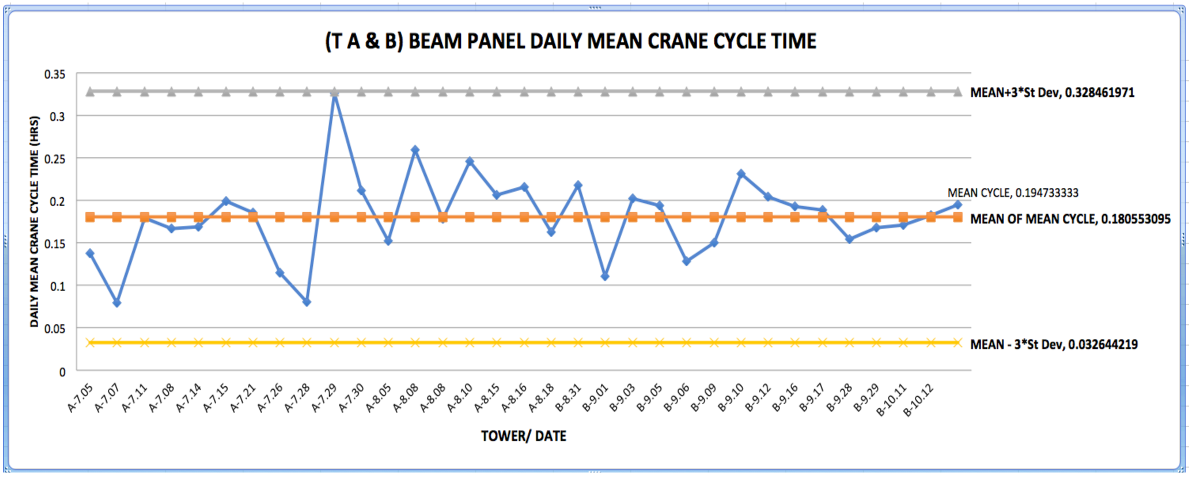


Figure 6.23 Towers A and B beam panel crane cycle time baseline control chart

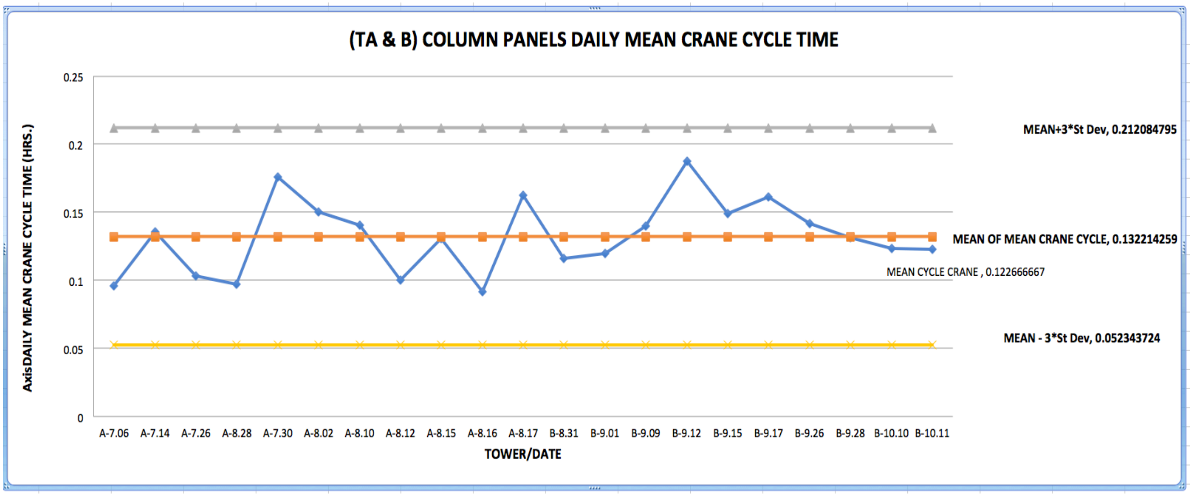


Figure 6.24 Towers A and B column panel crane cycle time baseline control chart

6.5.1.2 Productivity baseline control charts

The baseline productivity control charts for the panel size categories are illustrated in Figures 6.25 to 6.33. Similar to the crane cycle control charts the medium floor panel category is analysed for productivity in separate individual control charts for the relevant tower buildings. The review of the productivity outcomes of the 6-storey building charts are discussed in section 6.5.1.d below.

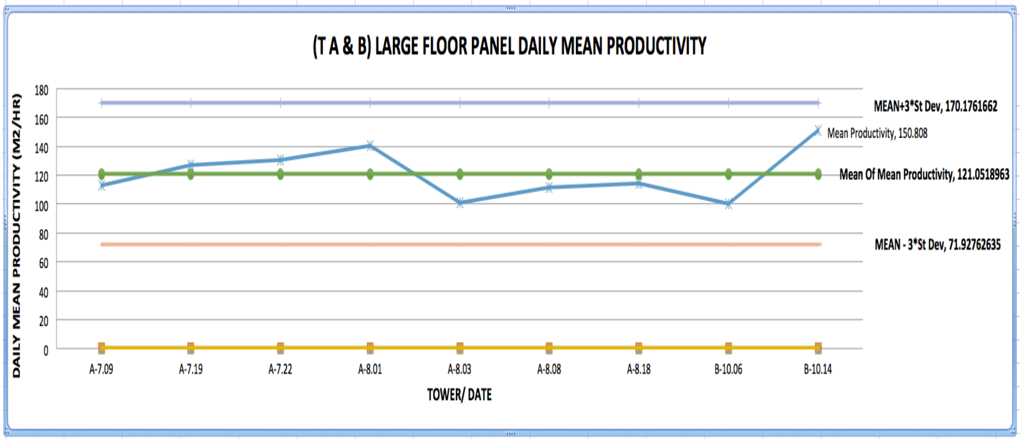


Figure 6.25 Towers A and B floor large panel productivity baseline control chart

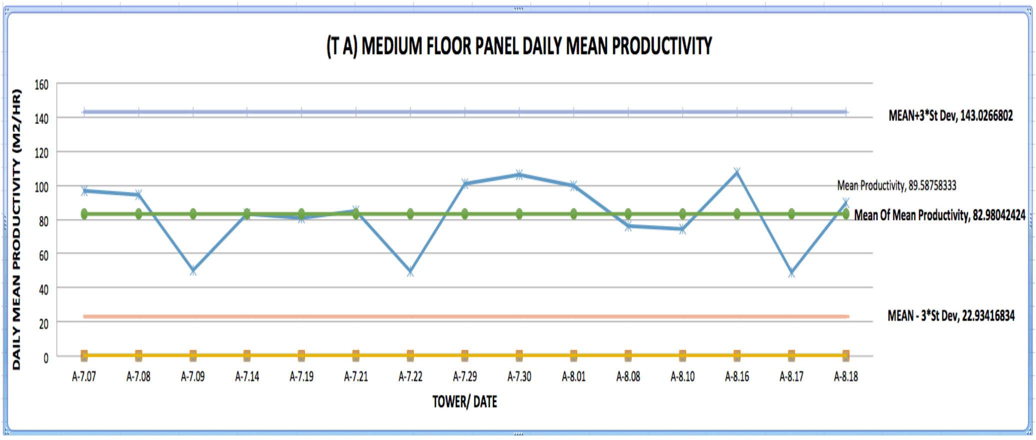


Figure 6.26 Tower A floor medium panel productivity baseline control chart

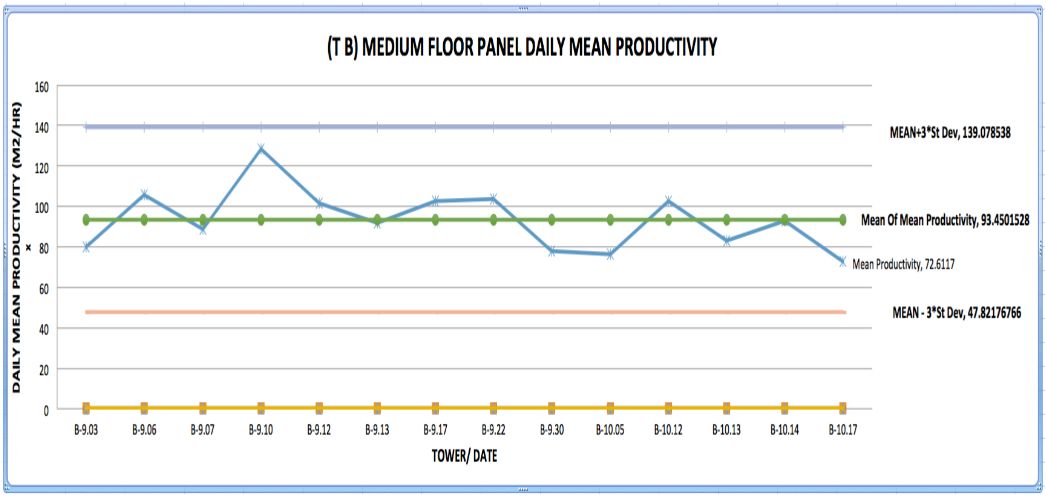


Figure 6.27 Tower B floor medium panel productivity baseline control chart

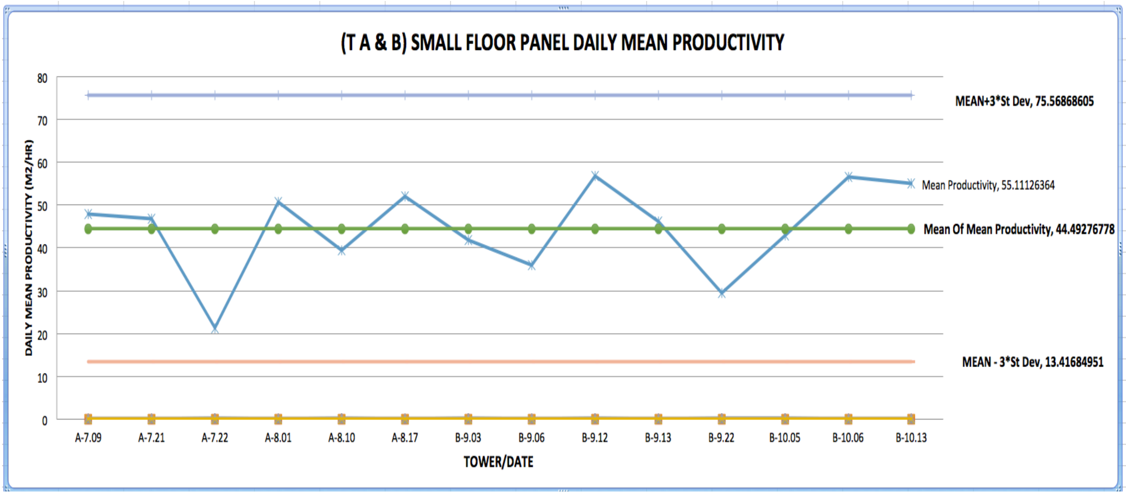


Figure 6.28 Towers A and B floor small panel productivity baseline control chart

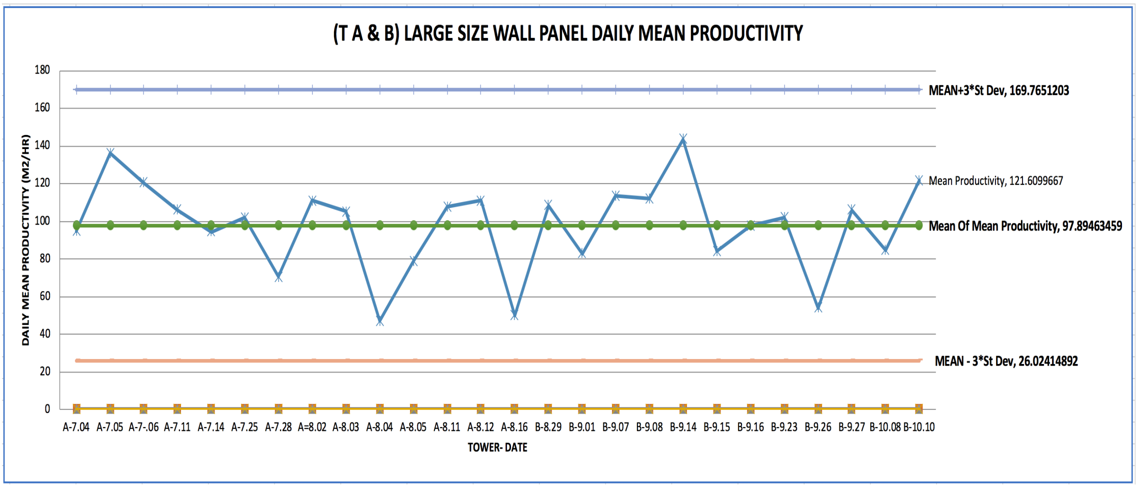


Figure 6.29 Towers A and B wall large panel productivity baseline control chart

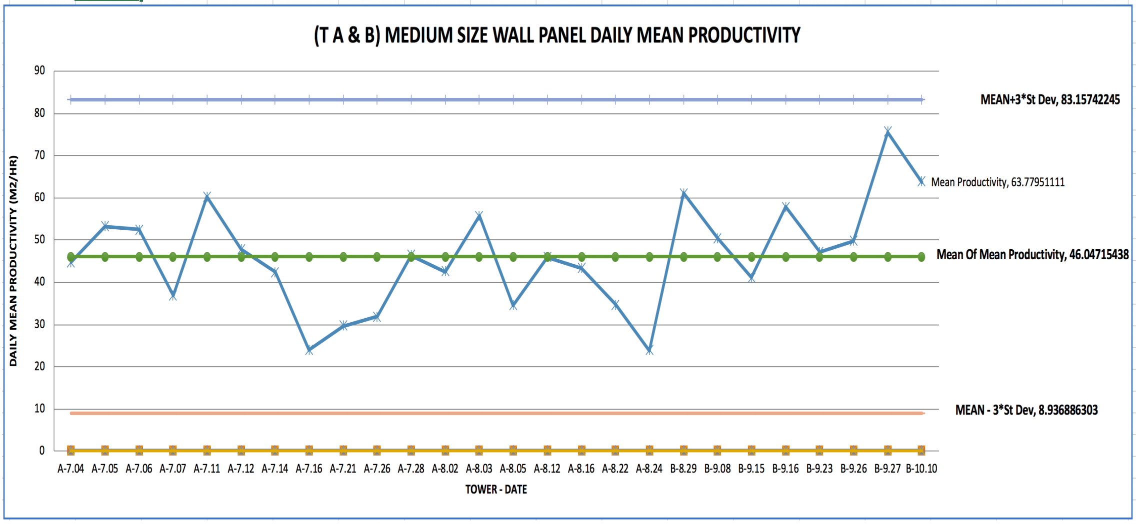


Figure 6.30 Towers A and B wall medium panel productivity baseline control chart

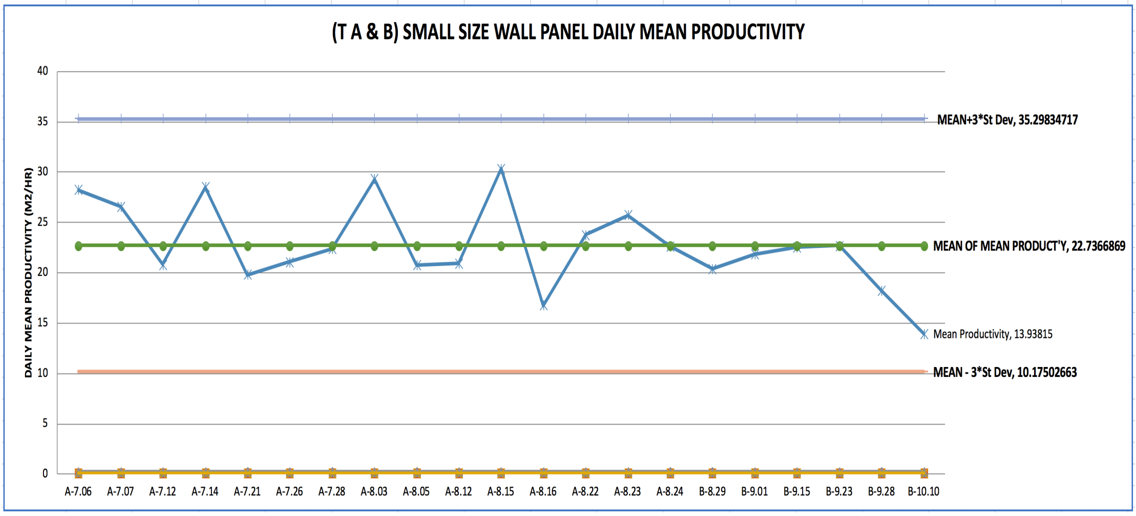


Figure 6.31 Towers A and B wall small panel productivity baseline control chart

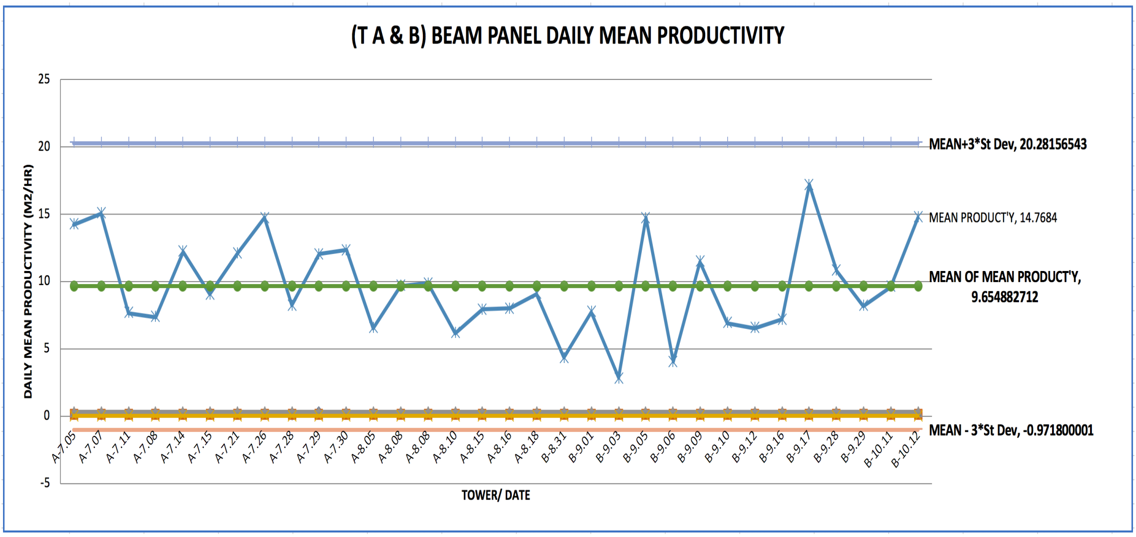


Figure 6.32 Towers A and B beam productivity baseline control chart

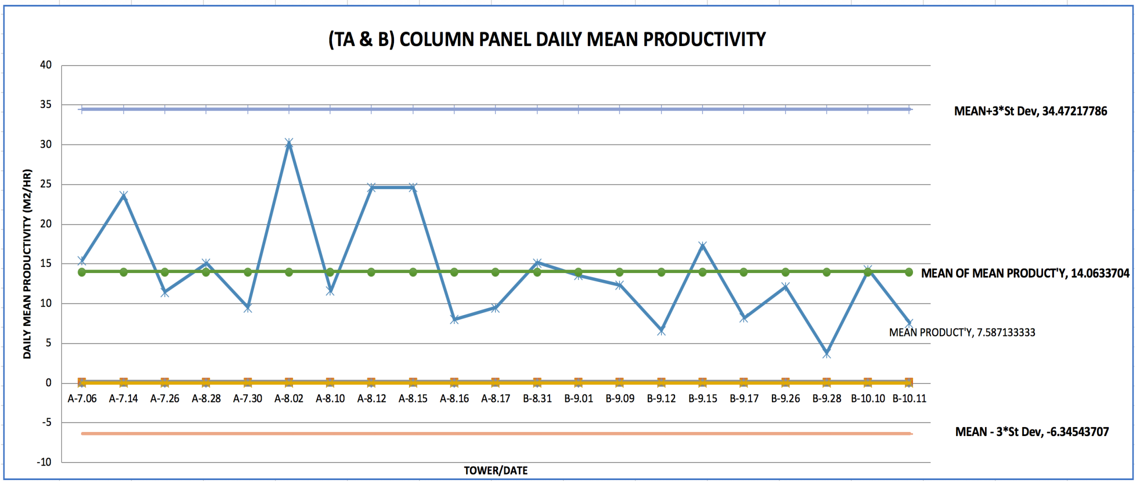


Figure 6.33 Towers A and B column panel productivity baseline control chart

All of the daily mean values within each panel category sample sets for both crane cycle time and productivity were within the upper and lower control limits in the above control charts. This determined that the CLT installation process had a consistent variation, in control and normally distributed across both Towers A and B. This finding provided confidence to use the above control charts' average daily mean findings for both crane cycle times and productivity as baseline installation rates for each CLT panel category (Gulezian et al., 2003b).

6.5.1.3 Review of Tower A & B crane cycle baseline findings

The baseline value for each CLT panel category was the centre line (CL) value in each control chart, which represented the average of the daily mean (M) crane cycle time, Figures 6.16-6.24. An "optimistic" expected crane cycle time, i.e., the shortest time, was determined as the mean minus 1 x standard deviation (M-1σ). The mean value plus one standard deviation (M+1 σ) represented the "pessimistic" crane cycle time, i.e., slowest time. The difference between these "optimistic" and "pessimistic" values was a range of 2 standard deviations, which provided a statistical range within which 68.26% of crane cycle times are located within a normal distribution (Guarnieri, 2015). The baseline cycle time together with the "pessimistic" and "optimistic" values from the control charts and the cycle time daily range recorded for each panel category, are provided in Table 6.19 below.

Table 6.19. 6-Storey building (Towers A & B) baseline crane cycle (input) matrix

CLT panel type (Towers A and B)	Pessimistic crane cycle time (mins: secs.)	Baseline crane cycle time (mean ave.) (mins: secs.)	Optimistic crane cycle time (mins: secs.)	Crane cycle time range (mins: secs.)
Floor (Large >10 m^2)	7:43	6:50	5:56	5:49-8:45
Floor (Small <5 m^2)	6:36	5:46	4:42	3:32-7:24
Wall (Large >10 m^2)	11:50	10:02	8:14	7:04-13:59
Wall (Medium <10>5 m^2)	11:27	9:23	7:19	5:45-14:02
Wall (Small <5 m^2)	10:50	9:23	7:56	6:53-13:09
Beam	13:47	10:50	7:53	4:48-19:33
Column	9:32	7:56	6:20	5:30-11:15
Note: Typically Crane type = Tower crane; Crane crew = 3 men; Install crew = 5 men.				

The baseline crane cycle time values, in Table 6.19 above, are the mean of the least affected time to install each respective CLT size category observed across the two-six storey building cases. For Towers A and B's medium floor panel category, which was found statistically significantly different in the previous analysis, the control chart results are tabulated in Table 6.20 below.

Table 6.20 Towers A and B medium floor panel cycle times

CLT panel type and tower	Pessimistic crane cycle time (mins: secs.)	Mean of average daily crane cycle time (mins: secs.)	Optimistic crane cycle time (mins: secs.)	Crane cycle range (mins.: secs.)
Tower A Floor (Medium <10>5 m^2)	6:53	6:11	5:29	5:11-7:17
Tower B Floor (Medium <10>5 m^2)	6:36	5:52	5:08	4:29-7:20

There was only a 19-second difference found in the mean of daily crane time between Towers A and a 17-second gap in "pessimistic" time and 21 seconds in "optimistic" time, which is likely to be insignificant in a practical scenario. Using a hypothetical project, which consisted of the installation of 1,000 medium size floor panels, this 19-second baseline difference would equate to an overall 5.27 hours extra. One could theoretically propose that the baseline time for medium size floor panels is the mean crane cycle time between the two, i.e., 6:01 minutes.

The baseline times, in Tables 6.19 and 6.20 above, are typically from the input resources of the tower crane with a crane crew consisting of three workers and an installation crew of five workers (one supervisor and four carpenters) for the six-storey buildings.

6.5.1.4 Review of Towers A & B productivity (m^2/hr) baseline findings

Baseline productivity rates were calculated for each panel category from their respective control charts, Figures 6.25 to 6.33 above, for both Towers A and B. In contrast to the crane cycle time values, the "optimistic" expected productivity (m^2/hr), i.e., the highest value expected, is represented as mean value plus 1 x standard deviation (M+ 1σ). The "pessimistic" predicted productivity (m^2/hr), i.e., the least expected, is mean value minus 1 x standard deviation (M-1σ). The baseline productivity values, together with the "optimistic" values, "pessimistic" values and recorded ranges for the seven panel categories are in Table 6.21 below.

Table 6.21- 6-Storey Building (Tower A & B) baseline productivity values matrix

CLT panel type (Towers A and B unless otherwise noted)	Pessimistic productivity output (m^2/hr.)	Baseline productivity output (mean ave.) (m^2/hr.)	Optimistic productivity output (m^2/hr.)	Productivity range (m^2/hr..)
Floor (Large ≥10 m^2)	104.68	121.05	137.42	100.25-150.08
Floor (Small <5 m^2)	34.13	44.49	54.85	21.33-56.83
Wall (Large ≥10 m^2)	73.94	97.89	121.85	46.89-143.60
Wall (Medium 5<10 m^2)	33.68	46.05	58.42	23.81-75.55
Wall (Small <5 m^2)	18.55	22.74	26.92	13.94-30.33
Beam	6.11	9.65	13.20	2.87-17.19
Column	7.25	14.06	20.87	3.81-30.27
Note: Typically Crane type = Tower crane, Crane crew = 3 workers, Install crew = 5 workers.				

The findings for the medium floor panel category from the respective control charts are tabulated in Table 6.22 below.

Table 6.22 Towers A and B medium floor panel productivity matrix

CLT panel type /tower	Pessimistic productivity output (m^2/hr.)	Mean of daily mean productivity output (mean ave.) (m^2/hr.)	Optimistic productivity output (m^2/hr.)	Productivity range (m^2/hr.)
Tower A Floor (Medium 5<10m^2)	62.96	82.98	103.00	48.90-107.67
Tower B Floor (Medium 5<10m^2)	78.24	93.45	108.66	71.61-128.38

Table 6.22 identified that the medium floor panel from the findings provided an average daily mean productivity value of 93.45 m^2/hr. for Tower B, compared to 82.98 m^2/hr. in Tower A. The average medium floor panel size partly explained this, as for Tower B it was 8.79 m^2 compared to 7.85 m^2 for Tower A. This panel size difference equates to a 10.47 m^2/hr. productivity improvement for Tower B.

The difference between "optimistic" and "pessimistic" values in the case of each panel category in Tables 6.19, 6.20, 6.21 and 6.22 was a range of 2 standard deviations.

The findings in Table 6.19 and 6.21 provide the productivity and crane cycle time baseline rates for each respective panel category, for a 6-storey CLT building under regular working operation with an installation crew of five typically using a tower crane.

6.5.2 Tower C: 3-storey building

6.5.2.1 Tower C: control charts of baseline cycle time

Tower C's control charts addressing the crane cycle times for the individual panel type categories are first illustrated in Figures 6.34 to 6.41 below. The findings from the charts below are brought together and reviewed in sections 6.5.2.c and 6.5.2d.

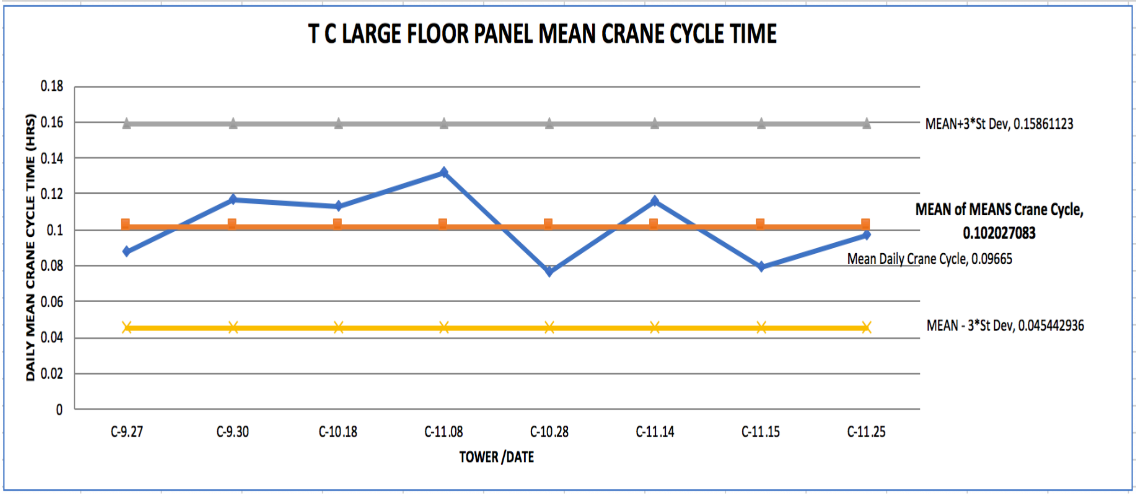


Figure 6.34 Tower C floor large panel: baseline crane cycle time control chart

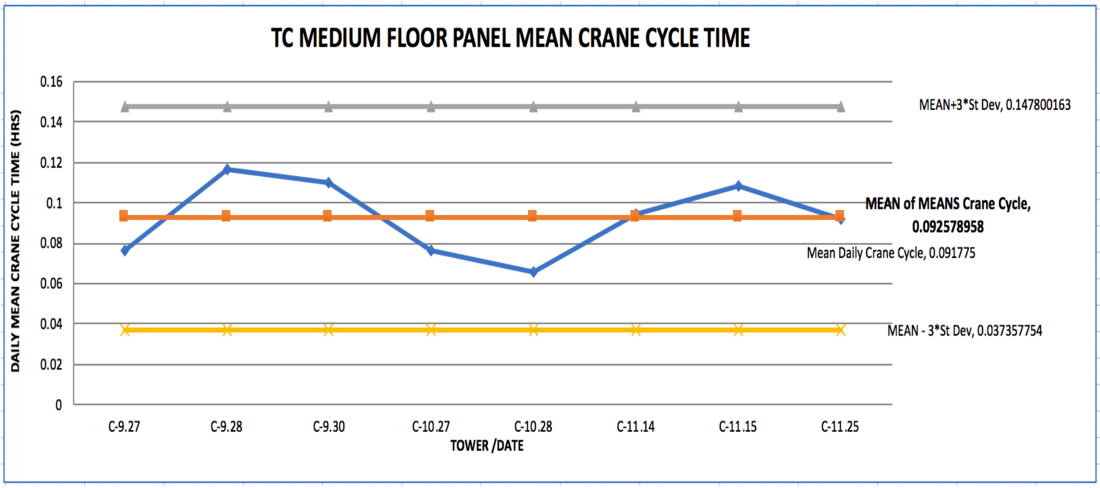


Figure 6.35 Tower C floor medium panel: baseline crane cycle time control chart

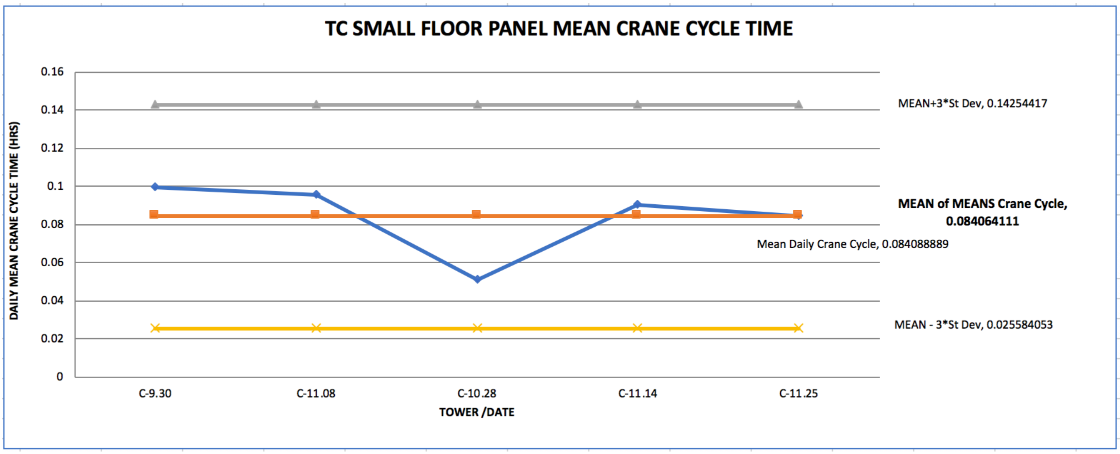


Figure 6.36 Tower C floor small panel: baseline crane cycle time control chart

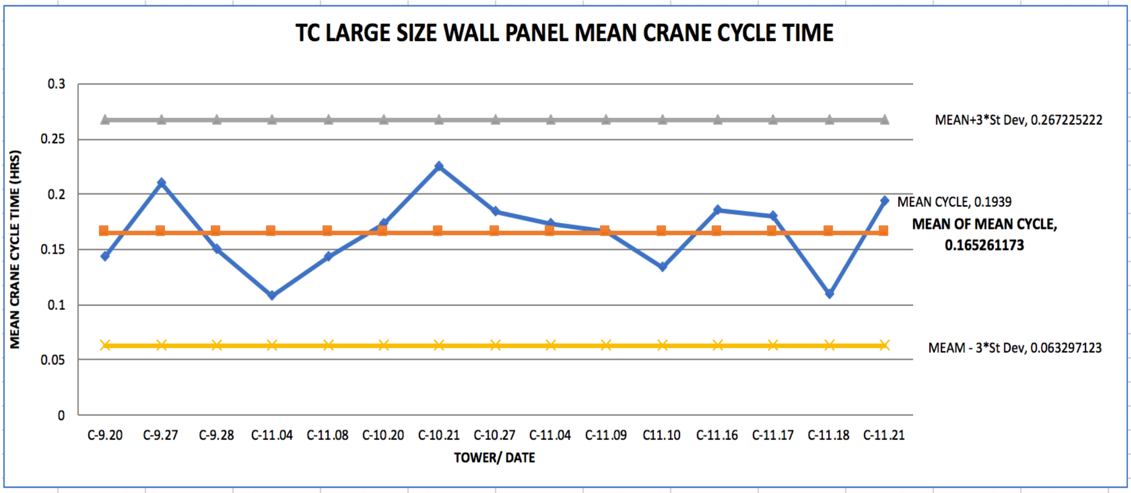


Figure 6.37 Tower C wall large panel: baseline crane cycle time control chart

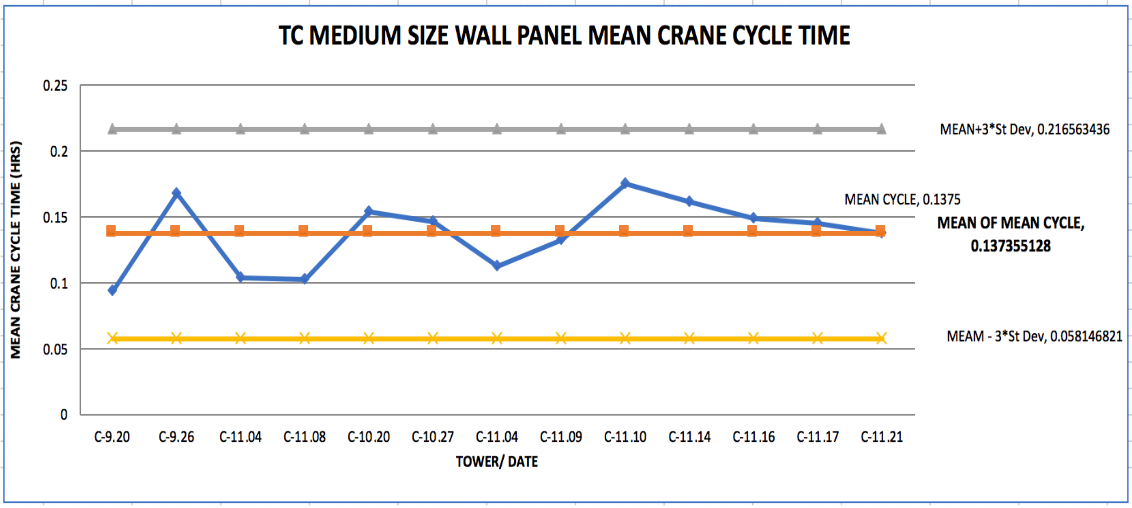


Figure 6.38 Tower C wall medium panel: baseline crane cycle time control chart

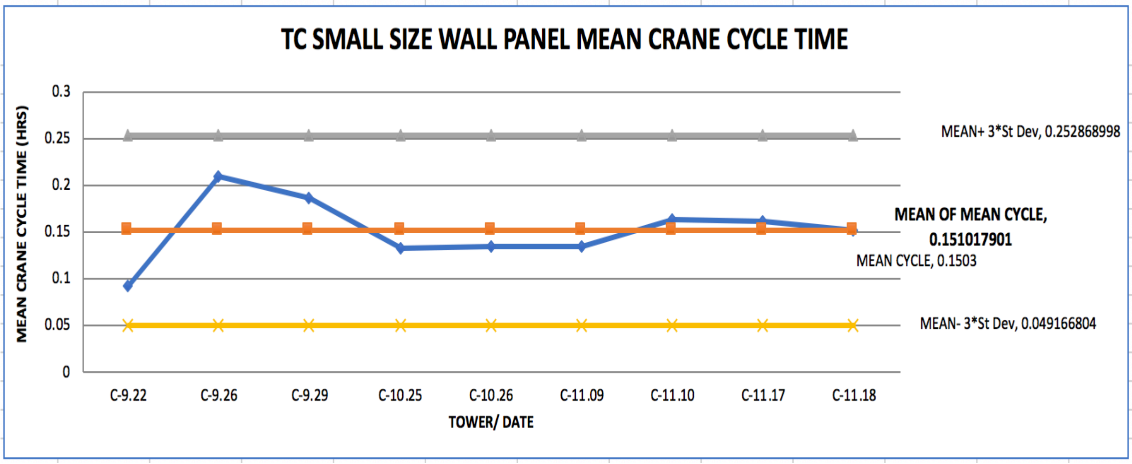


Figure 6.39 Tower C wall small panel: baseline crane cycle time control chart

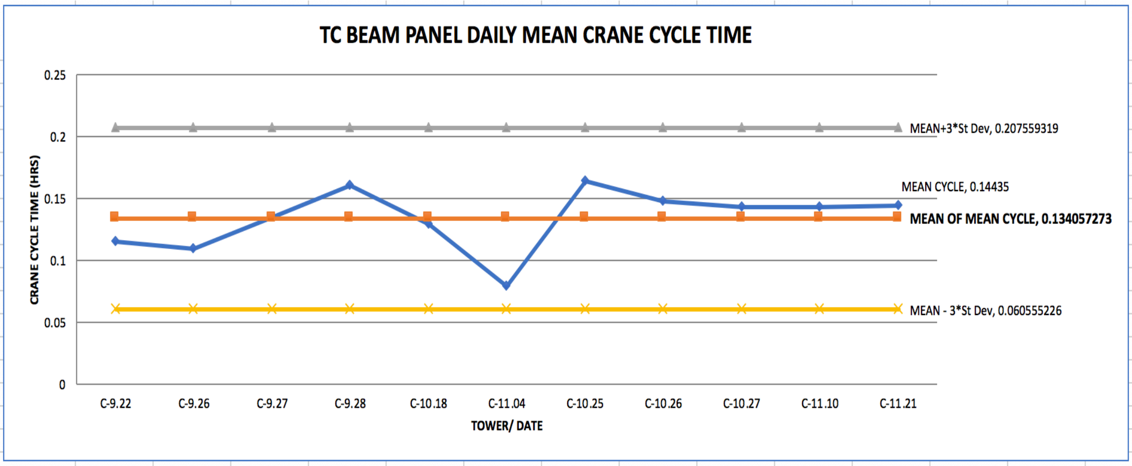


Figure 6.40 Tower C beam panel: baseline crane cycle time control chart

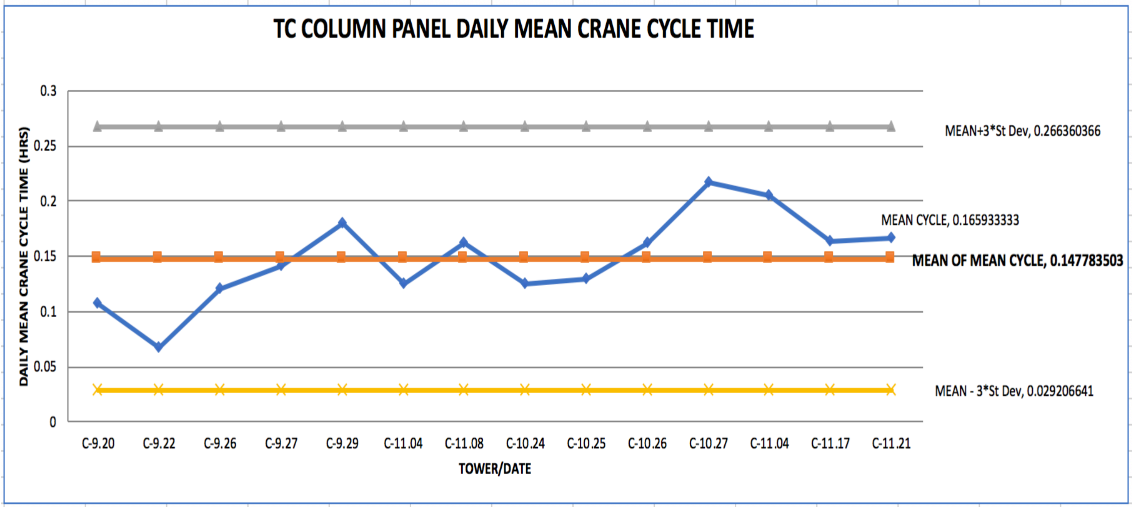


Figure 6.41 Tower C column panel: baseline crane cycle time control chart

6.5.2.2 Tower C productivity baseline control charts

Following control charts, illustrated below in Figures 6.42 to 6.49, are relating to productivity for each panel type category.

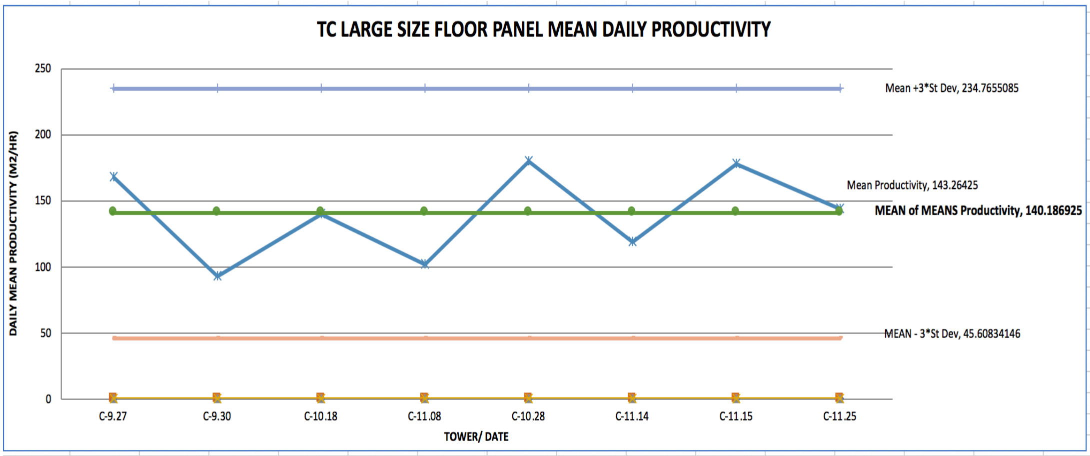


Figure 6.42 Tower C floor large panel productivity baseline control chart

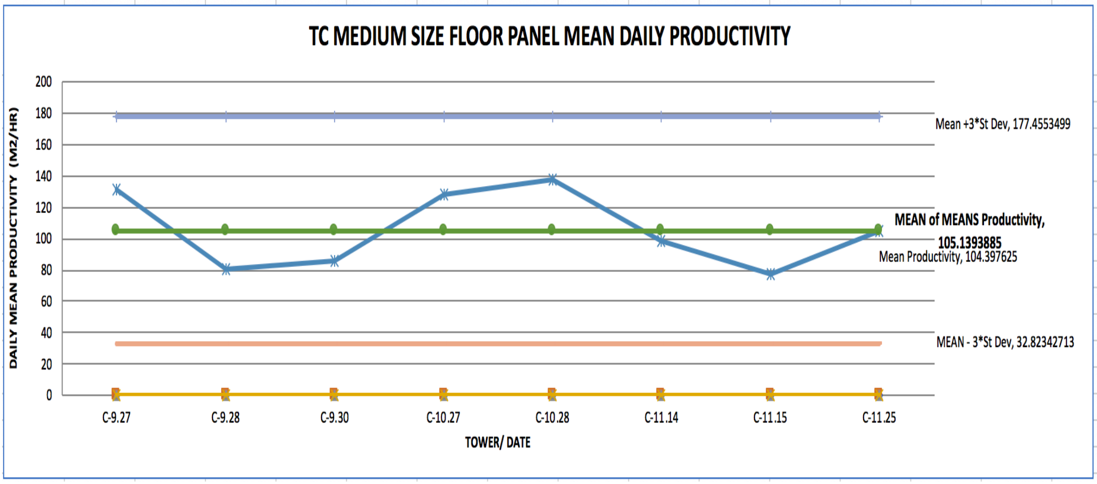


Figure 6.43 Tower C floor medium panel productivity baseline control chart

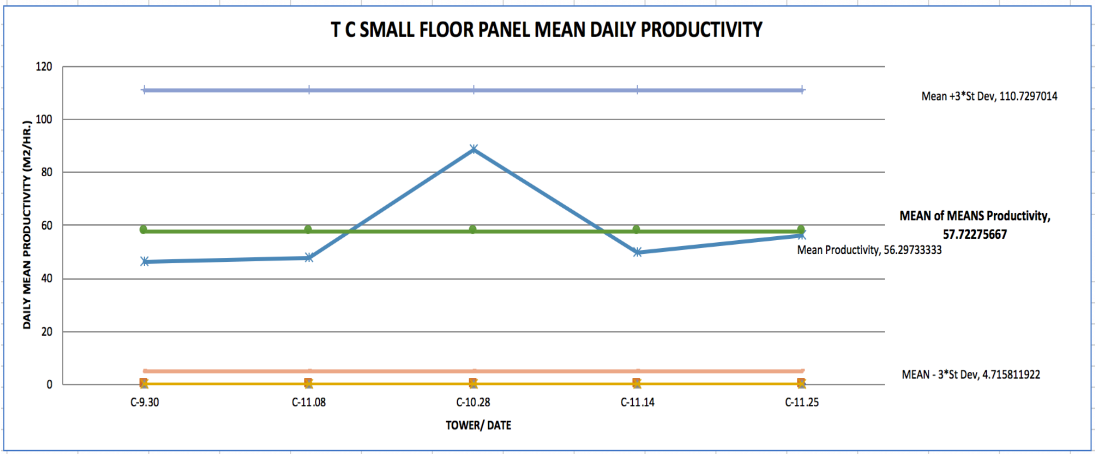


Figure 6.44 Tower C floor small panel productivity baseline control chart

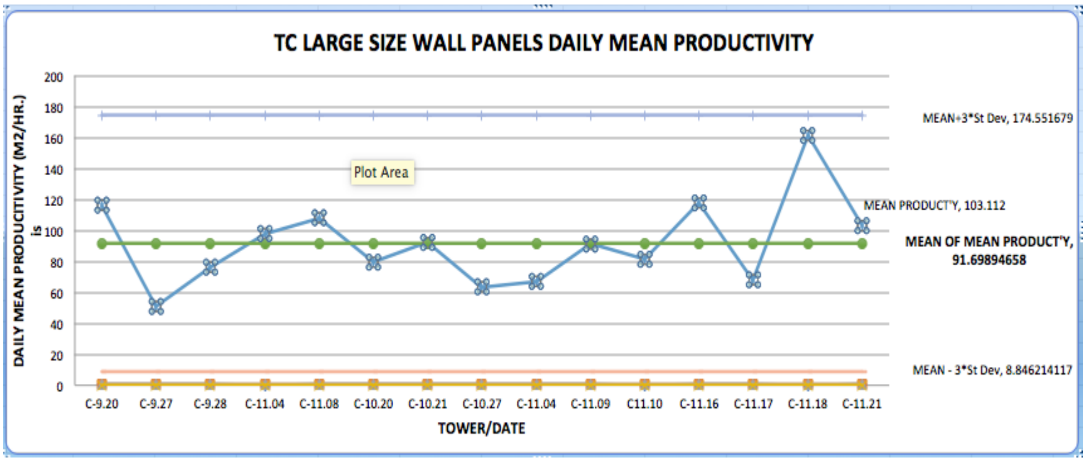


Figure 6.45 Tower C wall large panel productivity baseline control chart

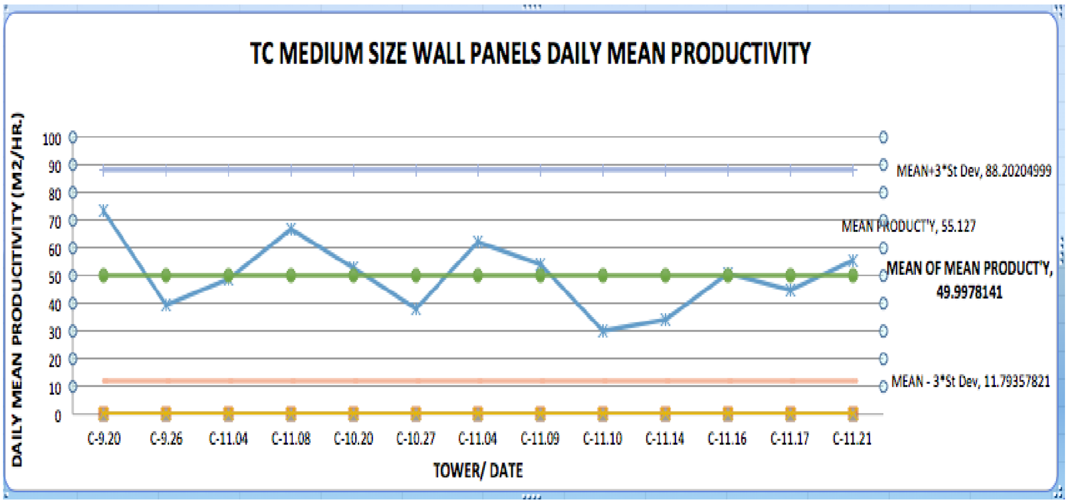


Figure 6.46 Tower C wall medium panel productivity baseline control chart

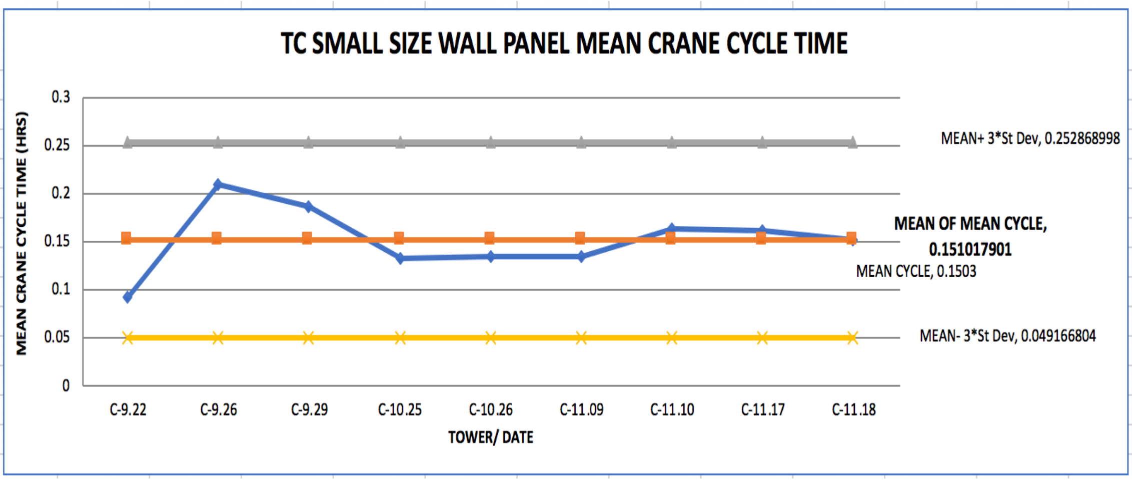


Figure 6.47 Tower C wall small panel productivity baseline control chart

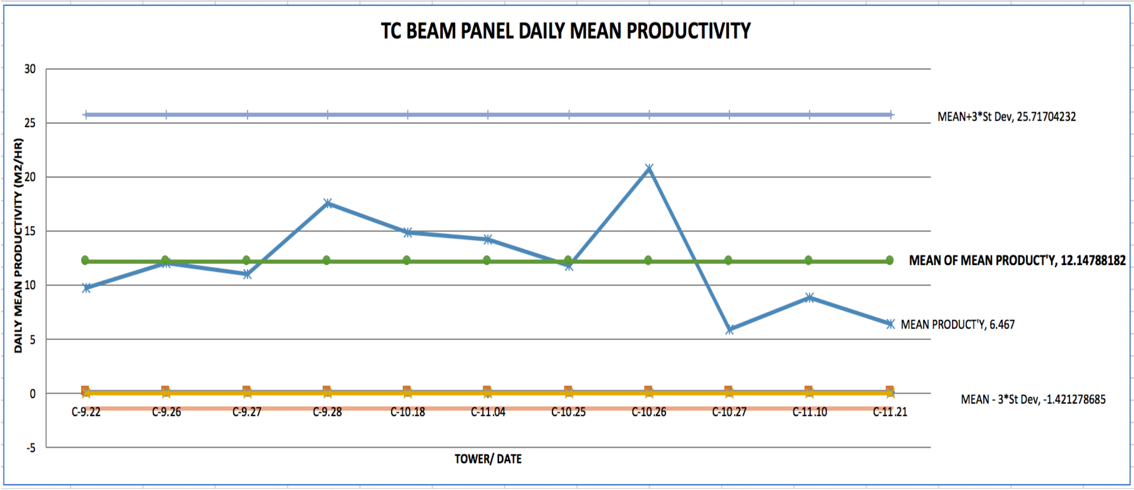


Figure 6.48 Tower C beam panel productivity baseline control chart

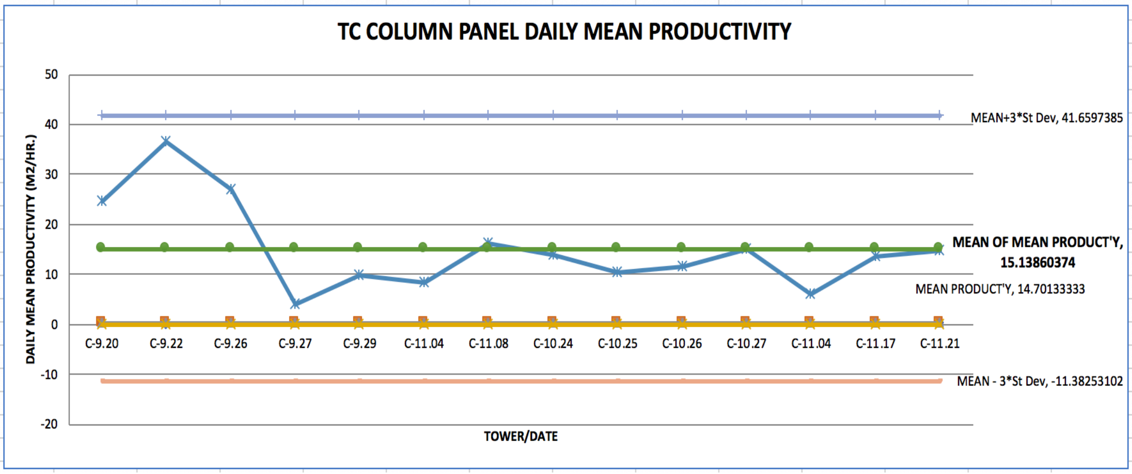


Figure 6.49 Tower C column panel productivity baseline control chart

Each of the daily mean values of both crane cycle time and productivity for all panel category sample sets, fell within the upper and lower control limits of each control chart. This, therefore, determined that the CLT installation process had consistent variation and normally distributed across the three levels of Tower C.

The mean of the daily averages in the baseline control charts, for both crane cycle times and productivity, were adopted for baseline rates of each CLT panel category for the 3-storey building (Gulezian et al., 2003b).

6.5.2.3 Review of baseline crane cycle findings

Using the same criteria as in the 6-storey baseline study, both "optimistic" and "pessimistic" expected crane cycle time, is represented by M-1σ and M+1σ respectively. These values, together with baseline crane cycle times and the range for each panel category from Figures 6.34-6.41, are provided in Table 6.23 below.

Table 6.23 Tower C baseline crane cycle time (input) matrix

CLT panel type	Pessimistic crane cycle time (mins: secs)	Baseline crane cycle time (mean ave) (mins: secs.)	Optimistic crane cycle time (mins: secs.)	Crane cycle range (mins: secs.)
Floor (Large ≥10 m^2)	7:15	6:07	4:59	4:34-7:54
Floor (Medium 5<10m^2)	6:40	5:33	4:27	3:56-7:00
Floor (Small <5 m^2)	6:13	5:03	3:52	3:03-5:59
Wall (Large ≥10 m^2)	11:57	9:55	7:53	6:30-13:30
Wall (Medium 5<10 m^2)	9:50	8:14	6:39	5:38-10:31
Wall (Small <5 m^2)	11:06	9:04	7:01	5:31-12:30
Beam	9:31	8:03	6:34	4:47-9:53
Column	11:14	8:52	6:30	4:00-13:00

The above baseline crane cycle times in Table 6.23 are from the mean of the cycle times, least impacted by assignable causes, to install each respective panel size category for the observed 3-storey installation on Tower C. Table 6.23 is the determination of findings for the crane cycle time baseline analyses of Tower C.

6.5.2.4 Review of productivity (m^2/hr) baseline analysis findings

Baseline productivity measurements were calculated for each panel category from their respective control charts, Figures 6.42 to 6.49 above. Similar to Towers A & B productivity baseline table, M+ 1σ represents the "optimistic" expected and M-1σ the "pessimistic" expected values (m^2/hr). These values, plus the baseline productivity and the measured range for the individual panel categories, are provided in Table 6.24 below. The baseline productivity values tabulated in Table 6.24 provides a resource to compare average productivity outputs for similar 3-storey buildings.

Table 6.24 Tower C baseline productivity values matrix

CLT panel type	Pessimistic productivity output (m^2/hr.)	Baseline productivity output (mean ave) (m^2/hr.)	Optimistic productivity output (m^2/hr.)	Productivity range (m^2/hr.)
Floor (Large >10 m^2)	108.66	140.19	171.71	92.57-179.75
Level (Medium 5<10 m^2)	81.03	105.14	129.24	76.89-137.35
Level (Small <5 m^2)	40.05	57.72	75.39	46.45-88.58
Wall (Large ≥10 m^2)	64.08	91.70	119.32	50.93-161.35
Wall (Medium 5<10 m^2)	37.26	50.00	62.73	30.01-73.2
Wall (Small <5 m^2)	14.53	23.12	31.70	9.48-36.97
Beam	7.62	12.15	16.67	5.91-20.72
Column	6.30	15.14	23.98	4.09-36.6

The findings in Table 6.23 and 6.24 provide the crane cycle time and productivity baseline rates for each respective panel category, for a 3-storey CLT building under regular working operation with an installation crew of 2.5 workers typically using a mobile crane.

6.6 Conclusion

This chapter discussed the study's findings of the three cases from a micro activity review of analysis. The micro activity level review first determined that the data for each of the three-tower buildings were statistically significantly different. This established that the research analyses needed to consider three separate case studies, i.e., a multi-case study. From analyses, normality and baseline control charts, productivity and crane cycle time baseline rates were determined for each of the eight-panel categories. It was determined to segregate the baseline rates for mid-rise, 6-storey, buildings, using Towers A and B, and a 3-storey, low rise, building from Tower C.

It was established, from the findings from the above analyses, that the above 6-storey and 3-storey baseline crane cycle times and the productivity values, in Tables 6.19, 6.21, 6.23 and 6.24 above were able to be developed. These rates could be replicated under normal operating conditions on similar buildings to that of these case studies. For conciseness, the baseline productivity and crane cycle time values for both the mid and low-rise building types from the above tables are compiled into one matrix, Table 6.25 below.

Table 6.25- 6 and 3 storey baseline productivity and crane cycle values matrixes

6 Storey (Mid Rise) Buildings- CLT structure with tower crane				
CLT panel category	**Baseline Crane Cycle time (mins: secs.)**	**Crane cycle (Optim/Pess'c) range (mins: secs.)**	**Baseline Productivity (m^2/hr.)**	**Productivity (Pess/Optm'c) range (m^2/hr..)**
Floor (Large >10 m^2)	6:50	5:56-7:43	121.05	104.68-137.42
Floor (Medium 5<10 m^2)[17]	6.01	5.08-6.53	88.21	62.96-93.45
Floor (Small <5 m^2)	5:46	4:42-6:36	44.49	34.13-54.85
Wall (Large ≥10 m^2)	10:02	8:14-11:50	97.89	73.94-121.85
Wall (Medium 5<10 m^2)	9:23	7:19-11:27	46.05	33.68-58.42
Wall (Small <5 m^2)	9:23	7:56-10:50	22.74	18.55-26.92
Beam (Small <5 m^2)	10:50	7:53-13:47	9.65	6.11-13.12
Column (Small <5 m^2)	7:56	6:20-9:32	14.06	7.25-20.87
3 Storey (Low rise) Building- CLT structure with mobile and tower crane				
CLT panel category	**Baseline crane Cycle time (mins: secs.)**	**Crane cycle (Optim/Pess'c) range (mins: secs.)**	**Baseline Productivity (m^2/hr.)**	**Productivity (Pess/Optm'c) range (m^2/hr.)**
Floor (Large >10 m^2)	6:07	4:59–7:15	140.19	108.66-171.71
Floor (Medium 5<10 m^2)	5:33	4:27–6:40	105.14	81.03-129.24
Floor (Small <5 m^2)	5:03	3:52–6:13	57.72	40.05-75.39
Wall (Large ≥10 m^2)	9:55	7:53–11:57	91.70	64.08-119.32
Wall (Medium 5<10 m^2)	8:14	6:39–9:50	50.00	37.26-62.73
Wall (Small <5 m^2)	9:04	7:01-11:56	23.12	14.53-31.70
Beam (Small <5 m^2)	8:03	6:34–9:31	12.15	7.62-16.67
Column (Small <5 m^2)	8:52	6:30–11:14	15.14	6.30-23.98

[17] Not a true baseline calculation but compilation from Tables 6.20 and 6.22

Within the above matrix, Table 6.25, the productivity and crane cycle “optimistic” and “pessimistic” time ranges were included for each panel baseline value. The values in the matrix are subject to the sizes of panels designed and installed in these case study buildings. The baseline rates are based on the adoption of the nominated CLT panel categories with similar crane equipment input resource to that employed.

Comparison of findings between the three levels of analysis provided clarity that a high-level project review does not consider or focus on all relevant critical factors, e.g., the quantum of non-value-added activities and delays. It does not provide a detailed assessment of the actual outcome compared to that from an activity level, micro perspective. However, the difference highlights the necessity to change or re-engineer the traditional on-site construction process to a more production process approach, a focus on flow, to compliment industrialised building systems. This approach would reduce waste from non-value-added time and activities, such as observed in this study, which would improve the overall production at a project level. This point is discussed in more detail in Chapter 8.

It was concluded that from the above findings the main research question was confirmed in the affirmative.

Chapter 7 Results and findings (Part 3): Propositions #1-5 analysis

This chapter provides an account of the findings of the five propositions determined from the literature review and establishes whether their assumptions could be verified. The chapter commences with proposition #1 and continues in sequence to conclude with an account of proposition #5.

7.1. Proposition #1 – the crane is the primary construction input resource

Proposition #1 proposed that equipment, i.e., the crane in this study, is the primary on-site productivity input resource for the installation of mass timber systems and not the traditional selection of labour.

To test this proposition Tower C was selected for analysis, as it was the most suitable tower to test this proposition because half of the first three floor levels were constructed by an installation crew of five workers and the remainder by a team of two to three.

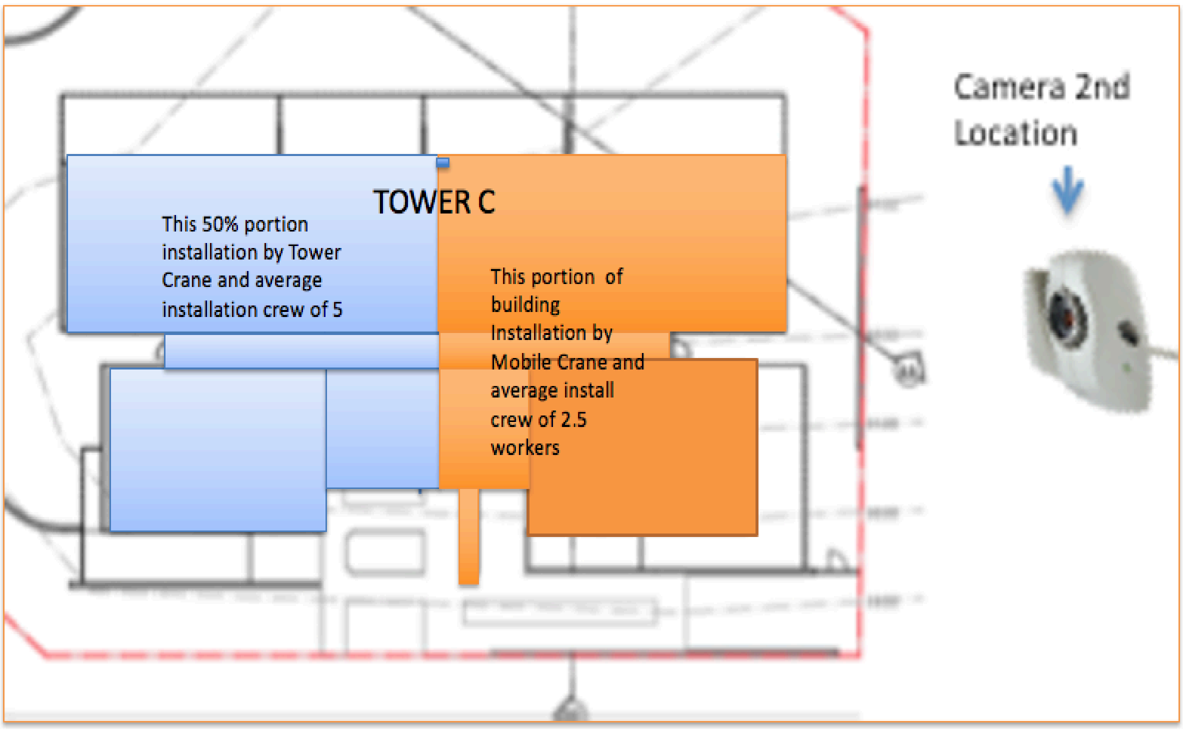


Figure 7.1 Plan of Tower C illustrating two methods of installation

The site plan of Tower, C in Figure 7.1 above, illustrates the northern half shaded in an orange colour and the southern half shaded in blue. For the lower floor levels of the structure's northern half (orange), a crew varying between two and three carpenters installed the CLT using a mobile crane with its two riggers. The remaining southern half of the lower structure (blue) was installed with the full crew of five carpenters using the tower crane with its two riggers. Each of the southern and northern sections, for comparison, contained all four panel types as tabulated in Table 7.1 below.

Table 7.1 Panel installation sample sets of the three crew sizes

Tower C Panel type	South half: Number of panels installed by 2 men crew	South half: Number of panels installed by 3 men crew	North half: Number of panels installed by 5 men crew	Total panel crane cycles
Floor	15	28	56	99
Wall	28	14	55	97
Beam	15	6	18	39
Column	8	15	10	33
Total	**66**	**63**	**139**	**268**

To ascertain whether labour was a significant factor in the productivity outcome, it had to be determined whether there was a significant difference in productivity with an increased labour force compared to a reduced one, i.e., a smaller input number of worker hours. If labour was a significant factor, then productivity should improve with an increase in the quantity of labour.

7.1.1. Test 1 Significance of labour size

To test the Null hypothesis, that there was no significant difference (p>0.05) in crane cycle times or productivity with increased labour, the four types of panels installed by 2-men and 3-men crew (northern half) were compared to the southern half with a 5-men team, using One-way ANOVA. Each of the panel type sample-sets tested was previously determined normally distributed data sets, Tables 6.3, 6.5, 6.7 and 6.9. The sample sets, Table 7.1 above, were tested using the One-way ANOVA tests with Scheffe's post hoc tests. The ANOVA test findings are outlined in Table 7.2 below, for the different crew sizes (independent variable) to the dependent variables of both crane cycle times and productivity output.

Table 7.2 ANOVA test results for variance in the three crew size outputs

Crew size study	N	Mean	St Dev.	F	p-value	η^2
Crane cycle	268	7:38 mins	2:40	(2,265) 2.012	0.181	.015
Productivity	268	66.66 m^2/hr	51	(2,265) 1.010	0.407	.007

From the analyses, Table 7.2 above, it was determined that there was no statistically significant difference in crane cycle times or productivity values for increasing crew sizes for Tower C case. The findings of crane cycle times were $F=(2,365)$ 2.012, $p=0.181$ ($p>0.05$) and productivity output F (2,265) 1.10, $p=0.407$ ($p>0.05$). For both factors $\eta^2 > 0.015$, which indicated that crew size had a weak (1.5% and 0.7%) variance effect. The F value was close to 1 for productivity, and crane cycle was almost 2. Both of which indicate that the variation among the groups was small.

These findings supported the Null hypothesis that there was no statistically significant difference in crane cycle times or productivity rates by an increase in labour for CLT installation.

7.1.2. Test 2 Regression analyses on crew size

To investigate this proposition further, a secondary analysis, using linear regression analyses, tested if crew size affected crane cycle time or productivity. The findings are tabulated in Table 7.3 below.

Table 7.3 Regression analysis findings crane cycle times to crew size

Regression test: Independent/ Dependent Variable	Sig.	r^2	Unstandardised coefficient	Beta	F
Crew size/ crane cycle	.221	.006	0.003	.075	1.50
Crew size/ productivity	.475	.002	1.719	.044	.512

In the case of crane cycle time p=0.221 (p>0.05), Table 7.3, which indicated that there was no statistically significant difference in crane cycle time for different crew sizes. The crew size coefficient was 0.003, which is insignificant and r^2=0.006, which determined that crew size was not a good fit for the model. The results were similar for productivity, as crane cycle time, with p=0.475 (p>0.05), unstandardised coefficient=1.719 and r^2=0.002.

These regression findings supported the Null hypothesis, H_o, that a difference in crew size does not have any significant effect on productivity or the crane cycle time. This was the first step in the determination of the proposition that labour was not the primary input factor in the on-site productivity outcome.

7.1.3. Test 3 Different crane type significance to cycle time

As the mobile crane was used primarily on the northern half and the tower crane used on Tower C's southern half, it could be argued that the differing equipment, i.e. crane type, affected the outcome. To test this possibility, the two cranes were analysed for variance using t-test. For this analysis, the crane type was the independent factor with the dependent factors of crane cycle time. The Null hypothesis was that there was no significant difference between the two crane type's cycle times across the three levels of Tower C's CLT installation (p>0.05). The findings from the analysis are outlined in Table 7.4 below.

Table 7.4 Crane cycle t-test results for the tower and mobile cranes variance

Crane type study (crane cycle)	N	Mean mins: secs. (hrs)	St Dev. mins: secs. (hrs)	F	p-value
Mobile crane	128	7:19 (0.1220)	2:44 (0.04553)	(2,266) 0.34	0.854
Tower crane	140	7:54 (0.1317)	2:34 (0.04287)		

The findings for the crane cycle times are indicated in Table 7.4 with p=0.854 (p>0.05) and F value=(2,266) 0.34. The p-value shows a strong similarity of crane cycle times between the two crane types and the F critical value indicates that the variances between the two populations were small.

The results supported the Null hypothesis that there was no statistically significant difference in crane cycle time between the tower crane and the mobile crane.

7.1.4. Test 4 Different crane type significance to productivity

To test this further, the significance and effect of the two crane types on both crane cycle time and productivity was tested by linear regression analysis. For this test all panel types across both the southern and northern portions were utilised. The predictor was crane type first tested with crane cycle time as the dependent variable then secondly tested with productivity. The findings are tabulated in Table 7.5 below.

Table 7.5 Linear regression test crane type to a) crane cycle and b) productivity

Crane type to crane cycle	**N**	**Mean**	**Pearson r**	**Sig.**	**F**	**Unstandardised coefficient B**	**Beta**
Crane cycle	268	.1271	.11	.073	3.237	0.01	.11
Crane type	268	1.52					
Crane type to productivity	**N**	**Mean**	**Pearson r**	**Sig.**	**F**	**Unstandardised coefficient B**	Beta
Productivity	268	66.79	.055	.374	.794	5.56	.055
Crane type	268	1.52					

The regression analyses findings, Table 7.5, determined that different crane type did not have any linear correlation to either crane cycle time or productivity. For crane cycle time, p=0.073 (p>0.05). The unstandardised coefficient was almost zero (0.01), indicating that there was no significant increase in time between the two crane types. Beta was also close to zero (0.11), which determined that cycle time would not significantly increase by varying the crane type.

For productivity, p=0.394 (p>0.05), which indicated there was no significant difference in productivity between the two cranes and the unstandardised coefficient for productivity was small (5.56). This meant that there was only a very slight increase in productivity between the two crane types with Beta again close to zero (0.055). The two regression analysis results determined that there was not a significantly statistical difference in crane time nor productivity between the use of either mobile or tower crane. Therefore, the crane type did not have any bearing on the determination of findings for the lead resource.

7.1.5 Test 5, Linear relationship: crew size and crane type

Finally, correlation and regression analyses determined whether there was a linear relationship or correlation between Tower C's crane cycle time of both crane types and crew sizes. The findings from the correlation analyses are shown in Table 7.6 below. Each of the three correlation analyses found p>0.05 and all Pearson's R-values were close to zero. This indicated there was no linear correlation between the variables of cycle times and the installation crew size.

Table 7.6 Pearson r and 95% correlation test results for crane types

Tower crane analysis	**N**	**Mean**	**St Dev.**	**Pearson's coefficient**	**p-value (2-tailed)**
Crew size	140	4.9	0.253	-.127	.134
Crane cycle time mins: secs	140	7:54	2:34		
Mobile crane analysis	**N**	**Mean**	**St Dev.**	**Pearson's coefficient**	**p-value (2-tailed)**
Crew size	128	2.49	0.5	-.091	.305
Crane cycle time mins: secs	128	7:19	2:44		
Both cranes combined analysis	**N**	**Mean**	**St Dev.**	**Pearson's coefficient**	**p-value (2-tailed)**
Crew size	268	3.79	1.30	.075	.221
Crane cycle time mins: secs	268	7:38	2:40		

Contrary to expectation, the mean cycle time was slightly faster with a smaller installation crew, i.e., 7:38 minutes, as opposed to 7:54 minutes with a larger team. This alludes to the premise that larger crews may reduce efficiency.

7.1.6 Test 6 Multivariate regression analysis: crane and crew cycle time

A multivariate regression analysis was conducted on the crane cycle time and the installation crew cycle time (independent variables) to ascertain if either had a significant effect on productivity (dependent variable) for the full three levels of Tower C and the findings are summarised in tables 7.7 and 7.8 below.

Table 7.7 Multivariate regression analysis: crane time, crew time to productivity

Factor	**N**	**Mean time (hrs)**	**St Dev**	**Pearson Correl.**	**R^2**	**F**	**Sig.**
Crane Cycle time		0.127	.044	-.347			
Crew time		0.486	.250	-.188			
Total	268		9.40	1.00	.128	(2,265)19.422	0.000

The overall regression findings, shown in Table 7.7 above, were significant: F(2,265)=19.422; p<0.001 (p<0.05); R^2=0.128. As p<0.01, the combination of the predictors, crane cycle time and crew time, were found to be significant in the productivity output. The combined predictors accounted for 12.8% of the variance (R^2=0.128) in the total productivity output. The residual statistical analysis showed there were no outliers or any undue influence on the result: mean Mahalanobis Distance= 1.993 (MD<13.82), mean Cook's Distance=0.004 (CD<1.00)(Glen, 2020).

Table 7.8 Crane and crew cycle time multivariate regression coefficient analysis

Model	**Unstandardised coefficients**		**Standardised coefficients**			**Collinearity statistics**	
	B	Std. Error	Beta	t	Sig	Tolerance	VIF
(Constant)	118.17	8.89		13.293	.000		
Crane cycle time	-499.23	94.15	-.434	-5.303	.000	.491	2.036
Crew time	24.79	16.67	.122	1.487	.138	.491	2.036

From the regression findings in Table 7.8 above, it was found that the crane time (p=0.000 (p<0.05)) had a statistically significant effect on productivity. Whereas crew time did not have a significant effect on productivity, p-value=0.138 (p>0.05).

The collinearity statistics showed that there was no multicollinearity within the predictors, with collinearity tolerance=0.491 (CT>0.1) and VIF=2.036 (VIF<10) (University of California et al., 2019). The Beta values of -0.434 for crane time and 0.122 for crew time determined that the crane had the more substantial effect and accounted for 43.4% of the variance in total productivity (University of California et al., 2019).

7.1.7 Conclusion

From the above findings, there was sufficient statistical evidence to conclude that the crane time was the statistically significant predictor for the productivity outcome, not the crew time, in installing mass timber panels. Increasing or changing crew sizes did not achieve any statistically significant difference in either crane cycle times or on-site productivity. Neither did the selection of either a mobile or tower crane type have any statistically significant effect on this finding. Although labour was a necessary input resource for mass timber, on-site productivity was not significantly affected by varying the quantity of labour engaged. Consequently, it was found that labour was not a linear significant input resource for CLT on-site productivity.

There were only two input resources for CLT installation: labour and equipment. Labour, although required, was found not to be significant. Therefore, the crane was found to be the significant leading and primary input resource for on-site installation of mass timber panels. The above statistical analysis tests supported proposition #1.

7.2. Proposition #2 – productivity is similar by floor level

Proposition #2 proposed that a differential in floor level height above ground will not cause significant variance in productivity rates. For conventional construction it is noted that there has been significant reduction in productivity as height increases. To test this proposition different panel types, i.e., walls, floors, beams and columns, were analysed separately from the six-storey towers A and B. Tower

C was excluded from this analysis because it did not provide a suitable range in height, as there were only three-floor levels of panel installation captured.

For the two towers, the crane cycle time and productivity for each of the four panel type sample sets were separately tested for variance using One-way ANOVA with Welch and Brown–Forsythe tests. The different floor levels were selected as the independent factor, and dependent factors were the crane cycle time and the productivity for the various panel types.

7.2.1 Crane cycle analysis

The first Null hypothesis, H_o, tested was that crane cycle times were similar for higher floors compared to lower levels. The results of the ANOVA tests for crane cycle times are outlined in Table 7.9 below, for the four different panel types for each tower. Five of the eight cases the crane cycle times were found not significantly different and supported the H_o.

Table 7.9 ANOVA test results for the variance of crane cycle time to floor level

Tower case study	Panel type	N	Ave. Mean mins: secs.	Ave. St Dev. mins: secs.	F	p-value	η^2
Tower A	Floor	141	6:13	1:05	(4,136) 10.676	0.001*	.239
Tower B	Floor	125	5:40	1:09	(4,120) 4.227	0.002*	.13
Tower A	Wall	189	9:33	2:25	(5,183) 3.128	.011*	0.079
Tower B	Wall	117	8:57	2:26	(4,112) 1.492	.268	.052
Tower A	Beam	62	11:15	3:37	(4,57) 1.262	.298	.081
Tower B	Beam	57	10:58	3:14	(4,52) 0.550	.650	.043
Tower A	Column	24	7:00	2:10	(3,20) 1.028	.307	.133
Tower B	Column	46	7:46	1:52	(4,41) 2.21	.133	.186

For crane cycle times the three cases where p<0.05, Table 7.9 above, post hoc multiple comparison tests were carried out. These three cases consisted of:

- Tower A floor panels with p=0.001 (p>0.05), F-value (4,136) 10.676,
- Tower B floor panels with p=0.002 (p>0.05), F-value (4,120) 4.227 and
- Tower A wall panels with p-value=0.011(p>0.05), F-value (5,183) 3.128.

The post hoc test findings for each of these panel types are in Table 7.8 below.

The post hoc tests, tabulated in Table 7.10 below, found that for Tower A, the mean crane cycle time for floor panel installation at Level 4 was significantly different to the other floors, it was slower. The test found significant difference between Ground Floor and Level 4: p-value=0.001(p>0.05), between Level 1 and Level 4: p-value=0.009 (p>0.05), between Level 2 and Level 4: p-value<0.001 and between Level 4 and Level 5: p-value=0.002 (p>0.05). For Tower B, the only comparison that was significantly different was for floor panels between levels 2 and 4, p-value=0.009 (p>0.05).

In both towers, level 4's mean crane cycle time was considerably longer than other floor levels. Tower A's level 4 =7:14 mins, compared to the mean of 6:08 mins. for its remaining levels and Tower B's level 4 =6:36 mins compared to an average of 5:33 mins. for the remaining levels.

Table 7.10 Crane cycle multi comparison Scheffe's post hoc test

Panel type/ Tower	Floor level	Mean (mins: secs.)	p-value	N
Floor – Tower A	Lv 1–Lv 2	5:57–6:14	.916	46
	Lv 1–Lv 3	5:57–5:42	.918	59
	Lv 1–Lv 4	5:57–7:14	0.001*	48
	Lv 1–Lv 5	5:57–6:10	.961	51
	Lv 2–Lv 3	6:14–5:42	.335	63
	Lv 2–Lv 4	6:14–7:14	.009*	52
	Lv 2–Lv 5	6:14–6:10	1.00	55
	Lv 3–Lv 4	5:42–7:41	<0.001*	65
	Lv 3–Lv 5	5:42–6:10	.415	68
	Lv 4–Lv 5	7:14–6:10	.002*	57
Floor – Tower B	Lv 1–Lv2	5:57–5:12	.178	56
	Lv 1–Lv 3	5:57–5:33	.841	43
	Lv 1–Lv 4	5:57–6:26	.733	43
	Lv 1–Lv 5	5:57–5:30	.668	58
	Lv 2–Lv 3	5:12–5:33	.891	49
	Lv 2–Lv 4	5:12–6:26	.009*	49
	Lv 2–Lv 5	5:12–5:30	.879	64
	Lv 3–Lv 4	5:33–6:26	.217	36
	Lv 3–Lv 5	5:33–5:30	1.00	51
	Lv 4–Lv 5	6:26–5:30	.086	51
Wall – Tower A	GF–Lv 1	8:13–9:24	.337	64
	GF–Lv 2	8:13–10:17	.006*	65
	GF–Lv 3	8:13–10:09	.020*	61
	GF–Lv 4	8:13–9:36	.204	61
	GF–Lv 5	8:13–9:38	.145	66
	Lv 1–Lv 2	9:24–10:17	.648	65
	Lv 1–Lv 3	9:24–10:09	.817	61
	Lv 1–Lv 4	9:24–9:36	1.00	61
	Lv 1–Lv 5	9:24–9:38	.999	66
	Lv 2–Lv 3	10:17–10:09	1.00	62
	Lv 2–Lv 4	10:17–9:36	.855	62
	Lv 2–Lv 5	10:17–9:38	.863	66
	Lv 3–Lv 4	10:09–9:36	.948	58
	Lv 3–Lv 5	10:09–9:38	.954	63
	Lv 4–Lv 5	9:36–9:38	1.00	63

Note: * identifies post hoc crane cycle p-value<0.05

Tower A's wall panel comparison between Ground Floor and Level 2: p-value= 0.006 (p>0.05) and Ground Floor to Level 3 p-value=0.020 (p>0.05) were significantly different.

However, the three-panel types where crane cycle time was significantly different, the post hoc test found that the subsequent higher floor Level 5 returned to similar crane input time as the lower floors. In the three cases, either Level 4 or isolated ground floor cycle times were an anomaly, not the highest floor level. Therefore, the test found that there was no significant difference in crane cycle time between the lowest and the highest floor levels in all eight cases.

7.2.2 Productivity analysis

The second Null hypothesis to be tested was that productivity was similar across all floor levels. The results of the ANOVA tests are outlined in Table 7.11 below for the four different CLT panel types.

Table 7.11 ANOVA test results for the variance of productivity (m^2/hr) to floor level

Tower case study	Panel type	N	Ave. Mean productivity (m^2/hr.)	Ave. St Dev. (m^2/hr.)	F	p	η^2
Tower A	Floor	141	83.2	31.18	(4,136) 3.928	0.006*	.103
Tower B	Floor	125	83.68	33.45	(4,120) 4.34	0.001*	.126
Tower A	Wall	189	61.75	41.24	(5,183) 9.755	0.001*	.21
Tower B	Wall	117	71.71	40.59	(4,112) 0.561	.642	.019
Tower A	Beam	61	10.32	5.51	(4,56) 1.67	.205	.107
Tower B	Beam	57	8.78	5.63	(4,52) 0.747	.491	.054
Tower A	Column	24	16.42	10.04	(3,20) 0.65	.659	.089
Tower B	Column	46	12.9	8.86	(4,41) .234	.896	.022

As illustrated in Tables 7.9 and 7.11, the ANOVA findings supported the Null hypothesis in five out of eight tests. The three cases which were found to be significantly different were the same for both crane cycle and productivity. i.e., Tower A floor and wall panels and Tower B floor panels. Productivity post hoc tests were carried out on the three cases where panel types $p<0.05$, in Table 7.12 below. Tower A's floor panels had p-value=0.006 ($p>0.05$), F-value (4,136) 3.928, Tower B's floor panel had p-value=0.001 ($p>0.05$) F value (4,120) 4.34 and Tower A's wall panel had $p<0.001$ ($p>0.05$), F value (5,183) 9.755.

The productivity post hoc tests, Table 7.12 below, found that, for Tower A, only the floor panel comparison between Levels 4 and 3 was statistically significantly different (p-value=0.013 ($p>0.05$)) with the productivity at Level 4 reduced. Level 5, however, was not significantly different from level 1 (p=0.772).

Table 7.12 Productivity multi comparison Scheffe's post hoc test

Panel type/ Tower	Floor level	Mean difference (m^2/hr.)	p-value	N
Floor panel Tower A	Lv 1–Lv 2	-1.40	1.00	46
	Lv 1–Lv 3	-18.88	.257	59
	Lv 1–Lv 4	8.43	.919	48
	Lv 1–Lv 5	-11.44	.772	51
	Lv 2–Lv 3	-17.48	.279	63
	Lv 2–Lv 4	9.83	.844	52
	Lv 2–Lv 5	-10.04	.820	55
	Lv 3–Lv 4	27.31	.013*	65
	Lv 3–Lv 5	7.44	.904	68
	Lv 4–Lv 5	-19.87	.188	57
Floor panel Tower B	Lv 1–Lv 2	-12.20	.728	56
	Lv 1–Lv 3	-14.20	.720	43
	Lv 1–Lv 4	23.25	.238	43
	Lv 1–Lv 5	-4.01	.993	58
	Lv 2–Lv 3	-1.99	1.00	49
	Lv 2–Lv 4	35.45	.009*	49
	Lv 2–Lv 5	8.10	.903	64
	Lv 3–Lv 4	37.45	.017*	36
	Lv 3–Lv 5	10.10	.881	51
	Lv 4–Lv 5	-27.35	.078	51
Wall panel Tower A	GF–Lv 1	14.52	.784	64
	GF–Lv 2	28.03	.105	65
	GF–Lv 3	19.07	.549	61
	GF–Lv 4	17.07	.667	61
	GF–Lv 5	59.71	<.001*	66
	Lv 1–Lv 2	13.52	.827	65
	Lv 1–Lv 3	4.56	.999	61
	Lv 1–Lv 4	2.55	1.00	61
	Lv 1–Lv 5	44.19	<.001	66
	Lv 2–Lv 3	-8.95	.970	62
	Lv 2–Lv 4	-10.96	.930	62
	Lv 2–Lv 5	31.68	.036*	66
	Lv 3–Lv 4	-2.00	1.00	58
	Lv 3–Lv 5	40.64	.003*	63
	Lv 4–Lv 5	42.64	.001*	63

Note: * indicates post hoc floor level comparison p-value<0.05

In the case of Tower B, the post hoc test found that comparisons for floor panel between Levels 2 and 4 (p-value=0.019 ($p>0.05$)) and between Levels 3 and 4 (p-value=0.017 ($p>0.05$)) were statistically significantly different. Again, the higher level 5 was not significantly different to level 1 (p-value=0.993)

The post hoc multiple comparison findings determined that in the case of floor panels, the performance on Level 4 was an anomaly. This anomaly is clearly illustrated from the means plot of Tower B floor panel productivity in Figure 7.2 below.

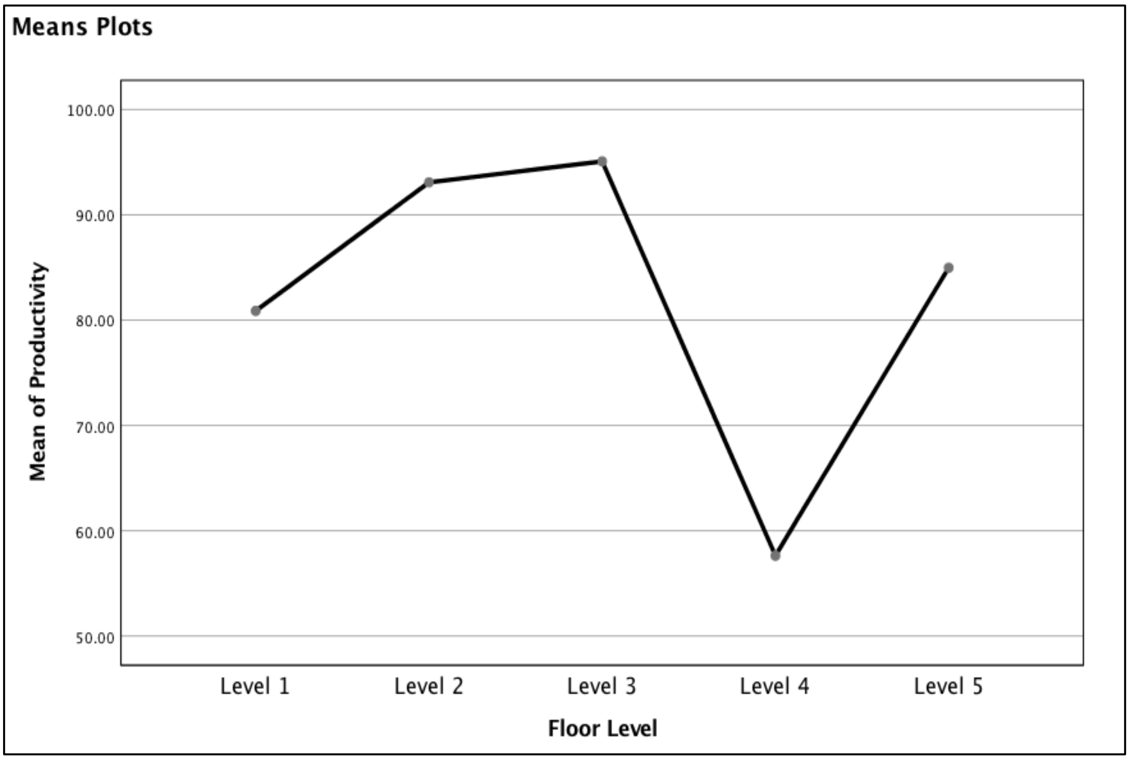


Figure 7.2 Means plot of Tower B floor level to floor panel productivity

It was concluded that for floor panels there was no significant difference in mean crane cycle time nor productivity outcome between the highest floor level and the lowest floor level.

Tower A's wall panel post hoc test revealed that Level 5's productivity was lower and statistically significantly different to all the other lower floors (Level 5 to Ground Floor, Level 1, Level 3 and Level 4 p-value≤0.003; Level 5 to Level 2 p-value=0.036 (p>0.05). However, Tower A's wall panel cycle time comparisons between Level 5 and other lower floors were not significantly different. Comparisons between Level 5 to Levels 1, 2, 3 and 4 p-value≥0.865, Level 5 to Ground Floor p-value=0.145 (p>0.05). It was noted that 95% of Level 5 wall panels consisted of small size (<5 m^2) panels, which was significantly different from all other floors. This was concluded to be a consequential factor in Level 5's inconsistent finding. Tower A's wall panel productivity rates for the other levels were similar and Tower B's highest and lowest floors were similar. Consequently, Tower A's sixth level was determined to be an anomaly due to the concentration of small panels.

7.2.3 Conclusion

The findings from the ANOVA tests and Scheffe's post hoc tests analysis as tabulated in Tables 7.9, 7.10, 7.11 and 7.12, illustrated in Figure 7.2, and discussed above, supports proposition #2, that a differential in floor level height above ground will not cause significantly statistical variance in productivity rates. The tests also found that there was not a significant difference in crane cycle times between lower levels and higher levels. This finding was supported by similar findings in the study of the Brock Common 18 storey timber building (Kasbar, 2017), which found installation was faster at higher levels than lower levels. This finding was assumed due, in part, to the learning curve and refinement in panel sequencing techniques. Future studies are recommended to verify if this the case for taller buildings over 18 storeys high.

7.3 Proposition #3 – larger panels improve productivity

Proposition #3 states that an increase in panel size will cause significantly positive upturn in productivity rates.

7.3.1 Test 1 Similarity of productivity across three size panels

To test this proposition, the first step was to determine whether the productivity was statistically significantly different across the three size categories for each tower. To test this, the collected data were analysed by one-way ANOVA. Floor and wall panel types were selected as these panel types included all three sizes of panels.

With the panel category size being the independent factor and productivity the dependent variable, the Null hypothesis (Ho) tested was that there was no significant difference in productivity between the size categories of panels tested ($p>0.05$). The findings from the ANOVA analyses for each tower's productivity are in Table 7.13 below.

For each of the findings the p-values <0.001. All the η^2 values were in the higher significance range indicating that between 57.6% and 77.3% of the variance in productivity is accounted for by the panel size. These findings, Table 7.13 below, determined that there was a statistically significant difference in productivity outcome between the small to large panel sizes.

Table 7.13 ANOVA test results: productivity to different panel size

Dependent factor / Tower case study	Panel type	n	Ave. Mean productivity (m^2/hr.)	Ave. St Dev. (m^2/hr.)	F	p	η^2
Productivity Tower A	Floor	141	83.22	31.18	(2,138) 93.66	<0.001	.576
Productivity Tower B	Floor	124	83.14	33.03	(1,122) 184.9	<0.001	.603
Productivity Tower C	Floor	99	103.45	45.24	(2,96) 62.228	<0.001	.565
Productivity Tower A	Wall	189	61.75	41.24	(2,186) 317.4	<0.001	.773
Productivity Tower B	Wall	117	71.71	40.59	(2,114) 83.22	<0.001	.593
Productivity Tower C	Wall	97	69.62	38.69	(2,94) 94.35	<0.001	.667

Table 7.14 below provides a comparison of the mean productivity values for the three sizes of wall and floor panels on both Towers A and B

Table 7.14 ANOVA test results: variance of mean productivity in panel size

Dependent factor / Tower case study	Panel type	Ave. Mean productivity (m^2/hr.)	Small panel Mean (m^2/hr.)	Medium panel Mean (m^2/hr.)	Large panel Mean (m^2/hr.)
Productivity Tower A	Floor	83.22	46.44	86.81	122.51
Productivity Tower B	Floor	83.14	48.09	101.75	N/A
Productivity Tower C	Floor	103.45	57.60	106.89	147.25
Productivity Tower A	Wall	61.75	24.61	44.71	106.74
Productivity Tower B	Wall	71.71	22.02	52.65	105.39
Productivity Tower C	Wall	69.62	19.09	49.88	96.17

The comparison of the mean productivity values between the panel sizes showed that productivity was significantly improved for large panels compared to both medium and small sizes in each of the above analyses, as illustrated in Table 7.14 above.

7.3.2 Test 2 -Panel size effect on cycle time

The next step was to determine whether crane cycle time was a contributing factor for the improvement and was statistically significantly different across the three size categories on each tower. Crane cycle times were tested using one-way ANOVA.

The panel categories were the independent variable, and the crane cycle times the dependent variable. The Null hypothesis (Ho) was that there was no significant difference for crane cycle times for the various size categories of panels (p-value>0.05). The findings from the test of variance for the crane cycle time findings are in Table 7.15 below.

Table 7.15 ANOVA findings: variance of crane cycle time to panel size

Dependent factor / Tower case study	Panel type	N	Ave. Mean mins: secs (hrs.)	Ave. St Dev. mins: secs (hrs.)	F	P (p>0.05)	η^2
Crane cycle Tower A	Floor	141	6:13	1:05	(2,138) 3.536	.028*	.043
Crane cycle Tower B	Floor	124	5:40 (.0944)	1:10 (.01932)	(1,122) 1.313	.239	0.00
Crane cycle Tower C	Floor	99	5:27	1:22	(2,96) 2.813	.078	.059
Crane cycle Tower A	Wall	189	9:33	2:25	(2,186) .802	.445	.0099
Crane cycle Tower B	Wall	117	8:57	2:26	(2,104) 1.006	.417	.0156
Crane cycle Tower C	Wall	97	9:18	2:18	(2,94) 5.673	.008*	.106

Note: *= p-value less than 0.05 equating to being statistically significantly different

The results from the tests determined that in four out of the six tests, there was no significant difference in crane cycle times for the three-panel sizes (p>0.05). Tower A floor panels and Tower C wall panels were the only two exceptions (noted *). Tower A's floor panel analysis of variance determined that the p-value=0.028 (p>0.05), however, eta squared was in the low range at 0.043, indicating that only a small 4.3% of the variance in crane cycle time was accounted for by panel size. The difference in crane cycle time is clearly illustrated in the Means plot of Tower A's floor panels in Figure 7.3 below.

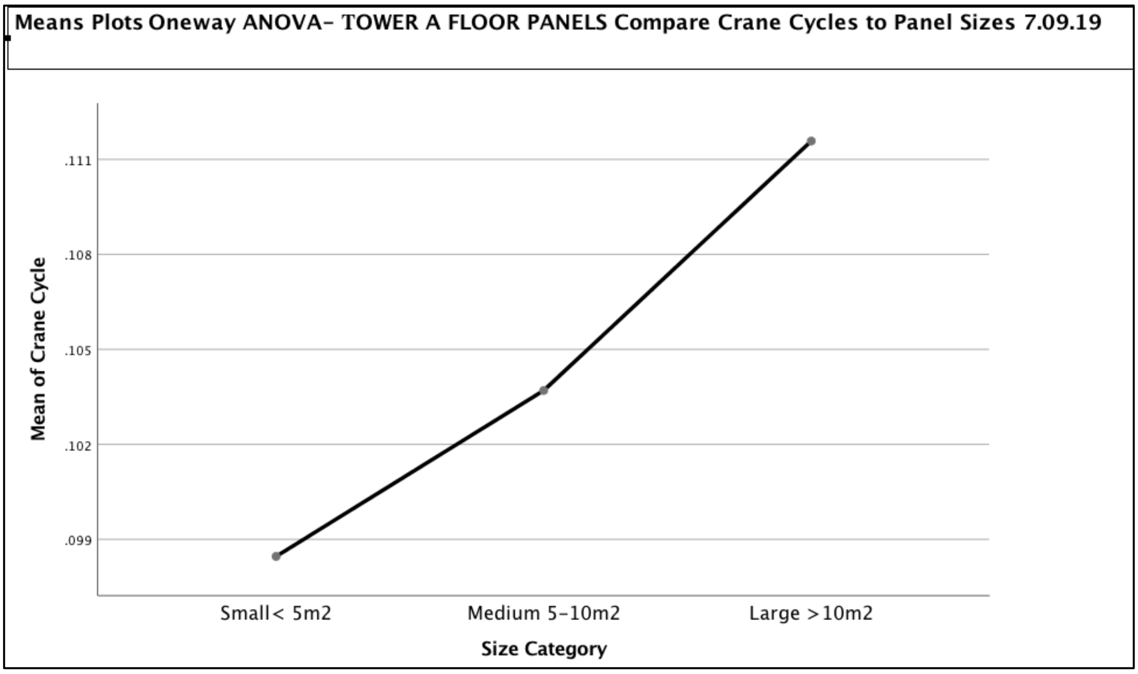


Figure 7.3 Means plot of Tower A floor panel size to crane cycle time

Figure 7.3 confirmed that the crane cycle times for large panels (0.1116 hrs. (6:42mins.)) took longer than for both medium (0.1037 hrs. (6:13 mins.)) and small floor panels (0.0985 hrs. (5:55mins.)).

In the case of Tower C's wall panels, the p-value was 0.008 (p<0.05). Similar to Tower A, the Means plot illustrates that Tower C's large wall panels took longer to install (0.1662 hrs. (9:58mins) compared to small (0.1406 hrs. (8:46mins)) and medium panels (0.1414 hrs. (8:29 mins)), as illustrated in Figure 7.4 below.

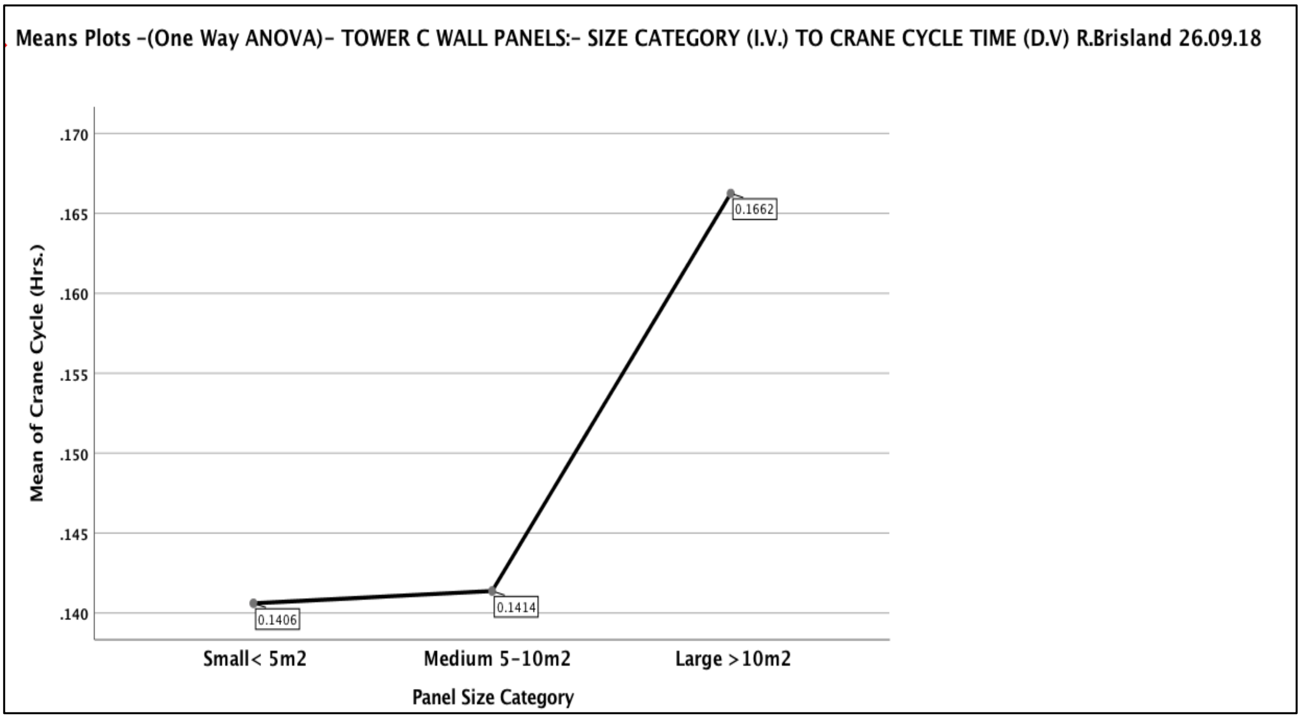


Figure 7.4 Means plot of Tower C wall panel size to crane cycle time

The longer cycle time to install large panels would negatively affect its productivity outcome. However, it was found that although the cycle time took longer, the mean productivity improved as the panel size increased for all panel types across the three-tower cases, as illustrated in Table 7.14 above. Therefore, the crane cycle time did not have a significantly statistical effect on productivity outcome.

7.3.3. Test 3 Panel size effect on cycle time

To support the above findings, additional tests used one-way ANOVA to determine whether panel size had any significant effect on either cycle time or productivity with data combined across all three towers. For this analysis, columns and beams were combined with wall panels as each was installed in a vertical direction. For this test these three types are referred to as "walls".

Crane cycle time, the dependent variable, was selected for test 3, commencing with floor panels as the independent factor and secondly with "wall" panels. The floor panel test found that the p-value=0.023 ($p>0.05$) and "wall" panels had p-value=0.023 ($p>0.05$), indicating that there was a statistically significant difference in crane cycle time between the three sizes for both floor and "wall" panels.

The ANOVA's "descriptives table" for floor panels indicated, in Table 7.16 below, as in Figure 7.3 and 7.4 above, that the mean crane cycle time of the large panel category took more time, 0.1040 hrs. (6:14mins) to install medium size, 0.0970 hrs. (5:49mins.), which took more time than small size, 0.0938 hrs. (5:38mins.).

Table 7.16 One-way ANOVA descriptives table: all towers, floor panel cycles time

Descriptives

Crane Cycle

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Small< 5m2	104	.0938	.01964	.00193	.0900	.0976	.05	.13
Medium 5-10m2	211	.0970	.02042	.00141	.0942	.0998	.05	.14
Large >10m2	50	.1040	.02186	.00309	.0978	.1102	.06	.14
Total	365	.0970	.02058	.00108	.0949	.0992	.05	.14

The floor panel "means plot", from the ANOVA test, in Figure 7.5 below, clearly illustrates the increase in mean cycle time from 0.0938 to 0.1040 hrs as the panel size increased.

Means Plots

Figure 7.5 Means plots of all towers floor panel size and crane cycle time

Similarly, in the case of walls, beams and columns, the ANOVA analysis found that the large panels took more time to install, 0.162 hrs. (9:43mins) than medium

(0.15 hrs. (9:00mins.) and small panels, 0.155 hrs. (9:18mins.), as shown in Table 7.17. Medium-size panels took 18 seconds longer, on average, than the small size.

Table 7.17 Descriptives table: all towers: wall, beam and column panel crane cycles

Descriptives

Crane Cycle

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Small< 5m2	357	.154689	.0509593	.0026971	.149385	.159993	.0586	.3258
Medium 5-10m2	130	.149600	.0401778	.0035238	.142628	.156572	.0625	.2347
Large >10m2	177	.161662	.0381689	.0028690	.156000	.167324	.0750	.2419
Total	664	.155552	.0459622	.0017837	.152049	.159054	.0586	.3258

The Means plot from the ANOVA test, in Figure 7.6 below, clearly illustrates this increase in mean crane cycle time for the combined wall, beam and column panel sample set, from small to large size.

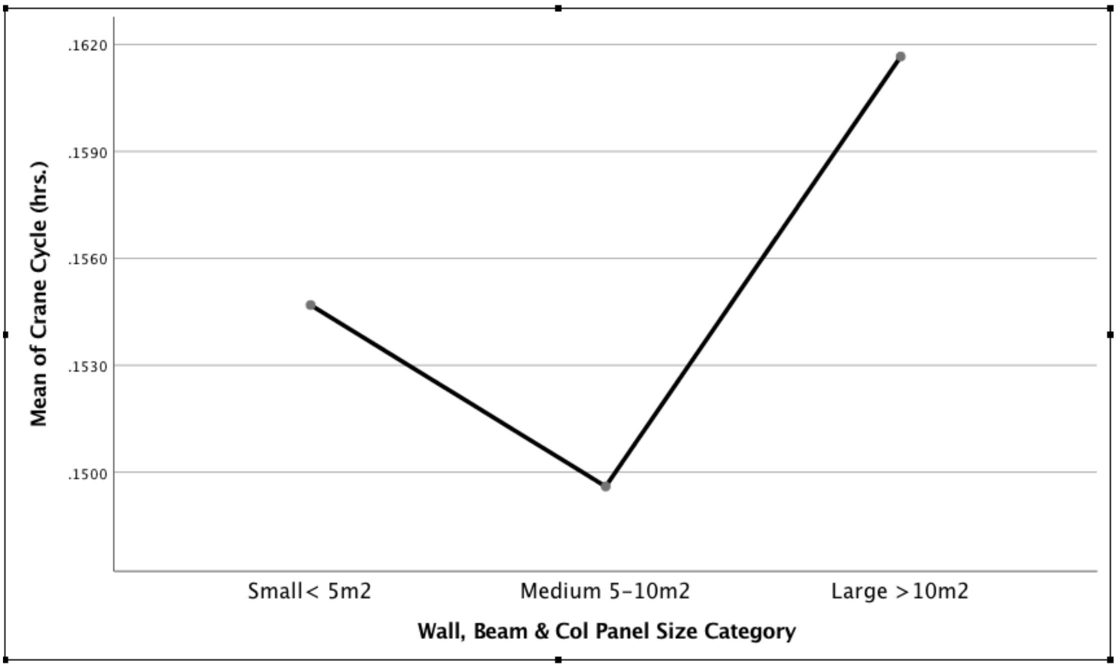


Figure 7.6 Means plot of all towers wall, beam and column panel size and crane cycle time

Similar to Test 2 above, this increase in crane cycle time would negatively affect the productivity outcome (Equation 1: Productivity=Output/Input); however, the opposite has occurred. This supports test 2's conclusion that the crane cycle time did not have a contributing statistical effect on the productivity outcome.

7.3.4 Test 4 Panel size effect on productivity

Productivity was tested across the combined three towers for floor and "wall" panels, using One-way ANOVA. Productivity rates across small, medium and large categories were found to be statistically significantly different ($p<0.001$) for both floor and wall panels, as indicated in Tables 7.18 and 7.19 below.

Table 7.18 ANOVA: "Wall" panel productivity (wall, beam and column), all towers.

	N	Mean	Std Deviation	F	Sig.
Small<5m2	357	14.744	9.903	1340.62	<0.001
Medium 5-10M2	130	48.779	15.546		
Large>10m2	177	103.127	30.373		
Total	664	44.967	41.74		

Table 7.19 ANOVA: Floor panel productivity, all towers.

Small<5m2	N	Mean	Std Deviation	F	Sig.
Small<5m2	103	50.015	13.086	223.08	<0.001
Medium 5-10M2	217	96.628	26.02		
Large>10m2	51	135.724	36.77		
Total	371	89.061	37.19		

Similar to Test 1 findings, in Table 7.14, the findings from Test 4 analysis, Tables 7.18 and 7.19, determined that the mean productivity rates were significantly different across the size categories for both floor and "wall" panels. Productivity increased dramatically as their size increased. Further examples of this substantial productivity improvement are illustrated in the Means plots in Figures 7.7 and 7.8 below.

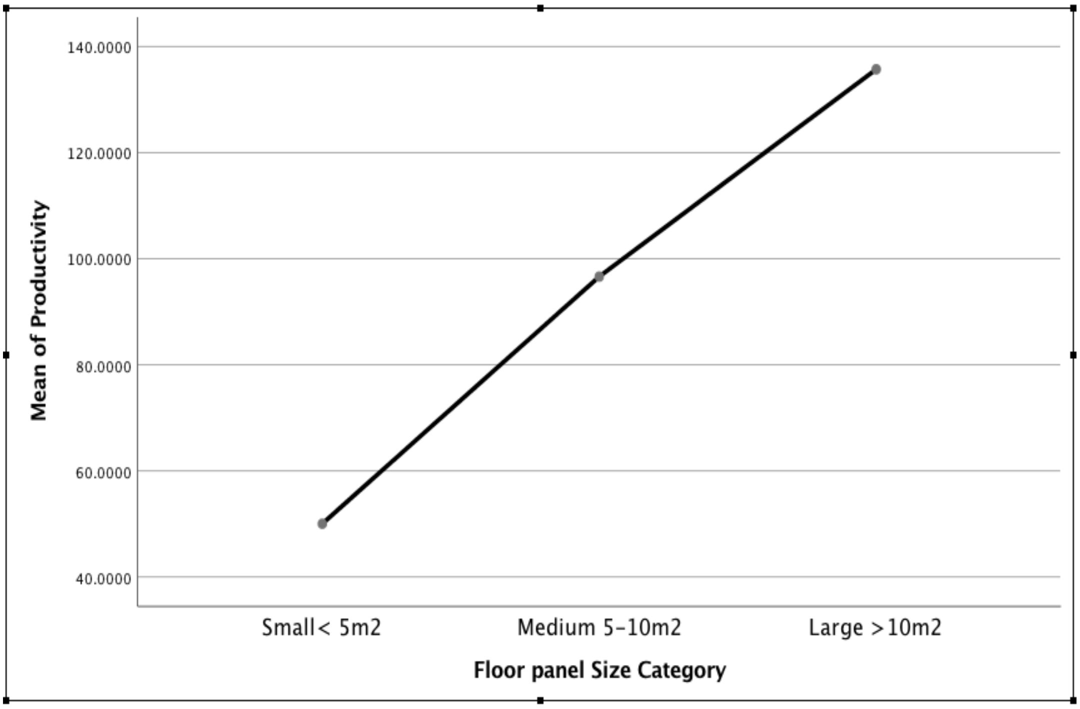


Figure 7.7 Means plot of all towers floor panels mean productivity

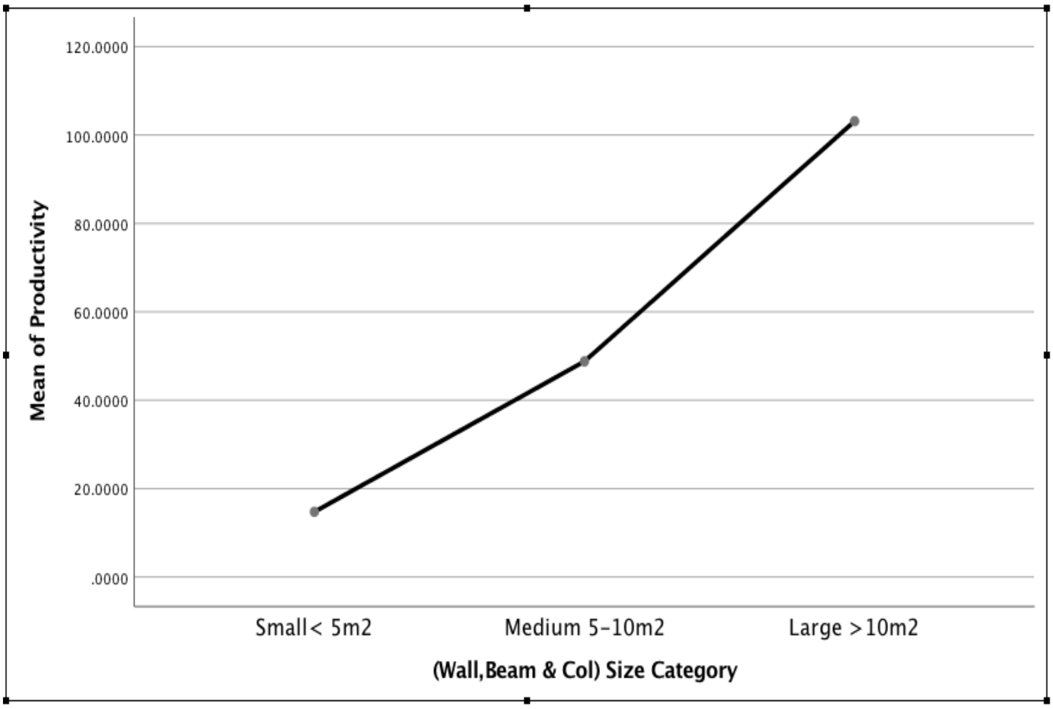


Figure 7.8 Means plot of all towers wall, beam and column panels mean productivity

In the case of floor panels in Figure 7.7 above, the mean productivity for large panels (135.72 m^2/hr.) was higher than the medium size (96.63 m^2/hr.) which in turn was an improvement to the small size (50.01 m^2/hr.). There was an 85.71

m^2/hr productivity increase found by selecting large floor panels in preference to small size panels. Similarly, for the vertical panels, i.e., wall, beam and column combination, the productivity gained 88.39 m^2/hr., from 14.74 m^2/hr. to 103.13 m^2/hr., by installing large panels compared to small, as illustrated in the Means plot in Figure 7.8 above. It was determined that statically larger panels significantly improved productivity compared to the use of small panels.

7.3.5 Determination

For proposition 3, the above analyses and findings showed that although small size panels generally had a faster crane cycle time compared to large or medium sizes, productivity significantly improved with the large panels. The analysis supports proposition 3 that an increase in panel size will provide significant positive variance in productivity rates.

7.4 Proposition #4 – weather affects productivity

Proposition #4 was that a) wind inclement weather negatively affects the on-site installation productivity of prefabricated timber panels and b) rain adversely affects the on-site productivity of timber panels. A summary of the inclement weather data recorded for each tower per floor level, and its effect is tabulated in Table 7.20 below. The table also includes the percentage effect of the two inclement weather categories on the total installation time.

Table 7.20 Inclement weather to value-add CLT time per floor level

Tower	Floor level	CLT value-add time (productive hrs.)	Rain stoppages (hrs.)	Wind stoppages (hrs.)	Total time (hrs.)	% Rain effect on total time	% Wind effect on total time
A	GF	8.59	4.83	0	13.42	35.99	0
A	Lv 1	15.90	0	12.18	28.08	0	43.38
A	Lv 2	19.71	10.46	12.39	42.56	24.58	29.11
A	Lv 3	16.72	2.65	0.33	19.7	13.45	1.67
A	Lv 4	18.66	0	0	18.66	0	0
A	Lv 5	33.24	2.25	1.04	36.53	6.16	2.85
TOWER A	**TOTAL**	**112.82**	**20.19**	**25.94**	**158.95**	**12.7**	**16.32**
B	GF	16.79	7.9	0	27.69	28.53	0
B	Lv 1	19.94	0	0	19.94	0	0
B	Lv 2	17.22	0	0	17.22	0	0
B	Lv 3	12.85*	14.57	3.27	30.69	47.47	10.65
B	Lv 4	16.25	0	1.00	17.25	0	5.80
B	Lv 5	11.3**	0	0	11.3	0	0
B	Lv 6	19.78	0	0	19.78	0	0
TOWER B	**TOTAL**	**114.13**	**22.47**	**4.27**	**140.87**	**15.95**	**3.03**
C	GF	16.59	5.38	0.38	22.35	24.07	1.10
C	Lv 1	25.93	0	5.13	31.05	0	16.52
C	Lv 2	17.18	1.04	0	18.22	5.70	0
C	Lv 3	4.58***	0.66	0	5.24	12.59	0
TOWER C	**TOTAL**	**64.28**	**7.08**	**5.51**	**76.86**	**9.21**	**7.17**

*16.19 hrs recording loss or view obscured; **14.84 hrs recording loss or view obscured; *** 50% floor panels only

As illustrated in Table 7.20, Tower A experienced in total more inclement weather, than Tower B or C. Tower B received more rain than Tower A or C and Tower C experienced the least amount of inclement weather. Tower A experienced the majority of high winds compared to the other buildings.

7.4.1 Inclement weather: multivariate regression analysis

A multivariate regression analysis was conducted on the above data and the findings are summarised in tables 7.21 and 7.22 below.

Table 7.21 Wind & rain combined multivariate regression analysis

Factor	N	Mean time (hrs)	St Dev	Pearson Correl.	R^2	F	Sig.
Wind		2.10	4.08	.655			
Rain		2.93	4.36	.521			
Total	17	22.33	9.40	1.00	.555	(2,14)8.731	0.003

The overall regression findings, shown in Table 7.21 above, were significant: F(2,14)=8.731; p=0.003 ($p<0.05$); R^2=0.56. As $p<0.05$, the predictors, wind and rain, were found to account for a significant amount of variance in total value-added CLT time. Wind and rain combined accounted for 56% of the variance (R^2=0.56) in the total value-added CLT time on days when inclement weather prevailed. The residual statistical analysis showed there were no outliers or any undue influence on the result: Mahalanobis Distance=8.071 (MD<13.82), Cook's Distance=0.499 (CD<1.00)(Glen, 2020).

Table 7.22 Wind & rain multivariate regression coefficient analysis

Model	Unstandardised coefficients		Standardised coefficients			Collinearity statistics	
	B	Std. Error	Beta	t	Sig	Tolerance	VIF
(Constant)	17.324	2.059		8.415	.000		
Wind time	1.275	.427	.533	2.984	.010	.925	1.081
Rain time	.797	.399	.370	1.995	.066	.925	1.081

From the regression findings in Table 7.22 above, it was found that wind (p=0.010 (p<.05)) had a statistically more substantial effect on productivity than rain (p>0.05). The rain did not have a unique[18] significance, p=0.066 (p<0.05), unlike wind, which did. The collinearity statistics showed that there was no multicollinearity within the predictors, with collinearity tolerance=0.925 (CT>0.1) and VIF=1.081 (VIF<10) (University of California et al., 2019). The Beta of 0.533 for wind and 0.37 for rain determined that wind had the more substantial effect and accounted for 53.3% of the variance in total value-added CLT time (University of California et al., 2019).

[18] A "unique" predictor is one that by itself affects the outcome of the dependent variable.

7.4.2 Proposed algorithm for inclement weather effect

To predict the total value-add time per floor level for the variances, the wind and rain, including the additional effect, an equation is proposed from the above findings using the unstandardised coefficients from Table 7.22, above. Using the regression formula: Y=a+$b_1(X_1)$ +$b_2(X_2)$, the proposed formula to calculate the total value-add CLT time for a total floor level mass timber installation with an inclement weather effect, for the study's case study, is as follows:

Equation (3):

Total value-add CLT floor level time (with inclement weather effect, hrs) =

$$\mathbf{17.32+1.275*(X_1)+0.797*(X_2)} \qquad \mathbf{(3)}$$

Where X_1= wind time (hrs) and X_2= rain time (hrs).
Equation 3 provides the overall time for a total floor level installation inclusive of the forecast or actual inclement weather and its additional subsequent effect.

7.4.3 Determination

From the above findings, wind and rain statistically affected the CLT value-add installation time. These findings strongly supported proposition #4a that wind negatively affects the on-site productivity of prefabricated timber panel installation. The wind was the unique predictor for the variance to CLT value-add time and was a more significant predictor than rain. The findings supported proposition #4b that rain negatively affected timber panel productivity, but it was not as statistically significant. In addition, Equation (3) is proposed to calculate total floor level time for CLT installation, which included the consequential time effects on the installation activity from inclement weather.

7.5 Proposition #5 – proposed equations to predict daily CLT productivity

Proposition #5 states: an equation, inclusive of the predictors from the above propositions #1-3, can be formulated to predict CLT panel daily productivity.
To test this proposition, a multivariate regression analysis was conducted with all predictors from propositions #1-3. In total 263 sample sets were compiled, using each (panel) category's mean daily productivity and crane cycle time, its mean panel size, and mean crew size for each CLT installation day across the three case

studies. The purpose of proposition # 5 is for an equation to forecast daily productivity of mass timber installation so that the designers and project team can determine the most efficient selection of panels, forecast the daily productivity of the design and monitor the actual to planned outcome. Once this is calculated then the inclement weather Equation 3 can be implemented to assess the time effect to a typical floor level with an estimated number of inclement weather type hours[19].

To commence the analyses, a matrix scatterplot was carried out using all the predictors and the dependent variable, productivity, to identify any predictors that had no significant effect on the dependent variable. Six predictors were selected: crane cycle time, floor level, panel type, crew size, crane type and panel size. A correlation analysis using all the predictors and the dependent variable productivity then tested if any predictors had a significant effect on productivity. The findings indicated that crew size (p-value=0.425) and crane type (p-value=0.291) did not statistically significantly affect the mean daily productivity. This result, coincidentally, provided robustness to proposition #1 findings. All the other predictors had p-value<0.05. However, it was decided to include these predictors into the proposed equation.

Multivariate regression analyses were carried out to assess the effect of each of the predictors on the mean daily productivity. The measurement criteria for the selected predictors, used in the analyses are in Table 7.23 below. The analyses, also, assessed whether a robust regression equation could be formulated to predict the mean daily productivity with known predictors.

[19] Inclement weather (Proposition # 4) was not included in this equation because it is arbitrary and would skew the findings unnecessarily.

Table 7.23 Selected factors' measurement criteria

Predictors	Measurement criteria	Level of measurement
Daily mean crane cycle time	Hours	Scale
Floor level	GF=1…. Lv 5=6	Interval
Panel type	Floor=1 Wall=2 Beam=3 Column=4	Nominal
(Installation) Crew size	Average no. of installers (1-6)	Scale
Crane type	Mobile crane=0 Tower crane=1	Nominal
Daily mean panel area	m^2	Scale
Dependent variable		
Daily mean productivity	m^2/hour	Scale

The analysis findings indicated that the overall regression model was significant: F=(6,256) 458.9, p<0.001 (p>0.05) and R^2=0.915.

As p<0.001, this indicated that the predictors accounted for almost all of the mean productivity. The coefficient of determination was R^2=0.915 (adjusted R^2=0.913), which indicated that the predictors provided a very strong model fit of 91.5%. This strong fit determined that there were no other significant linear or non-linear predictors that would affect productivity forecasted value. The multivariate regression findings for the six predictors are in Table 7.24 below.

Table 7.24 Proposition 5: multivariate regression analyses findings.

Model	Unstandardised coefficients		Standardised coefficients			Collinearity statistics	
	B	Std. Error	Beta	t	Sig	Tolerance	VIF
(Constant)	66.068	5.99		10.528	<.001		
Crane cycle	-315.326	20.351	-.316	-15.494	<.001	.798	1.254
Panel area	6.552	0.180	.802	36.331	<.001	.717	1.395
Panel type	-5.380	1.048	-0.126	-5.136	<.001	.551	1.815
Floor level	1.030	0.601	.037	1.712	.088	.713	1.402
Crew size	-0.351	.857	-0.009	-0.410	0.682	.560	1.785
Crane type	3.264	2.22	0.036	1.470	0.143	.681	1.468

As indicated in Table 7.24 above, crane cycle time, panel area and panel type ($p<0.010$ ($p<.05$)) had a more statistically significant effect on productivity than either floor level ($p=0.088$), crew size ($p=0.682$) or crane type ($p=0.143$). Panel area Beta=0.802, which determined that panel area had the most substantial positive effect on the productivity value. Crane cycle time and panel type were the next important with Beta=-0.316 and -0.126, respectively.

There was no multicollinearity within any of the predictors, with collinearity tolerance ranging between 0.551 and 0.798 (CT>0.01) and with all predictors' VIF ranging between 1.815 to 1.254 (VIF<10) (University of California et al., 2019). Although floor level, crew size and crane type were found not to have a statistically significant effect on the productivity outcome, these three predictors remained in the formula to provide robustness and granularity by providing an opportunity to future monitoring of these factors in this equation.

7.5.1 Determination

(i) A panel type productivity forecast model

An equation was developed to predict daily mean productivity of CLT panel type installation, using the unstandardised coefficients in Table 7.24 above. This equation provides a means to assess and calculate the forecast daily productivity of a particular panel type for a future project. From this one could ascertain the efficiency of the use of that particular type for the proposed project.

Using the regression formula template

$Y=a+b_1(X_1)+b_2(X_2)+b_3(X_3)+ b_4(X_4)+ b_5(X_5)+ b_6(X_6)$

where Y = dependent variable, a = constant and b_n= unstandardised coefficient and X_n= predictor value.

The equation for predicting a panel type's daily mean productivity is:

Equation (4):

$$\text{(Daily mean) panel productivity} = 66.068 - 315.326(X_1) + 6.552(X_2) - 5.38(X_3) + 1.03(X_4) - 0.351(X_5) + 3.264(X_6) \quad (4)$$

Where:

X_1= Mean crane cycle time (hrs),

X_2= Mean panel area (m^2),

X_3= Panel type (Floor=1, Wall=2, Beam=3, Column=4),

X_4= Floor level, Ground Floor=1, Level 1=2, Level 2=3…),

X_5= Installation crew size (number of workers),

X_6= Crane type (mobile crane=0, tower crane=1).

This equation was tested on arbitrary sample days of mean daily productivity for each of the three towers on various floor levels. In all cases, the predicted productivity from the above formula was accurate to within +/- 5%.

(ii) Project's Productivity Forecast Model

The above equation is enhanced to provide a project's mixed panel type daily productivity forecasting model by the proposed Equation 5 below.

Equation (5):

(Mean daily project productivity) Pp = *Pf(af/ta) + Pw(aw/ta) + Pb(ab/ta) + Pc(ac/ta)* ***(5)***

where:

Pf = Mean floor panel productivity,

Pw = Mean wall panel productivity,

Pc= Mean column panel productivity,

Pb= Mean beam panel productivity,

af = building's mass timber floor area,

aw = building's mass timber wall area,

ab = building's beam area,

ac = building's columns area,

ta = total combined panel area.

This equation provides an ability to assess and calculate average daily productivity of a mix and percentages of panel types for proposed projects. From this one could ascertain the efficiency of a mass timber design incorporating a mix of panel types for a proposed project. Once the design of the panel types has been decided

Equation 3 could be applied to ascertain possible time effects to floor to floor cycles of forecast inclement weather patterns.

7.6 Summary

This chapter discussed the study's findings from a cross case analysis to answer the five propositions nominated.

Analyses supported proposition #1 that equipment, not labour, was the primary and leading on-site productivity input resource for mass timber systems. The traditional assumption that labour is the primary input resource (Yi et al., 2014) was found not to apply to prefabricated timber on-site productivity. The output from an installation crew size of two workers was not statistically significantly different to that of three or five, and the type of crane used was also found not significant. The statistical examination also found that the crew hours were not statistically significant in productivity output for mass timber installation.

Proposition #2: Analyses of the sample sets from all three tower studies found that there was no statistically significant difference in CLT on-site productivity between lower and higher floor levels. It can be concluded that the additional time for the crane to lift a panel from ground floor level truck or store to higher floor levels was negligible, therefore did not significantly affect the productivity outcome. The findings supported proposition #2 with all p-values>0.05.

Proposition #3 proposed that an increase in panel size will cause significant positive variance in productivity rates. The selection of large panels were found to provide the optimum on-site productivity with large floor and wall panel baseline values of 140 and 91.7 m^2/hr, respectively. Argument that a change in installation sequence would affect the above findings would be unfounded. This is because all the assignable causes and extraneous factors were removed in the analyses and only unaffected or slightly affected data, that is only data from value-added crane cycles were considered in formulating the baseline rates.

Findings from analyses supported proposition #3 and concluded that in all cases, larger panels provided statistically significant improved productivity to small sizes.

Analyses for proposition #4 was found supported and that wind had a more significant effect on daily CLT installation time and productivity than did rain. Wind was found to be the prominent inclement weather predictor, although both types of inclement weather negatively affected CLT productivity. A proposed Equation 3 was formulated to forecast the effect of both forms of inclement weather on the overall CLT floor level installation time, once the design panel parameters are decided and Equation 5 is applied.

To answer proposition #5 on whether equations could be formulated to forecast mean daily productivity, several analyses were undertaken to determined that it was supported. Regression equations were formulated for forecasting daily productivity for individual panel type (Equation 4) and overall project CLT (the combination of all panels) (Equation 5). Each model identifies the coefficient (weighting) value of each independent variable (predictor) with its significance and the predictor's effect, either positive or negative, on the dependent variable, productivity. From this, each predictor's hierarchical impact on average daily on-site productivity was ascertained. The relevant predictors found and included in the formula were crane type, crew size, panel size, panel type, floor level (of installation) and crane cycle time. The equation was verified using random sample average daily cases from the overall case study. The verification tests forecasted productivity within +/- 5% of actual productivity achieved for each panel type in 100% of cases. The proposed forecast model may provide both designers and contractors with a forecasting tool to test the mass timber design and offer construction method efficiency before construction.

In summary, baseline matrix tables of crane cycle times and productivity outcomes were established for mid and low-rise (six and three-storey) buildings for each of the eight panel categories. All propositions were tested and were supported. Equation (3) was formulated to effect of inclement weather to CLT floor level time. Further proposed Equations 4 & 5, combined and complemented the baseline matrices and the first three propositions, providing proposed productivity forecast models. The following chapter discusses the study's key findings, anomalies and recommendations from the cross-case analyses.

Chapter 8 Discussion

This chapter discusses the key findings, including similarities and anomalies from the previous chapter's cross-case analyses. From these findings and concurrent observations, salient conclusions are constructed and presented. The chapter concludes with a merged model that synthesises the significant determinants and homogeneities from the case studies.

8.1 Non-value-added waste

The high-level project review outcome of the three buildings' average CLT productivity was significantly affected by the number of non-value added (NVA) activities later determined at the project and micro-level analyses. At the project level, the CLT productivity was 7.52 to 14.82 m^2/hour compared to that of 35 to 50 m^2/hour, from the intermediate floor level analyses across the three cases. It was determined that between 61.2% and 66.6%, daily crane time was devoted to NVA and non-related activities during the on-site CLT process. Only 33.4% to 38.8% daily crane time was allocated for the value-added (VA) CLT activities. Hence, on average, 65% of the CLT installation crew's time each day was spent idle, working on NVA or non-critical activities. Almost 35% crane time each day was allocated to arbitrarily servicing other trades, which consequently disrupted the flow of the CLT installation process.

In Chapter 5, Figure 5.2, the pie charts provide a break-down of crane times for the three timber structures. These charts identified the crane's VA and NVA hours including the time that the crane interrupted the CLT installation to service other trades. However, the pie charts cannot illustrate the effect of these arbitrary interruptions. To provide granularity to this effect, sample workdays were randomly selected, and work-flow charts were formulated for each tower. These are presented below, Figures 8.1-8.4. A daily sample of the "just in time" approach, experienced in the first week on Tower A, is presented in Figure 8.1. Figure 8.2 is a sample work-flow chart for a traditional approach using Tower A's floor level four; Figure 8.3 is a sample day chart for Tower B, and Figure 8.4 is the chart of a sample day for Tower C with the mobile crane.

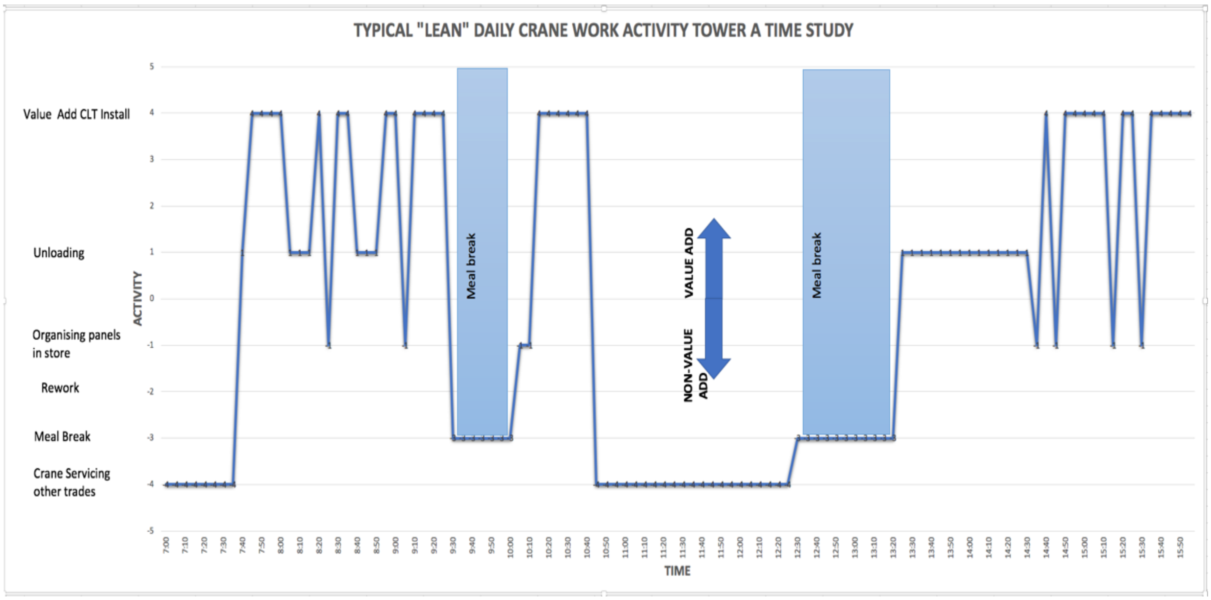


Figure 8.1 "Just in time" Tower A sample daily flow chart

The above chart, Figure 8.1, indicates a reasonable concentration on CLT installation and unloading but there are several hours, in the middle of the day, during which the crane was servicing other trades. The reason for this action was that during this period, the crane was not required for CLT duties as the next panel delivery had been delayed and the crew was waiting. It was not until after the mid-day break that the second delivery truck arrived with the panels which were loaded out of sequence. Consequently, many panels were unloaded and temporarily stored until the required panels could be accessed from the truck and installed. Installation continued until the end of the day. This example illustrated that to avoid on-site delays, there was need to ensure that panels were loaded in sequence on the delivery trucks for installation, and deliveries were arranged to coincide with installation.

In comparison to the above "just in time" approach, the flow chart Figure 8.2 below indicates the workflow achieved using traditional construction approach on the same tower.

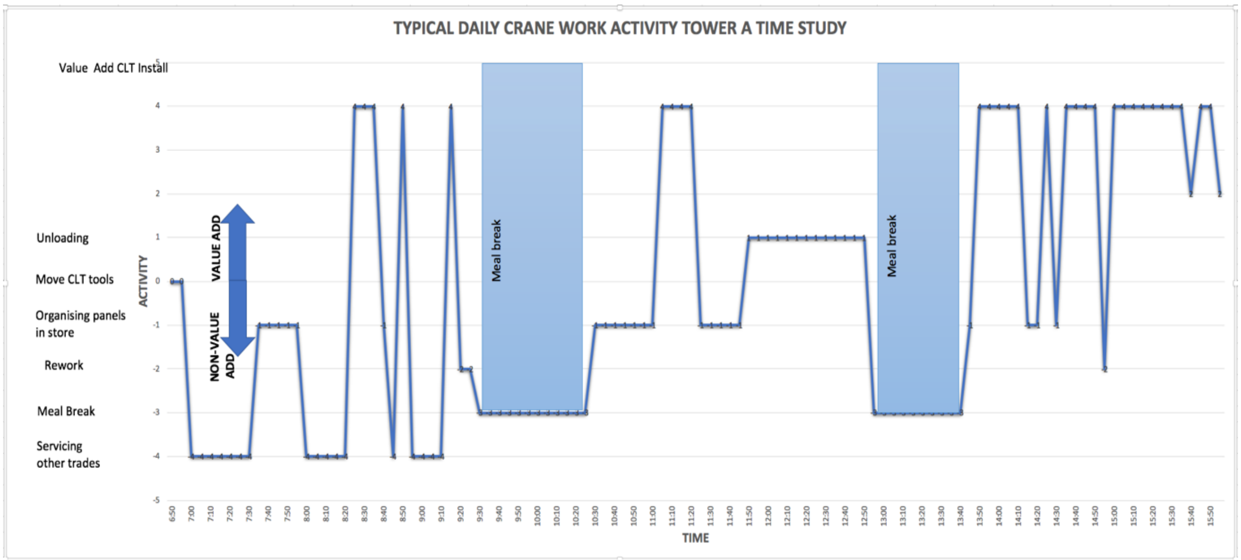


Figure 8.2 Tower A sample daily flow chart

The above chart, Figure 8.2, illustrates the workflow when a "just in time" approach was not implemented with the resultant disrupted workflow. This is clearly evident in the chart from the morning's commencement up to the first meal break. This was due to the crane endeavouring to service both the CLT process and other trades concurrently, causing interruptions to each. After the first break, the flow line indicates the effects on work-flow due to poor delivery logistics, the ramification being temporary on-site storage. This resulted in consequential delays in organising panels in the temporary stores and wasted time to identify the required panels for installation.

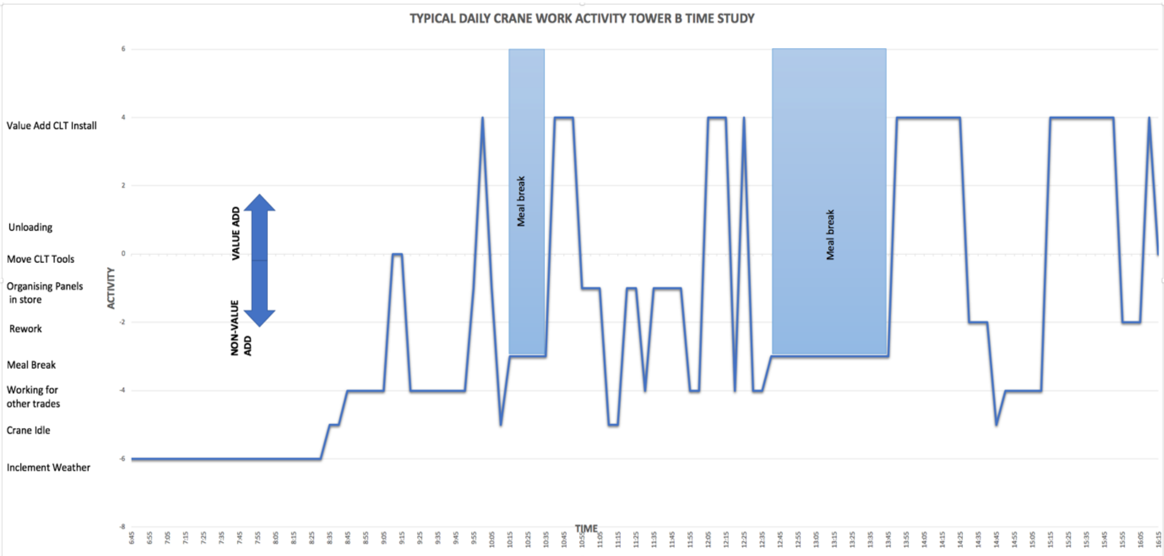


Figure 8.3 Tower B sample daily flow chart

In Figure 8.3 above, the workflow is erratic and depicts the effects of a single crane endeavouring to service other trades on two separate buildings, Towers A and B, in addition to the CLT installation. One can deduce that the randomness of workflow was that there was not a planned daily schedule of activities for the crane. There was no clear planned activity timetable and a consequential lack of focus on workflow, which is characteristic of an inefficient on-site approach.

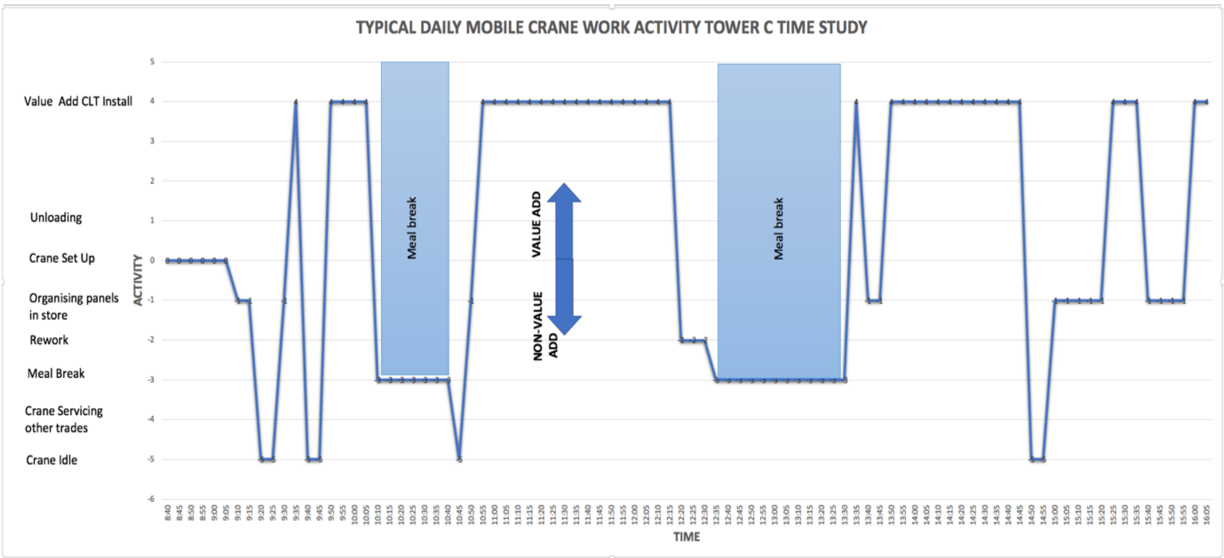


Figure 8.4 Tower C sample mobile crane daily flow chart

Figure 8.4 above illustrates the workflow from a dedicated mobile crane engaged on the CLT installation. Time spent sorting out and identifying the required panel for installation, is classified under the heading “organising the store”. Periods when the mobile crane was idle, as indicated in the above chart, were often due to safety procedures to avoid collision with the tower crane working in a close location. Even though this random sample did not capture the crane servicing other trades, the mobile crane was often required to do so. The less erratic workflow line compared to the previous charts is due to a lesser degree of the crane’ time servicing other trades than experienced with the tower crane. The above four daily sample flow charts, Figures 8.1-8.4, illustrates the interrupted work-flow patterns due to changes in crane activities from installation, identifying and selecting panels, rework and frequency of crane servicing other trades.

Workflow was less effected when a "just in time" approach was adopted (Figure 8.1) and when a dedicated crane is engaged. The first floor of Tower A's "just in time" process took just 5.5 days to complete compared to between 8 and 9 days for the remaining levels of Tower A. By adopting a "just in time" approach, a 35% improvement was experienced in the first floor's installation cycle compared its other floors, even with the crane's disruptions, delays and waste. Reviewing in detail these 5.5 days for Tower A's first level, the crane worked an average of 3.56 hrs. (56.4%) on CLT activities during the crew's daily average 6.33 hrs. 39.9% of the daily average time was allocated to VA CLT activities, which was a 19.6% improvement on the tower's average allocation of 33.3%. The duration of Tower A's first floor level included a total of 5.2 hrs. inclement weather (rain) stoppages. It was negatively affected by an average panel delivery factor of one per day, the crane servicing other trades and the crew not following the installation sequencing drawings. However, the findings indicated that significant resultant waste reduction in storage and double handling and improved VA activity occurred when an industrialised production process was adopted for the timber installation.

Apart from the inclement weather when the time for the non- value-added activities is eliminated from the first level findings, its floor cycle was only 17.1hours[20]. This is an improvement of 104% from its gross time and a 215% improvement on Tower A's other floors. As another example, hypothetically if the project team had pre-planned for the crane to be allocated to CLT process six and half hours each day, had focused on even flow and NVA activities minimisation, then applying a conservative baseline rate from Table 6.25 the large wall panel installation time of 10.02 minutes as an overall average time, the floor cycle would be 3.25 days (146 panels x 10.02 mins=24.4 hrs). This would equate to a 3.75-day saving to the observed time of that floor, a 47% improvement and 126% to the other floors. For such potential improvement to be realised, detailed preconstruction planning on the panel delivery and installation process would need to be undertaken to remove non-value-added activities rather than relying on traditional construction approach (Topliss et al., 2020; Woodard et al., 2019).

[20] This figure includes unloading panels and stage 1 and 2 cycles

The approach adopted in this study's calculation for baseline rates, presented at Table 6.25, extracted the NVA activities, i.e., waste, and produced unaffected units of measure. The matrix provided a means to determine target outcomes, forecasts, estimates and to enable project teams to strive for process efficiency. However, to achieve such efficiency there needs to be a focus on good flow and the reduction in variability and waste.

On the majority of floors there was not a focus on flow, either at the pre-construction or construction stages, which resulted in the workflow being haphazard, not "swift and even", leading to poor project level productivity. The random samples (Figures 8.1-4) indicated this haphazard flow and that the amount of NVA activities had an adverse effect on the project level productivity. This provided robustness to the argument for change from the traditional on-site process to more of a production process for industrialised systems.

8.2 Construction Attributes

The discussion above highlights that there is a necessity to rethink, change or re-engineer the traditional on-site construction process to a more production process approach to compliment industrialised building systems. The NVA activity data captured both CLT activities and non-CLT activities. CLT NVA activities fell under the general heading of delivery logistics and the non CLT activities were generally working for other trades or the crane idle. All of which are attributed to inefficient crane allocation and management issues. Consequently, reducing waste from NVA activities and time, such as observed above, will significantly improve overall production.

8.2.1 Delivery logistics

Between 16.7% and 20.3% of gross crane-time was allocated to resolving NVA delivery logistics issues (Figure 5.2). The on-site delivery logistics subsets were categorised into *double handling*, *unloading into the store* and *rework,* accounting for 10.8%, 6.4% and 1.6% of the average daily gross crane time, respectively.

8.2.1a) *Unloading to store* activity was, generally, a consequence of CLT panel deliveries changing from synchronised to out of synchronisation with the scheduled requirement and on-site installation progress. This action occurred due to the failure of the third-party off-site delivery logistics organisation meeting the agreed and planned delivery sequence. Dedicated CLT storage areas were not planned or existed for the out of synchronised CLT panel deliveries. Therefore, instead of the scheduled "just-in-time" approach with CLT panels unloaded to installation, the delivery process was forced to change panel deliveries to be unloaded into temporary on-site storage areas. Consequently, the CLT deliveries were haphazardly stored in transient on-site locations until that area was needed, e.g., for construction of buildings or long-term storage for other trades or panels used.

Disorganised storage resulted in a) loss of time; e.g. work held up at different places and waiting for correct materials (a direct loss), b) loss of space and c) a loss of capital due to labour and material side-tracked throughout the site (Koskela, 2000). The deficiency in available planned on-site storage area is illustrated in Figures 8.5 and 8.6, for Towers A and C, respectively.

Figure 8.5 Tower A limited CLT storage area

Figure 8.5 demonstrates that there was no storage available to the perimeter of Tower A. During this time the remainder of the site was under construction, for the in-situ concrete podium. The restricted on-site storage resulted in delivery of unscheduled panels, predominantly those from level 1 to the roof, temporarily stored adjacent to the site sheds, outside the construction area as noted on the photograph.

Figure 8.6 Tower C limited CLT storage area

Figure 8.6 is at a point in time when the three towers, A, B and C, were under construction. At this stage, storage became a premium commodity because all following trades required material storage. The CLT storage area was assigned adjacent to the fence lines, as buildings and access ways generally occupied the remainder of the site, as highlighted in Figure 8.6. The available CLT storage was reduced within three days of this photograph being taken, when Tower C's perimeter scaffold was erected. The *unloading to store* factor accounted for 7.9% and 6.7% gross crane for Towers A and B respectively, Figure 5.2 (Chapter 5).

8.2.1b) *Double handling*. The consequence of the above unloading to transient storage areas was unplanned *double handling* in storage, again, due to deficient delivery logistics. *Double handling* caused lost time in either moving panels to a new location, rearranging or sorting panels or searching and locating the required panels for installation. The latter generally involved moving several panels to obtain the required one, which took up to an unproductive 39 minutes to achieve. On an average day, 12.2% to 14% of the crane's gross time was devoted to storage *double handling* for Towers B and C respectively. Tower A had less *double handling* (7.7%) due to its initial "just-in-time" approach: the delivered panels lifted directly from the truck and installed on the deck (Figure 4.10, chapter 4).

8.2.1c) *Rework* represented 1.1%–2.66% of gross crane time which was the least affected delivery logistic activity. *Rework* covered alterations to panels to enable correct fit and relocation of panels to correct location. Frequently, the crew endeavoured to adjust panels into pre-formed openings, such as installing closing panels, beams or inserting atypically shaped panels, as discussed later. Whether such rework was due to error in panel manufacture or previous incorrect panel installation could not be determined.

A probable cause of *rework* was that the crew was observed not adhering to the installation sequence drawings. Specific installation sequence drawings were documented for each floor level's wall and floor panels. The planned sequence flowed, generally, from a corner point, completing all vertical or horizontal panels in each segment before progressing to the next. However, the crew usually commenced the vertical panel installation with the large wall panels, which were installed haphazardly across the whole floor, followed by the smaller panels, columns and lastly beams. This action contributed to an increased number of closing panels and caused panels to be installed in an incorrect location then later removed and installed to the correct position.

Missing, illegible or incorrectly read ID tags also contributed to incorrect installation. This deficiency could have been minimised at the pre-construction planning stage by early delivery logistics investigation into component tracking systems. These systems can minimise these observed NVA activities through lost or illegible ID tags. The benefit of component tracking systems is that they integrate field sensors, wireless communication and real time global positioning system (GPS) equipment. Panels scheduled for delivery to the site are tagged in the factory using radio-frequency transponders (RFID) or bar codes (Sarac et al., 2010). The panels can be tracked from the factory by the encoded information, which is scanned and wirelessly relayed to a remote project database. This process is also used for on-site project teams to make sure every panel is tracked to arrive at the designated date and time and on the correct delivery truck. The unique numbering system allows the installation crew to identify each panel and install it at the designated position in the building. With individual numbers, every panel can be followed through from the production to the finished structure (Zumbrunnen et al., 2012). This process of control is vital to delivering large projects on significantly reduced construction programmes and eliminating panels installed incorrectly.

To put this section into perspective, it was determined that delivery logistics issues accounted for 16.7% to 20.3% of resource waste and crane gross allocation time across the three case buildings.

8.2.2 Crane allocation time

Construction of a building's structure is a critical scheduled activity. Therefore, it is concluded that the recorded 65% daily average allocation of the crane's gross time to non-critical activities, Figure 5.2, was an inefficient allocation of resources. A proportion of this NVA time was allocated to *delivery logistics,* as discussed above. Between 44.5% and 47.5% of gross crane time was allocated to activities not related to the critical CLT activity. An average 33.4% of gross crane time was allocated to servicing other trades, such as material handling and assisting their activities.

Crane idle time was a secondary factor, averaging 13.1% of gross crane time. Crane idle time occurred when one crane, as well as both mobile and tower cranes, were operating on site. The most common causes were when the crane allocation interchanged between trades, trades not being ready, the crane waiting for deliveries or when two cranes were on site. When both cranes were operating on-site simultaneously and were working close to each other, crane idle time occurred because collision defect/avoidance detection ensured that one crane ceased working. The tower crane also experienced idle time on days when the mobile crane was on-site for CLT installation. For the majority of days when the mobile crane was on site, the volume of work to service other activities and trades was insufficient for the tower crane's full utilisation.

The crane unsystematically performed the non-CLT activities by irregularly interrupting the CLT installation process on a daily basis, which compounded the discussed disrupted workflow. For example, the crane would suddenly cease servicing the CLT process to expediently move waste skips, assist other trades, relocate their materials or unload their deliveries to loading platforms or storage areas. On average, the installation process was interrupted 4.6, 6.02 and 6.03 times per day on Towers A, B and C, respectively. The time duration recorded for these individual interruptions varied between 10 minutes to 3 hours at a time. The crane crew periodically compounded the effect of the disruption by not synchronising their meal-breaks with the installation crew, to service other trades. Consequently, at of the end of their break, the returning installation crew were delayed until the crane crew returned from their meal-break.

The CLT installation process broken by these irregular interruptions restricted the ability to maintain a smooth flow of work cycles or maintain a "rhythm" (Forsythe et al., 2019a). The effect of broken rhythm was not considered, except for outliers, in the formulation of the baseline matrix, as the affected time could not be verified. Off-site prefabricated components are adopted to create a continuous repetitious flow on-site to improve productivity. These random interruptions in effect nullified the opportunity to create or observe a learning curve effect as advocated by Thomas (1986). To avoid such interruptions and delays encountered, a regulated crane time allocation schedule for critical trades should be planned and issued before commencement of work, which should be strictly adhered to during installation. An example of a sample crane allocation is illustrated in Table 8.1 below.

Table 8.1 Proposed Crane Allocation example

Proposed Daily Allocated Time	**Proposed time %age**	**Crane Allocation Description**	**Study's % time**
7 am – 8 am	11%	Move waste skips and unload other trade deliveries	11%
8 am – 3 pm	66%	CLT installation (meal breaks synchronised)	66%
3 pm – 4 pm	11%	Other trade materials	12%
4 pm – 5 pm	11%	Unload all deliveries.	11%

Table 8.1 indicates that the proposed timetable's overall percentage of allocated time does not differ from the quantum observed in the study, however, such a routine would facilitate uninterrupted CLT installation and reduction in stoppages and disrupted flow. Adopting such a regime together with a focus on minimising NVA activities would improve process flow and maximise on-site project productivity.

Each of the above construction process factors should be addressed at the pre-construction stage to minimise NVA activities, create good flow and maximise efficiency and productivity. This can be achieved by detailed planning and sequencing all the tasks involved, both off and on site, and production of prototypes (Kasbar, 2017) or simulation modelling with all relevant actors involved (Topliss et al., 2020). Collaboration with all parties, such as architect, structural engineer, specialist timber supplier, timber installation subcontractor, delivery logistics, crane crew and, where possible, builder, at an early stage in the pre-construction and preferably at initial design stage has proven to obtain the best outcome (Topliss et al., 2020; Waugh Thistleton Architects and Softwood Lumber Board & Forestry Innovation Investment, 2018; Woodard et al., 2019; Zumbrunnen et al., 2012). The panel installation sequence plan should be agreed and practiced with the crews and the importance of following it acknowledged. Agreed resolution to the discussed issues by detailed planning and hands-on workshops at the pre-construction stage with relevant team members will improve a project's overall mass timber productivity.

8.3 Baseline productivity and crane cycle times

Table 6.25 provided mass timber baseline productivity rates, at an activity level, in addition to baseline crane cycle time for low rise and mid-rise buildings. It is hoped that the matrix table may create a step in filling the gap in knowledge of mass timber.

8.3.1 Key Baseline findings

The key findings from the analyses for baseline measurements are listed below.
Finding 1: Crane cycle times did not significantly differ with increase in panel sizes. For example, small wall panels' baseline crane cycle was 9:23 minutes compared to 10:02 minutes for large wall panels. Although times did change between panel types of similar size, for example small floor panels at 5:46 mins to beam at 10:50 mins.

Finding 2: A faster crane cycle time did not significantly improve productivity outcome in m^2/hr. The fastest panel baseline crane cycle was for small floor panels at 5:03 and 5:46 minutes with productivity 57.72 m^2/hr and 44.49 m^2/hr, for low and mid-rise buildings respectively, Table 8.2 below. However, the large floor panels provided superior productivity at 121.05 to 140.19 m^2/hr with over a one-minute extended crane cycle. The large wall panels' baseline productivity was more than four times improvement to that of small wall panels, even though their crane cycle time was 39 secs. slower for mid-rise structure.

Table 8.2 Baseline crane cycle and productivity comparisons

	Floor panels Small	Floor panels Large	Wall panels Small	Wall panels Large
6-storey cycle (mins)	5:46	6:50	9:23	10:02
6-storey productivity (m^2/hr)	44.49	121.05	22.74	97.89
3-storey cycle (mins)	5:03	6:07	9:04	9:55
3-storey productivity (m^2/hr)	57.72	140.19	23.12	91.70

Although large panel crane cycles were slightly more time-consuming to install, both in the 3 and 6-storey studies, large panel installation resulted in 243% to 430% improved baseline productivity over small panels, supporting proposition 3.

Finding 3: Beam installation had a cycle time at 10:50 mins., which was the slowest in the mid-rise matrix. Beams provided the lowest baseline productivity of all panels, at 12.15 m^2/hr for low-rise and 9.65 m^2/hr for mid-rise structures. The reason for this low productivity, in the case of beams, was not solely due to its small size. For example, small floor panels at an average size of 4.3 m^2 provided a 44.49 m^2/hr baseline productivity outcome (6-storey) with a crane cycle times of 5:46 minutes. In the case of beams, the low productivity, 9.65m^2/hr, was due to a combination of its slow crane cycle time, 10:50 mins., and its small size, average area 1.7 m^2. Beams were the least productive of all panel categories, followed by column panels at 15.15 and 14.06 m^2/hr. It was deduced that the slow cycle time was due to the difficulty in its installation activity, which will be discussed later in section 8.5.

8.3.2 Common outlier causation

Outliers and their causation were identified from the normality control charts, chapter 6, Figures 6.2–6.4 and 6.7-6.15. The highest percentage of outliers were identified in floor panels, averaging 30.2% across the three towers, Table 8.3 below. The causation was believed to be the fast cycle “rhythm” frequently disrupted by the crane servicing other trades and the difficulty of returning to the previous rhythm, once the crane was available.

Table 8.3 Percentage of outliers removed

Panel type	Tower A	Tower B	Tower C	Average
Floor	32.2%	31.7%	26.6%	30.17%
Wall	16.0%	13.3%	22.4%	17.23%
Beam	7.5%	20.8%	20.4%	16.23%
Column	24.2%	30.3%	17.5%	24.0%

Although beams had a lowest average outlier percentage for Tower A, Table 8.3, it was not a true reflection as the majority beams for this building (7.5%) were not captured on camera as they were generally installed manually. Wall panel type had, from a practical perspective, the least number of outliers with a 17.23% average. The common outlier causations identified across all panel types and common between certain panel types are outlined below.

- Crew not ready:
  - When the crew was not ready, after the selected panel was hoisted to the installation deck, the panel was consequently left suspended until the crew were available. This frequently occurred on the first panel lifted following a meal break, stoppage or when the crew was working on other activities. It was often as a consequence of unsynchronised meal breaks between crane and installation crews.
- Atypical shape:
  - Installing an atypically shaped panel, i.e., odd shape (chapter 6: Figure 6.6) or 2 to 3-storey columns, which required adjustments to fit into location. These activities were observed to require multiple attempts to install varying from 2 to 10 to accomplish the task.

- Lost or illegible ID:
  - Excessive time was taken to verify panel identification and selection (from store) before the panel was hooked and lifted to the installation location, e.g., lost or illegible ID tag.
  - Lost or incorrect identification, often resulted in vertical panels craned to a wrong location, and then subsequently relocated to the correct location for installation.

- Closing an opening:
    - A common source was found, in the case of floor, wall and beam panels, to be closing an opening, i.e., placing a panel between two installed panels. This was more frequently caused in the case of beams (77%), which were required to be lowered into preformed rebates in and between two adjacent wall panels.
- Set out point:
    - A common outlier situation was where a wall or floor panel acted as a set-out point for the subsequent panels, e.g., a corner location (Figure 6.5, Chapter 6). A set-out point required extra verification time by the crew to ensure accurate panel location for correct alignment of the following panels.

The sources of the above identified outliers can be planned to be eliminated, or at least minimised, during design and pre-construction stages with involvement from designers, builder, suppliers, design logistics and timber specialists.

8.4 Key proposition findings

Proposition #1 was supported. Equipment was determined to be the significant leading and primary input resource. It is argued that industrialised on-site construction should be measured by construction equipment productivity (CEP) and not the traditional CLP. Although the quantity of labour within the mass timber installation crew was found not to be significant, it was found that there was an optimal crew size of two to three installers. A larger team was found to provide no significant benefit.

Proposition #2 was supported: differential in floor level height above ground did not cause significant variance in productivity rates.

Proposition #3 was supported: The findings determined that productivity significantly improved with larger panels. It was determined that small panels provided poor productivity, the beam and column baseline productivity, 9.65 and 14.06 m^2/hr, respectively, reinforced this argument. It can be concluded that to maximise on-site productivity, the use of small panels in industrial building design should be minimised, where possible.

Proposition #4 was supported: wind was found to be the prominent inclement weather predictor affecting CLT time. The proposed Equation 3 calculates the gross inclement weather delay effects on CLT installation floor level time. This equation can supplement Equations 4 and 5 once the panel design is decided.

Proposition #5 was supported: the proposed CLT productivity regression formulae, Equations 4 and 5, augmented the baseline matrix tables and propositions #1–3. It provides a theoretical model for predicting mass timber productivity. Equation 4 provides inherent value at the design stage to help select mass timber panel types and sizes to maximise productivity. By selecting different compilations of panel types, Equation 5 can forecast productivity outcomes to meet predetermined time constraints. From the subsequent results, the designers can select the most advantageous combination. Applying these formulae during pre-construction planning can provide the capability to forecast and assist in maximising productivity and improve crane cycle time efficiency.

The proposed productivity model, together with the CLT baseline productivity matrix aims to minimise current miscalculation of benchmarking productivity across timber structures with dissimilar mass timber panel types and configuration. One such example was in a study on Brock Common building at the University of British Columbia (Kasbar, 2017). Kasbar claimed that the Brock Common project productivity was an improvement on other CLT buildings, however, they were not similar. Kasbar compared the mass timber hybrid 18-storey post and CLT floor plate structure to five small prefabricated timber projects. (Forsythe et al., 2016). The only mass timber project in Forsythe's study was a 2-storey house, consisting of a CLT cellular style structure with small/medium size panels. These were not similar structures for a valid benchmark comparison. However, using the proposed matrix as a guide it would have been clear that Kasbar was comparing "apples to oranges".

8.5 Design attributes.

Production management is at the heart of lean construction and runs from the commencement of the project: that is design to handover of the facility to the client (Ballard et al., 2002). In essence, to obtain improved on-site outcomes the facility must be designed for manufacture and assembly. In assessing or evaluating this case studies' mass timber design philosophy, it became evident that small panels were prominent in all three buildings. The average size across all panel types was 5.5 m^2 for Tower A, 4.7 m^2 for Tower B and 5.8 m^2 for Tower C (item 5÷6; Table 5.2). Across all buildings, the average panel size was on the cusp of the small and medium panel category, which was associated with low productivity. To provide a more in-depth understanding, a detailed dissection was conducted.

8.5.1 Panel size

On average, 75% of Tower A, 72% of Tower B and 68% of Tower C's vertical panels (wall, columns and beams) were small panels (<5 m^2). Column and beams represented 61%, 67% and 62% of the vertical panels and were less than 3 m^2 in area, for Towers A, B and C respectively. There was an improvement for the horizontal floor panels with 22%, 34% and 22% being small panels, for Tower A, B and C, respectively.

Of note, in the case of floor panels, the average width was a slender 1.37 metres. This selected floor panel width was the standard width from the contractor's selected manufacturer, Binderholz GmbH. There are opportunities for productivity improvement by maximising floor panel sizes by selecting manufacturers with increased panel width, during the design stage. From investigation, nine out of the ten top CLT manufacturers plus the local Australian manufacturer do not have fixed standard widths and can produce panels of any width up to 2.95 m, without extra cost. Although the slim panel selection may have been material cost-driven or because of pre-alliance with a supplier, size needs to be an important consideration to gain improved productivity. Prior to commitment to a timber supplier, its standard sizes and size limitations need to be investigated early in the design.

In mass timber structural design, small panels, such as narrow floor and wall panels, beams and columns, where possible, should be minimised. The inclusion of small panels in a design needs to be considered against the additional on-site lifts and joints that can penalise and elongate the construction period. Small panels have the potential to reduce accuracy and structural performance compared to one large panel (Waugh Thistleton Architects et al., 2018).

One large panel with openings can be manufactured, faster and cheaper, instead of a multiple of panels producing the same configuration. This point is illustrated in the examples below, applying Design for Manufacture and Assembly (DfMA) principles. Figure 8.7 illustrates one configuration of nine panels, which can be substituted for one large panel as in Figures 8.8 (Woodard et al., 2019).

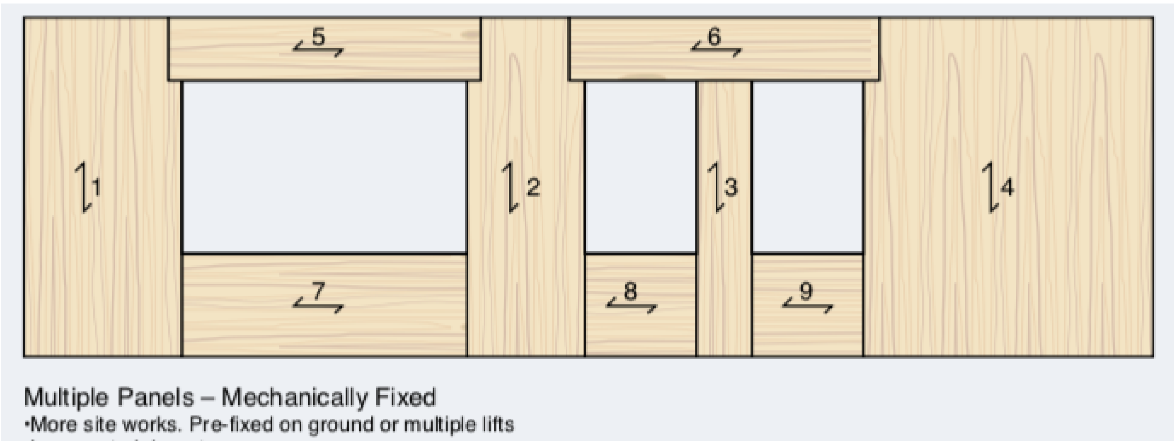


Figure 8.7 Openings by multiple panels

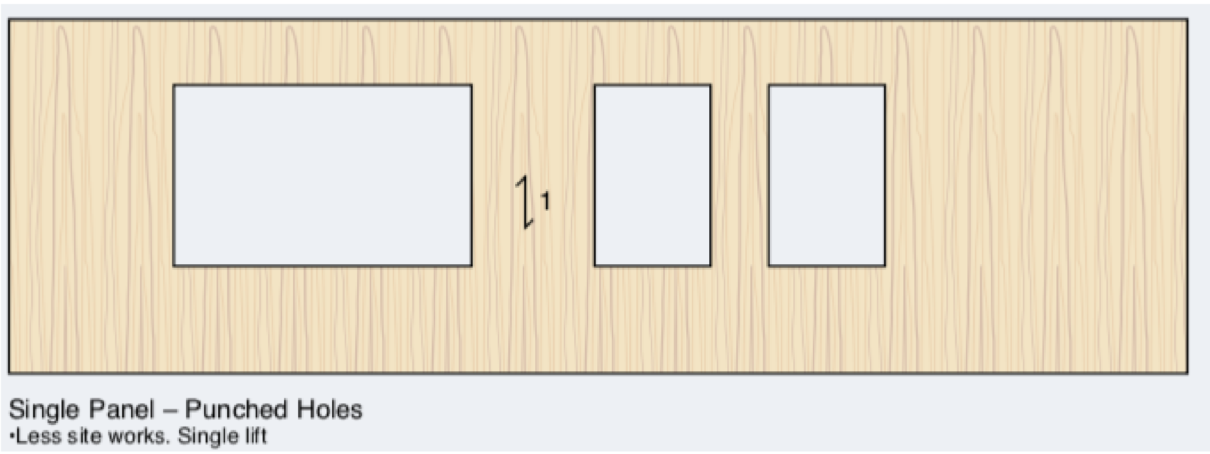


Figure 8.8 Single large panel with openings

The large panel in Figure 8.8 can be installed in one crane lift, whereas the alternative solution, in Figure 8.6, requires nine crane cycles if installed "just in time" from the truck, which includes two columns and two beams. The latter option will take considerably more time and cost to install, in crane and labour resources.

The cost to manufacture the multiple panels is also more expensive A study carried out by XLam Australia found that a seven-panel configuration to manufacture would take an extra 17 minutes machine time, costing an extra $400 plus an extra 6 quality checks to that of a single panel. The seven panels would entail an additional twelve crane lifts on-site and in excess of 85 mins. to install, (Hewson, 2019b), approximately an extra $1,000-1,500.

The majority of CLT manufacturers produce panels up to 16m. long and 2.95m. wide and their preference is to manufacture large panels rather than small (Hewson, 2019b). Where the adoption of large panels includes window and door openings, the resultant CLT off-cuts from forming these openings can be recycled on-site or at the factory for doors and tables. Often these off-cuts can be re-used within the project. For example, in Kingsdale School, the UK and MK40 Tower, UK, the cut–out material were used as furniture, retaining the value of the content within the project (Waugh Thistleton Architects et al., 2018). In general, depending on transport costs and site access, smaller panels will be more expensive than large to manufacture and install.

It is advantageous to optimise panel mass to reduce material use and therefore cost. Further savings are available by progressively reducing the thickness of wall panels up the height of the building which uses less material, reducing the overall loadings (Waugh Thistleton Architects et al., 2018).

8.5.2 Panel shapes

As discussed, beams, closing panels and atypical complex-shaped panels were all observed to have inherent installation difficulties, resulting in extensive installation time and consequently low productivity. The majority of atypical and closing panel installations were identified as outliers due to abnormal crane cycle time and therefore removed from analysed final sample sets, Figures 6.2–6.14, 6.7-6.15.

Atypical (or complex) shaped panels occurred in all three case studies and across all panel types, representing 3.2% of the total panels. Although not as common as small panels, atypically shaped panels took a long time to install, often over 32 minutes, the majority of which were identified as outliers. While basic routing of openings is included within the CLT manufacturing costs, complex cutting atypical panels can significantly increase these costs (Waugh Thistleton Architects et al., 2018). Consequently, the inclusion of atypical panels in the design should be avoided due to additional time and cost in both manufacture and installation.

As raised earlier in this chapter, the most prevalent beam outlier causation was found to be installation difficulties, often caused by beam-ends jamming when lowered into preformed wall panel rebates. This finding necessitated a review of the current configuration of CLT beams, especially with the conventionally rectangular shaped ends, as in the example Figure 8.9 below, an extract from Figure 8.7, illustrating the beam, panel 5, and its span direction.

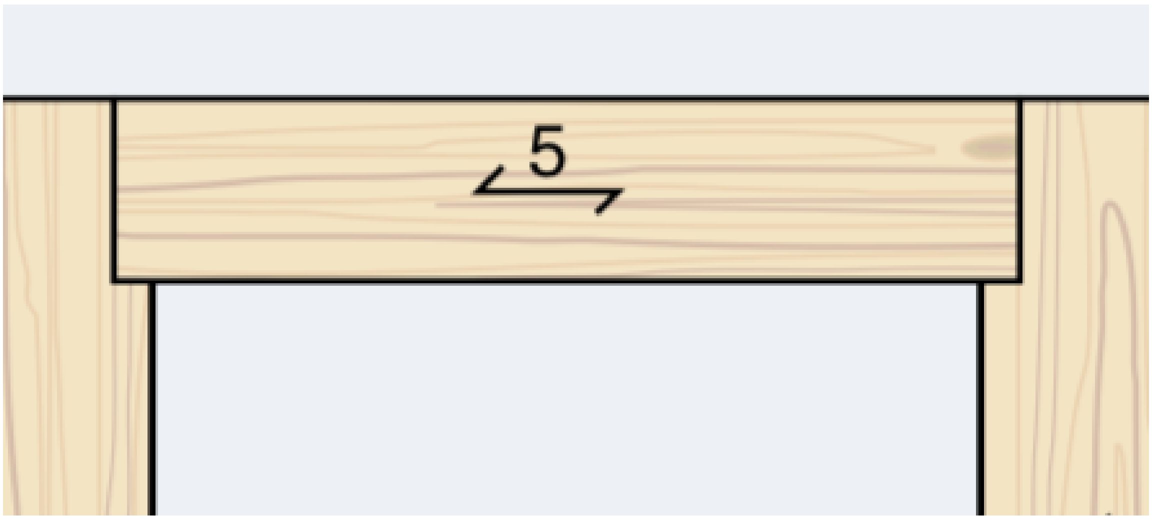


Figure 8.9 Conventional beam end configuration

A proposed solution, where a design necessitates beam inclusion, is to eliminate the jamming tendency by fabricating beam panels wedge-shaped ends, i.e., tapered or chamfered, as in Figure 8.10, instead of rectangular ends.

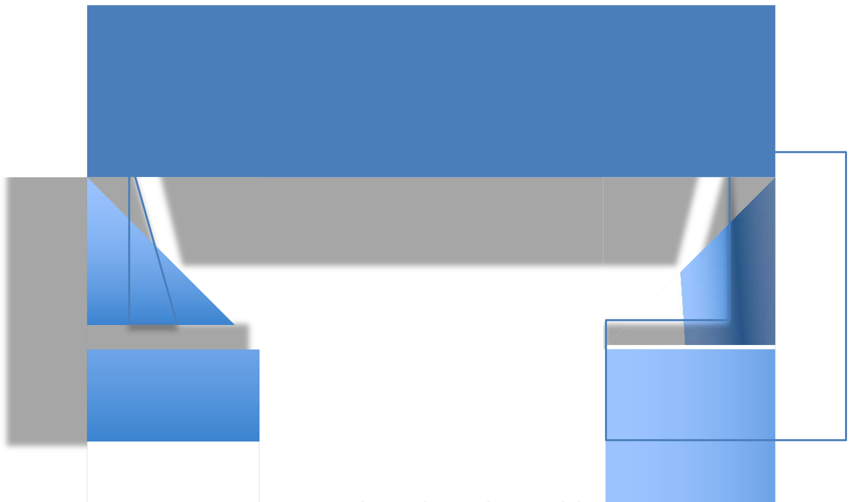


Figure 8.10 Proposed wedge-shaped beam connection

The proposed connection detail, in Figure 8.10, would facilitate a smooth installation, eliminate the tendency to jam and promote faster installation cycle times with improved beam productivity. The proposed jointing detail could be adopted where closing floor panels are a design deemed necessity. An alternative to the above beam solution is a "quick-fit" connection, e.g., Rotho Blaas' x-rad fitting (Rotho Blaas SRL, 2019), however this would incur an additional material cost.

It is recommended that design consultants should endeavour to minimise closing panels, beams, atypical/complex shape panels and small panels to improve the production efficiency of a mass timber construction.

8.6 Design Approach

8.6.1. Alternative design solutions

There are alternative structural designs to minimise or eliminate the need for beam panels, as in this case studies' cellular structures, in which the internal walls are loadbearing. There are solutions, such as: designing the structure with thicker floor panels to span openings in walls or adopting one of the various structural design systems as discussed in Chapter 3. Systems for consideration would be load bearing tenancy party walls (Zumbrunnen et al., 2012), a post and plate, post and beam design or CLT band beams (Hewson, 2019a; Kuzmanovska et al., 2018).

To minimise beams by increasing floor panel thickness, an increase of approximately 40 mm in panel depth may be required to span openings (Dunn, 2020b). Dependent on the quantum of beams and the actual increased floor panel depth for the individual floor layout, this option, in some circumstances, may not be found to be cost-efficient.

A CLT loadbearing "stacked" tenancy/ party wall design, may be found more suitable than the case studies' cellular structure. It would reduce the need for columns or beams as the vertical load travels directly through building via only the tenancy walls. This would eliminate load bearing internal apartment walls and provide flexibility to wall layout (Woodard et al., 2019; Zumbrunnen et al., 2012). Loadbearing party walls should be designed in locations to allow generally consistent spans for the floor panels that they supported (Woodard et al., 2019). Significant variation in span dimensions between adjacent floor panels may give differential displacements at junctions (Woodard et al., 2019).

Alternatively, a structural system applying a post and plate design may be more suitable to eliminate the need for CLT beams and in so doing provide flexibility of individual wall layouts. The loadbearing wall panels are eliminated in the post and plate design and, instead, are replaced by columns as vertical load transfer elements. With its maximum span limitation of 5.6 metres, larger grid sizes necessitate introduction of transverse beams to support the floor panels. However, often the introduction of these transverse beams creates problems with reticulating services in the ceiling space due to the resulting deep beams and consequently increases floor to floor heights (Hewson, 2019a), as Figure 3.11, Chapter 3.

A new mass timber engineering design system that overcomes the need for these deep beams is the CLT band beam concept, Figure 3.12. The narrow depth wide "band beams" are similar to a secondary floor panel, which transfers the load onto the columns (Hewson, 2019a). This design system is able to provide a 9.00m x 9.00m grid without the need for loadbearing walls (Hewson, 2019a). This design will provide, as the post and plate, the flexibility of internal floor layouts with a selection from CLT and lightweight stud and plasterboard.

These latter three alternative structural systems, provide flexibility for internal apartment layout by the substituting the apartment's CLT interior walls with lightweight stud walls, thus eliminating beams and small panels. In addition to meeting structural performance, selected wall systems will also have to demonstrate compliance with acoustic and fire performance requirements. However, this substitution will necessitate additional trade activities and materials stored on each floor level. The consequence will be congestion for following trades, i.e., services contractors, extra time and reduction in the building's timber mass and therefore reduction in carbon storage.

As each project is unique, there is no one solution that provides the best outcome for the design of every mid-rise timber building. Designers need to find a balance between structural design system, structural efficiency, fire resistance, acoustic performance, ease of fabrication, constructability and cost in order to optimise the overall project delivery (Woodard et al., 2019).

8.6.2 Early design stage benefits

From the discussion above, it was concluded that the decision to adopt mass timber should be during the project's concept design stage. This would provide the most efficient and beneficial outcome. It is also essential to involve a timber specialist engineer from this early stage to provide the best structural solution and delivery to site (Zumbrunnen et al., 2012) and where possible, early contractor involvement (Ballard et al., 2002; Woodard et al., 2019). Figure 8.11. below, provides a generic design flowchart from concept to construction to assist in an explanation on this point. A number of recent very successful timber projects have also demonstrated the benefits of early contractor involvement (ECI) process that can significantly de-risk the project, concerning cost, time, quality, constructability and commercial arrangements (Woodard et al., 2019).

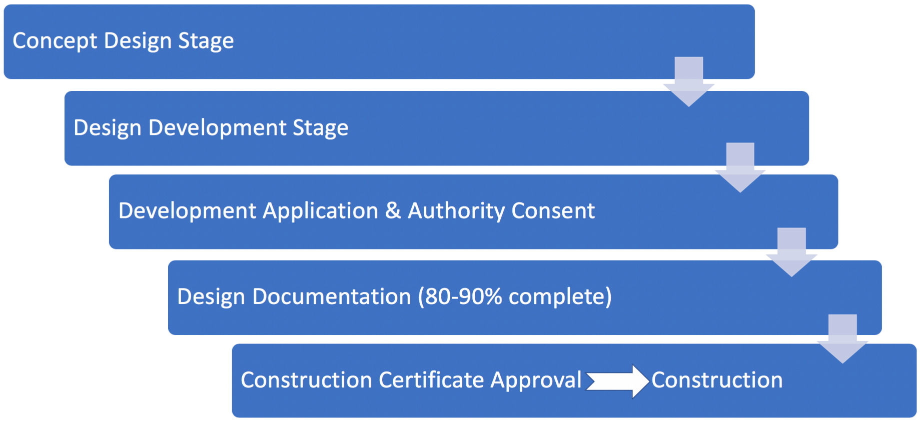


Figure 8.11 Typical project design process

An early and interactive collaboration involving all the project team usually provides the optimal design solution. This approach is particularly beneficial to the structural engineer when it includes the timber system specialists and, where possible, early builder involvement (Woodard et al., 2019). Where is it not possible to convene all parties, having representatives of each relevant speciality assigned to each team will always be essential (Ballard et al., 2002). Project team collaboration, during the initial design stages, will readily address issues such as fire and acoustic requirements and procurement and logistic considerations (Woodard et al., 2019). Such matters will direct the structural approach taken, materials and systems used and which building elements can be supplied and assembled on-site (Woodard et al., 2019).

Designing from the outset with acknowledgement of the system's benefits and restrictions will result in a far more efficient solution, as CLT components do not perform the same as concrete or steel. All the associated benefits are encompassed when this approach is adopted. While designs may be adapted for CLT at a later stage, this will often result in compromised designs, increased costs and missed opportunities (Waugh Thistleton Architects et al., 2018).

At the concept design stage, with load-bearing wall structures as discussed above, or cellular structures as in the research case studies, the architect and engineers can configure the floor layouts to minimise beams, align loadbearing wall layouts through floor levels and maximise the use of large panels. Repeating the same floor plan on each storey will allow load-bearing walls to align vertically in the building.

If the floor plan needs to be changed, it should only be to the top floor (i.e., penthouse). It is structurally challenging to accommodate layout changes at lower levels (Woodard et al., 2019).

If a building is initially designed as traditional reinforced concrete, and then later the design is converted to mass timber structure it becomes problematic (Woodard et al., 2019; Zumbrunnen et al., 2012). In the redesign the designers would need to consider panel span limitations and the deeper timber beam section required on the initial floor layouts relative to that of a reinforced concrete structure, which does not have the same design limitations. Designers can often face changes in required solutions for fire and acoustic compliance due to differences in materials characteristics (Woodard et al., 2019; Zumbrunnen et al., 2012). There can often be a floor-to-floor misalignment of loadbearing walls, i.e., not "stacked", or large floor spans to accommodate. When converting structures, this may necessitate compromises in floor layouts, consequently overall design philosophy and lost potential benefits and efficiency of mass timber. Where projects are procured in a way where wood is the second option to conventional structural materials, the learning process will start each time at zero (Zumbrunnen et al., 2012).

It is therefore vital to get a timber specialist engineer involved from the start of the project to get the best solution to the structure and delivery to site. CLT needs to become a natural choice for designers, like steel and concrete. Architects should think from the start of a project that it could be CLT and involve the engineers at that stage (Zumbrunnen et al., 2012).

To convince clients and contractors to use CLT, it is crucially important that they understand the benefits of the whole building process when compared to traditional methods (Topliss et al., 2020; Woodard et al., 2019; Zumbrunnen et al., 2012). Once the decision is made to adopt a mass timber structure, it would be prudent for the designers to incorporate current empirical knowledge into the design to maximise mass timber efficiency. The designers must have the tools to design an efficient building, yet creative, both in buildability and environmental sustainability aspects.

8.7 Summary

The need to maximise a project's overall mass timber productivity potential by pre-construction planning its implementation, has been discussed. It has been determined that project-level productivity improvement could be achieved by designing efficiently for manufacture and assembly and also by changing the on-site process from the tradition approach to a production process to suit industrialised systems and in so doing minimising non- value-added activities. With regard to the three cases, there was similarity in the number of non-value-added activities and productivity for the various panel categories, even though each building had different design and volumes. The only case that varied was Tower A in which implemented a more industrialised, "just in time" on-site process on the first two floor levels. This supported the argument providing improved flow and productivity for those floors.

The above dissection of design and construction attributes confirm the importance of implementing mass timber efficiency during the early design stage and the detailed pre-construction stage. Accordingly, Figures 8.12 and 8.13 below, propose a merged model for mass timber design and construction efficiency. It augments the productivity model from proposition #5 and the formulated units from the baseline matrix.

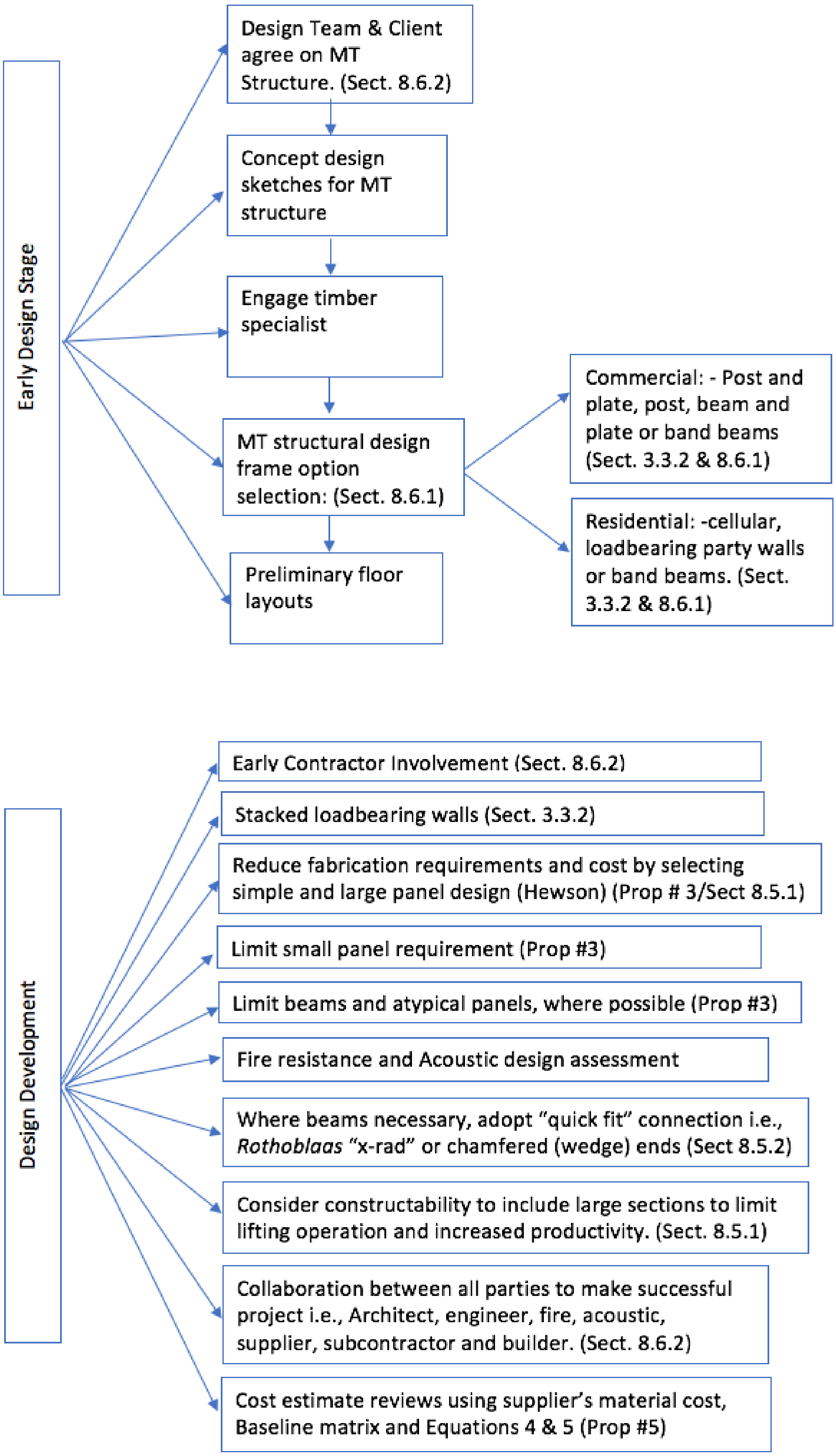


Figure 8.12 Merged design model for productivity efficiency

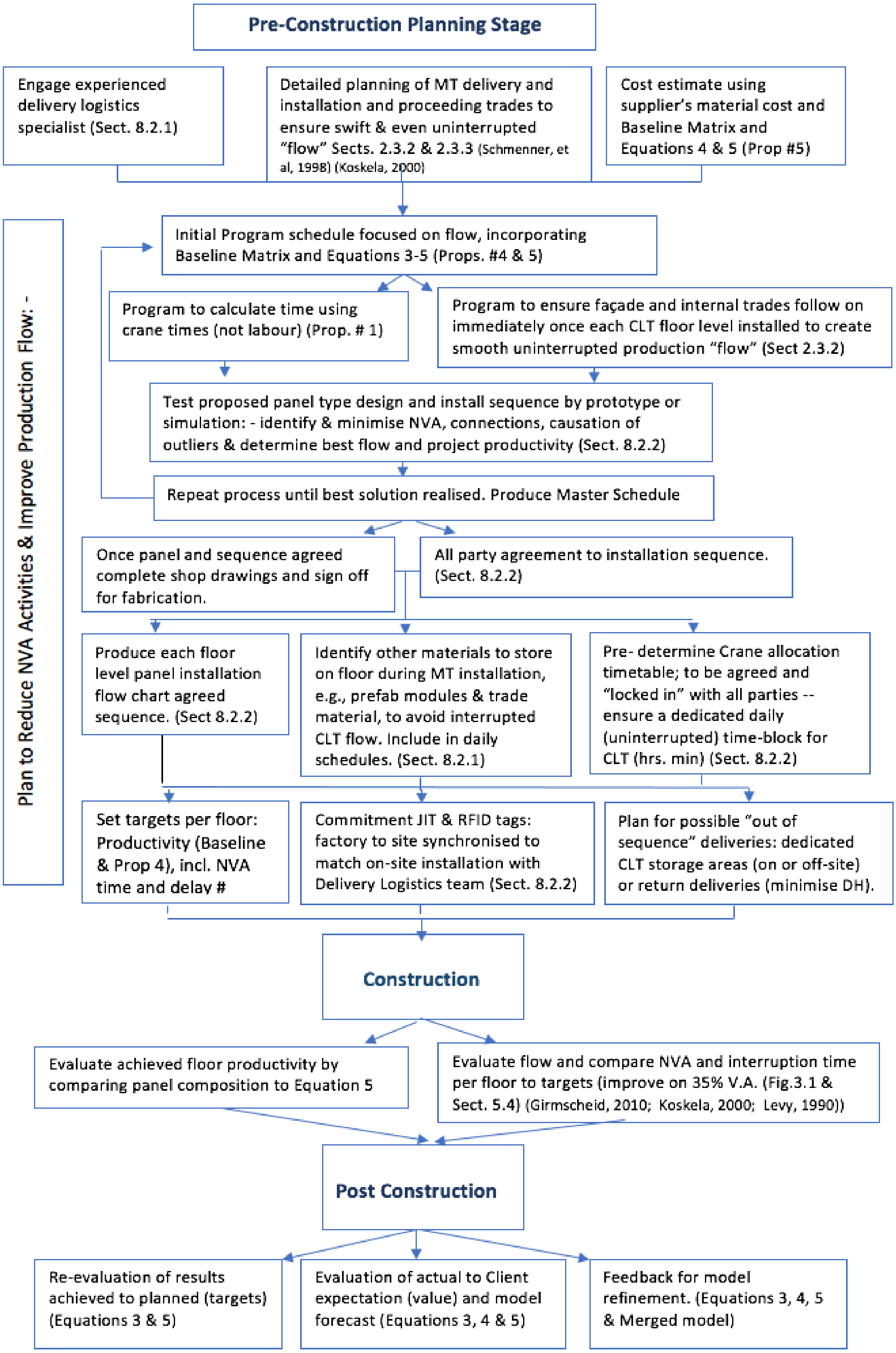


Figure 8.13 Merged construction model for productivity efficiency

The above combined merged model in Figures 8.12 and 8.13 provides a detailed view(scheme) of the "how and when" of each important step within a proposed project's overall process in order to maximise its project level productivity efficiency. The process commences at the client's initial mass timber decision and continues through the various stages to post-construction. The model identifies the critical stages and relevant actions that require detailed focus during the overall design and construction process.

The merged model is based on findings from the cross-case study analyses. Further verification by future mass timber case studies would be beneficial to strengthen and improve the model's forecasting model and baseline matrix. To achieve this the above model provides a "gap finding feedback process", between expectation and final evaluation. It provides opportunity for future investigation to further verify the findings, possible identification of rogue factors and their subsequent incorporation for the model's evolution.

The model, together with the productivity model and baseline matrix, provides an ongoing framework for assimilating mass timber projects. The model incorporates both the design process and detailed pre-construction planning to facilitate on-site mass timber productivity efficiency based on the three case studies.

The merged model in Figures 8.12 & 13, culminating in the proposed framework to manage improved on-site productivity of mass timber multi-storey buildings, is significant for three reasons:

- The model is process-driven, outlining the sequence of events from the client's decision to adopt mass timber to the completion of construction. The framework's sequence provides ability to address the critical factors to maximise improved productivity and reduction in (NVA) waste.
- The model allows for evaluation of productivity using the productivity forecasting Equations 3, 4 and 5, and baseline matrix, Table 6.25, during design and pre-construction.
- The model identifies the critical factors to address during both the design and pre-construction stages.

Chapter 9 Conclusion

9.1 General

The main research objective was to gain a theoretical conceptualisation of mass timber, as an example of industrialised building systems, as a significant determinant to improve on-site productivity in multi-storey construction. The theoretical evaluation of productivity, industrialised building systems and specifically mass timber was investigated by way of a literature review. A multi-case study was conducted in an Australian context to examine mass timber's on-site productivity and identify the significant related factors on three multi-storey buildings.

The main aim of the research was to address the current gap in on-site industrialised mass timber multistorey construction in order to improve its general take up and industry's overall productivity. To achieve this, the study also aimed to assist the industry in a deeper understanding of the on-site process and factors to promote mass timber's improved productivity potential by way of undertaking quantitative empirical research on multi-storey buildings.

In summary, the research aims were to:

- Provide a measurable quantitative benchmarking model of on-site baseline productivity for the various size categories of mass timber CLT panels (floors, walls, beams and columns) to assist in estimating its productivity on projects.
- Identify potential areas for productivity improvements in mass timber construction.
- Identify the significant site related variables such as size-related panel productivity, floor height, weather and the leading input resource (i.e., crane or labour).
- Propose an algorithm to assist in predicting mass timber productivity.
- Propose a merged model framework to maximise the benefits of mass timber construction during design and pre-construction stages.

This chapter discusses the level to which the above objective and aims have been met. The first aspect of discussion concerns the literature review as to the subject's fit in the context of the industrialised building systems significance as a potential remedy for the construction industry's history of poor productivity performance. A discussion then follows on to the main research question, propositions and conceptual models from quantitative empirical research and their research contribution. The research limitations on the research and future objectives are then discussed.

9.2 Literature review

The literature review established a gap in the construction knowledge of on-site performance industrialised systems using mass timber. It was identified that whereas most other industries had improved their productivity through their up-take of new technologies, the construction industry had not and as a result its productivity had stagnated and declined over the past four decades (Australian Productivity Commission, 2014; Barbosa et al., 2017). Industrialised building systems are an enhancer of improved production workflow and output and a more efficient alternative to the current haphazard on-site construction process (Girmscheid, 2010; Sacks, 2016; Seppanen, 2009). An investigation into traditional on-site work practices indicated that approximately 35% of work is attributed to value-added activity with the resultant 65% being wasted activities, resources and time (Girmscheid, 2010). As a consequence, to maximise the performance of industrialised building systems current on-site processes require a change to a more production process with a focus on workflow construction with a focus on workflow, akin to a lean construction approach. Although there is qualitative evidence of improved on-site productivity and benefits using mass timber, the construction industry has an underlying reluctance to embrace and adopt such new technology (Bayne et al., 2006; d'Errico, 2016; Kremer, P. D. et al., 2015; Lehmann, 2012b, 2013; Mahapatra et al., 2008; Riala et al., 2014). This risk-averse attitude and lack of up-take emanates from a gap in knowledge due to the limited empirical quantitative information and lack of knowledge transfer about mass timber (d'Errico, 2016; Forsythe et al., 2019b; Lehmann, 2012b).

The review culminated in the formation of the main question and the five associated propositions that focused on the quantitative analyses of mass timber on-site productivity evaluated from a multi-storey construction perspective.

9.3 The research question

The research question was:

If and how on-site productivity baseline rates can be developed in a reliable way to assist predictable installation expectations for mass timber panels.

It aimed to provide independent quantitative data to help fill the gap in current information available to industry in order for it to be disseminated to facilitate estimating and benchmarking and specifically to assist in mass timber's general up-take.

The objective of the main question was to develop productivity and a crane cycle baseline matrix (Table 6.25) to assist contractors and designers in estimating and assessing mass timber productivity efficiency. Analyses established productivity (m^2/hr) and crane cycle time matrix for both 6-storey and 3-storey buildings, at the lower and upper range of mid-rise buildings. The findings revealed that productivity increased according to panel type and with an increase in panel size. However, crane cycle time did not significantly differ between panel type or size, except for beam panels, which took longer to install and provided the lowest productivity.

The contribution to knowledge that the main question findings provided is the first mass timber baseline matrix known with detailed productivity and crane cycle measurements, for each CLT panel category size and type. The matrix (Table 6.25) also provides a pessimistic and optimistic range of expected outcomes for each category as outlined in Tables 6.19 to 6.24. The only known previous four quantitative studies on this subject by Forsythe and Kasbar had only provided general productivity findings. Neither of these previous studies had drilled down to the panel sizes or types to provide either crane cycle times or productivity rates (Forsythe et al., 2016; Forsythe et al., 2019a; Forsythe et al., 2019b; Kasbar, 2017).

9.4 Propositions #1–5

Proposition #1

The case study provided analytical findings to support proposition #1 that equipment, i.e., the crane, was the leading on-site productivity input resource for prefabricated timber construction. Labour, although a vital input resource, was found not to be the primary leading input contributor. It was determined that the optimal crew size was two or three installers, and greater numbers were found to be inefficient. The findings from proposition #1 are a contribution to knowledge because although previous studies, such as Forsythe and Sepasgozar (Forsythe et al., 2019b), had alluded this be the case, they had not provided quantitative analytical findings to support the statement proposed.

Proposition #2

Analyses supported proposition #2 that mass timber panels installed on lower floor levels achieve similar on-site productivity outcome as those installed on higher floor levels. No significant difference in on-site productivity was found between the floor levels, although there were small variances in the intermediate floors. This finding is an extension to theory and assists in filling the gap in quantitative information on mass timber knowledge. Although Kasbar with his seventeen timber storey building study and Forsythe & Fini, with their nine storey building, had the opportunity to analyse this proposition, neither had (Forsythe et al., 2019a; Kasbar, 2017), although the findings of Kasbar's study indicated similar and faster installation cycles at higher levels.

Proposition #3

There was significant support from the findings to endorse proposition #3 that larger surface area size panels increased productivity output compared to smaller panels. Although the type of panel had, in some cases, affected the productivity outcome, with floor panels being the most efficient, all types increased their productivity with larger panel sizes. Panel size is a crucial issue for consideration during a mass timber project's design stage to provide on-site productivity efficiency. Proposition #3 findings are the only known quantitative evidence that larger prefabricated timber panels offer increased productivity and therefore, a contribution to knowledge.

Proposition #4

The findings supported propositions #4a that inclement wind weather negatively affects the on-site installation productivity of prefabricated timber panels. Proposition #4b that rain adversely affects the on-site installation productivity of timber panels was also supported. The wind was found the most significant of the two factors to affect on-site productivity and overall time adversely. From these findings, the first known model to forecast the overall effect of inclement weather on the floor cycle time was established in Equation 3 to extend theoretical knowledge in mass timber.

Equation 3:

Total value-add CLT time with inclement weather effect (hrs) per floor level =

$$17.32+1.275*(X_1)+0.797*(X_2)$$

Where X_1= wind time (hrs) and X_2= rain time (hrs).

Proposition #5: productivity forecast regression model

The critical productivity factors determined from the research findings were amalgamated into a unique multivariate regression formula to forecast on-site CLT panel installation's daily productivity, which supported proposition #5. Two productivity models, Equations 4 and 5, were developed to provide a mass timber productivity tool for both designers and contractors. They provide the ability to evaluate a mass timber project's proposed design and mass timber installation process's productivity efficiency before construction. The model for predicting the mean daily productivity of the panel type was established in the regression formula **Equation 4** below:

(Daily Mean) panel type productivity $= 66.068-315.326*(X_1) + 6.552*(X_2) - 5.38*(X_3) + 1.03*(X_4) - 0.351*(X_5) + 3.264*(X_6)$

where: X_1= Mean crane cycle time (hrs); X_2= Mean panel area (m^2); X_3= Panel type (Floor=1, Wall=2, Beam=3, Column=4); X_4= Floor level, Ground Floor=1, Level 1=2, Level 2=3…); X_5= Installation crew size (number of workers); X_6= Crane type (mobile crane=0, tower crane=1).

Equation 4 was further developed to provide a project level productivity forecasting model in **Equation 5** below:

(Mean daily project productivity) Pp = *Pf*af/ta + Pw*aw/ta + Pb*ab/ta + Pc*ac/ta*

where: Pf = Mean floor panel productivity; Pw = Mean wall panel productivity; Pc= Mean column panel productivity; Pb= Mean beam panel productivity; af = project's mass timber floor area; aw = project's mass timber wall area; ab = project's beam area; ac = project's columns area; ta = total combined panel area.

Both models are a contribution to extend theoretical knowledge in mass timber as these are the first mass timber forecasting quantitative productivity models known which can assist in its industry's up-take.

9.5 Merged model

The design and construction findings from the study, culminated in the development of a productivit*y* merged model as presented in Chapter 8, Figures 8.12 and 8.13. The merged model adopted a flow chart format to illustrate the process for the delivery of a project, from the initial client's mass timber decision, through the design stage to the post-construction phase. The model identifies the crucial steps and relevant actions that are required during the overall process to maximise the project's production and productivity efficiency. This merged model presents a framework that focuses on the design and pre-construction processes of a proposed mass timber project to produce beneficial outcomes and value during and after its construction stage.

An investigation into design attributes found that early inclusion of mass timber in a project's design contributed to maximise its on-site productivity efficiency. An early design decision for mass timber provides an opportunity to effect design for manufacture and assembly and maximise the proportion of large panels (≥10 m^2), reduces the need for beams, aligns floor-to-floor loadbearing walls and provide the optimum structural design option.

After the decision to use timber, the flow chart leads onto the design stage. At this stage the team needs to action five points during the concept design and eleven points in the design development stage to ensure that the critical determinates are addressed. To provide the maximum benefit, it is recommended that all relevant parties, including a timber specialist, manufacturer and early contractor be involvement in the design stages. To complete the design process, the designers are to evaluate the proposed design for productivity efficiency, using the forecast model.

Following the design process, during the pre-construction process a detailed pre-construction planning and subsequent prototype or simulation modelling to evaluate in detail the proposed mass timber on-site construction process and workflow can be formulated. The purpose of these two activities is to determine the proceeding tasks such as the master schedule, crane allocation time and delivery logistics, evaluation of installation sequence and connections, and minimisation of non-value-added activities. Then, together with the proposed productivity model, the forecasted project on-site mass timber productivity can be appraised and, if required, previous decisions made can be re-evaluated to attain maximum production efficiency.

It was found that detailed pre-construction planning was significantly crucial for industrialised building projects. Meticulous pre-planning with all parties enabled minimisation of non-value added (NVA) activities and resource wastage, consequently improving on-site mass timber performance. A focus, during the pre-planning stage, is essential on proposed delivery logistics and crane allocation time, as well as workflow by applying lean principles and a just in time approach to minimise NVA activities. The findings identified NVA activities to be predominantly associated with a lack of focus on workflow, due to using traditional on-site processes, poor delivery logistics, lack of predetermined trade activity coordination and poor information transfer.

Previous studies lacked detail in how factors influenced or improved mass timber productivity or how to evaluate resulting outcomes. This research expands mass timber knowledge further in terms of providing the key factors that affect the on-site activity, the on-site process and the project level productivity during both the design and construction stages. Propositions #1 to #5 identify significant factors that affect on-site productivity. The forecasting productivity model (Equations 4 and 5) provides the weighted effects of these factors on the resulting productivity. The findings of these propositions and the forecast equations were used to develop the merged model that provides a process-driven framework to manage the design and pre-construction process for productivity efficiency.

The research findings in respect of the research question (Table 6.25), propositions #1 to #5, the productivity forecasting models (Equations 4 and 5) and the merged model (Figures 8.12 and 8.13) extends the existing theoretical knowledge to improve the on-site productivity of industrialised building systems, specifically mass timber.

9.6 Practical commercialisation of study's findings

The study's findings can be practically used as guideline for future similar mass timber projects in respect to:

- estimating and forecasting mass timber costs,
- at design stage to design for manufacture and assembly to create the most efficient overall process,
- at pre-construction planning stages to minimise on-site waste of resources, delays, non-value add work and so create a smooth workflow.

Estimators can establish costs of mass timber installation using the developed baseline installation panel installation productivity rates and cycle times (Table 6.25) and using the finding that an installation crew of 3 carpenters was the optimum size, with a crane driver and two riggers. As the cycle time and productivity rates are in hours, these rates can be used in any state and, potentially any country by multiplying the times by the carpenter's local hourly cost rates. To arrive at an overall mass timber cost, one would need to include an additional worker to follow up behind installation crew to check and rectify any missed fixings to panels, cost of equipment such as the crane, access equipment and back-braces for wall panels and the cost of timber panels delivered to site from the manufacturer. For non-similar mass timber projects, for example high-rise multi-storey structures, the methodology applied in the case study can replicated.

For forecasting mass timber duration for construction programmes and for feasibility studies the Equations 4 and 5 can be used to estimate the overall project mass timber productivity and from this using the total area of the project's mass timber the overall time period for installation of the panels can be calculated. In addition, using Equation 3 and historic inclement weather records of the region and season for installation, the user can forecast the potential additional time for the effects of inclement weather on the installation period for that project.

At Design Stage from the concept the design team can adapt the merged model, Figure 8.12, for their mass timber project and follow the steps and explanation outlined, in sections 8.7 and 9.5 above, to potentially achieve an efficient design for manufacture and assembly.

Similarly, at the pre-construction stage for a mass timber project, the construction team can adapt and follow the steps of the relevant merged model, Figure 8.13, and as outlined in sections 8.7 and 9.5, above, to improve the construction on-site process to align with an industrialised process and so reduce waste, delays and non-value add time, consequently, improve workflow, overall productivity and value. The merged model proposes evaluation and feed-back at completion of each future project. Similarly, it is recommended that Equations 3, 4 and 5 be further tested on future mass timber projects to provide additional verification and therefore confidence in their accuracy.

9.7 Limitations & recommendations for future research

This research has provided a more in-depth insight into industrialised building systems, specifically an understanding of how mass timber's potential productivity and benefits and on-site processes can instigate positive change to the construction industry. However, this study cannot be considered as a100% generalisation of all mass timber building types. Specific areas that require further investigation extend from the models presented and supported propositions mentioned in this and the previous chapter. These areas of further research emanate in part from the limitations of this study as mentioned below.

The limitations in connection with this research are:

- The productivity outcomes and crane cycle times were attained from three case study multi-storey buildings, each located within the same project and built by the same construction organisation. While this presented benefits in keeping the significant factors constant, it would provide further robustness to study a variety of projects by different organisations in future research.
- The case study included timber structures up to a maximum of seven stories in height. It would be constructive for future case studies to incorporate taller multi-storey structures, when and if available. Such studies could determine whether mass timber installation productivity reduces at floors levels in excess of seven storeys compared to lower floor levels.

In addition to research directions suggested from the above limitations, recommendations for future studies are:

- Further case studies to test and verify Equations 3, 4 and 5, and if identified, adjust for any anomalies.
- Studies to ascertain whether mass timber projects produce less on-site waste than created by traditional construction.
- Quantitative research to verify whether the main contractor's preliminaries cost savings would be realised with the use of mass timber compared to traditional construction.
- Quantitative case studies on multiple mass timber projects to verify the significance of detailed pre-planning, focusing on minimisation of NVA activities and flow on the mass timber project level productivity.
- Studies to further investigate the significance of incorporating a *just-in-time* lean construction approach to mass timber installation to ascertain if it would a) avoid products being stored on-site, b) reduce the requirement

and cost for weather protection, c) reduce double handling, and d) reduce overall resource (and material) wastage.

There are opportunities to continue to improve the utilisation of mass timber and achieve its benefits by way of further quantitative studies, dissemination of mass timber information and change of attitude of the general construction industry. The academic sector can take the lead in this and increase mass timber’s utilisation and awareness by its unique ability in reaching both industry and public audiences (d'Errico, 2016). Universities have well established mechanisms for disseminating findings of research and investigation for the benefit of all.

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Appendices

Appendix 1: Pilot Study Projects

Pilot study sample details.

Project No.	Building type	Floors levels above ground	Prefabricated assemblies measured	Crane type
1	Single Apartment building.	4	Nil (traditional construction)	Remote-controlled fixed hammerhead crane, 40-metre reach.
2	2 x Townhouses (Single building)	2	Timber floor cassettes	Mobile crane (20 tonnes, all-terrain, 15m reach,)
3	12 x Townhouses (a complex of 2 rows)	2	Timber floor cassettes; pre-clad framed walls	Delivery truck with remote control crane, 20m reach.
4	Single Apartment building.	3	Timber floor and roof cassettes	Mobile crane (130 tonnes, 45m reach).
5	3 x Apartment buildings	3	Timber floor cassettes	Remote-controlled fixed hammerhead crane, 40-metre reach.
6	1 x large single dwelling (steep site, difficult access)	2	CLT wall and floor panels, engineered beams	Mobile crane (40 tonnes, 20m reach)

Projects:
1. Traditional constructed medium-high apartment building, Mosman NSW (manual study)

2. Two townhouses, Carnarvon Court, Qld Dec 2014: Timber floor cassettes (time-lapse digital video)

3. Townhouses, Cranbourne East, Vic 2015: pre-clad wall panels and floor cassettes time-lapse digital video & manual time & motion sample)

4. Apartment building Westmeadows, Vic 2015-16: timber floor cassettes (time-lapse digital video)

5. Apartment buildings Highfield Circuit, Port Macquarie, NSW 2015-16: timber floor cassettes (time-lapse digital video & manual time & motion sample)

6. House, Maianbar, NSW: CLT and glulam beams 2015 (time-lapse digital video & manual time & motion sample)

Appendix 2: Ethics Compliance

1. Completed Module1 Research Integrity and Code of Conduct – 18 October 2015.

2. Completed Modules 2 Plagiarism and Misconduct, 3 Risk Assessment, 4 Risk Management and Health and Safety and 5. Project Management completed 1 November 2015.

3. UTS Approval Number ETH 16-0462 for Richard Brisland for Research on Mass Timber Productivity in Multistorey Construction.

4. Copy of Ethics Information Sheet issued for agreement from participants of interviews and organisations for recording activities.

INFORMATION SHEET

MASTER TIMBER PRODUCTIVITY IN MULTISTOREY CONSTRUCTION (AND UTS APPROVAL NUMBER ETH16-0462)

WHO IS DOING THE RESEARCH?
My name is Richard Brisland and I am a research assistant at the University of Technology Sydney. (My supervisor is Professor Perry Forsythe)

WHAT IS THIS RESEARCH ABOUT?
This research is to find out about productivity benefits concerning new methods of prefabricated timber construction

IF I SAY YES, WHAT WILL IT INVOLVE?
I will ask you to give details of your involvement with and views on the use of prefabricated timber components on your project and answer some questions. I also want to watch the process to gain a firsthand understanding of what is involved.

ARE THERE ANY RISKS/INCONVENIENCE?
There are very few if any risks because the research has been carefully designed. However, it is possible that the questions may take approximately 20 minutes of your time.

WHY HAVE I BEEN ASKED?
You have a direct involvement in the process and can give me the firsthand information I need to find out the pros and cons of prefabricated timber construction, from a productivity perspective.

DO I HAVE TO SAY YES?
No, it is purely voluntary.

WHAT WILL HAPPEN IF I SAY NO?
Nothing. I will thank you for your time so far and won't contact you about this research again.

IF I SAY YES, CAN I CHANGE MY MIND LATER?
You can change your mind at any time and you don't have to say why. I will thank you for your time, and won't contact you about this research again.

WHAT IF I HAVE CONCERNS OR A COMPLAINT?
If you have concerns about the research that you think I or my supervisor can help you with, please feel free to contact me (us) on [redacted] or (02) 9514 8725.

If you would like to talk to someone who is not connected with the research, you may contact the Research Ethics Officer on 02 9514 9772, and quote this number *(ETH 16-0462)*

Appendix 3: Case Studies High Level Review Summary

HIGH LEVEL SUMMARY PANEL AREAS MEASURED -TOWERS A, B & C — R.Brisland

TOWERS A BLOCK	FLOOR #	TOTAL WALL, BEAM & COL. PANELS AREA/ M2	MEASURED WALL PANELS AREA/ M2	TOTAL FLOOR PANELS AREA/ M2	MEASURED FLOOR PANELS AREA/ M2	TOTAL STAIRS AREA / M2	MEASURED STAIRS AREA / M2	TOTAL COLUMNS/ BEAMS AREA/M2	MEASURED COLUMNS/ BEAMS AREA/M2	ACTUAL WALL PANEL QUANTITY	MEASURED WALL PANEL QUANTITY	ACTUAL FLOOR PANEL QUANTITY	MEASURED FLOOR PANEL QUANTITY	ACTUAL STAIR PANEL QUANTITY	MEASURED STAIR PANEL QUANTITY	ACTUAL COLUMNS BEAM QUANTITIES	MEASURED COLUMNS BEAM QUANTITIES	ACTUAL TOTAL # PANELS	MEASURED TOTAL # PANELS	ACTUAL TOTAL M2 PANELS	MEASURED TOTAL M2 PANELS		
A	GROUND	491.61	439.71			4.61		incl	incl	101	52			2		incl	incl	103	52	496.22	439.71		
A	FIRST	501.27	489.9	381.89	380	9.79		incl	incl	100	60	44	43	2		incl	incl	146	103	892.95	869.9		
A	SECOND	504.96	460.17	381.29	381.29	9.83	17.32	incl	incl	99	58	43	43	2	4	incl	incl	144	105	896.08	858.78		
A	THIRD	503.31	414.5	381.89	381.89	9.83	8.66	incl	incl	98	57	43	43	2	2	incl	incl	143	102	895.03	805.05		
A	FOURTH	507.68	450	381.89	381.89	9.83	4.33	incl	incl	98	58	43	43	2	1	incl	incl	143	102	899.4	836.22		
A	FIFTH	601.64	478.07	380.66	316.89	5.5		incl	incl	192	130	43	37	2		incl	incl	237	167	987.8	794.96		
A	ROOF			44.93	30.68			incl	incl			7	3			incl	incl	7	3	44.93	30.68	%age Area Capture/ Measured	%age Panels Captured/Measured
TOTALS TOWER A		3110.47	2732.35	1952.55	1872.64	49.39	30.31	incl	incl	688	415	223	212	12	7	incl	incl	923	634	5112.41	4635.3	90.67%	68.69%
TOWER B								incl	incl														
B	GROUND	420.58	367.56			12.55	9.78	incl	incl	107	75			4	3	incl	incl	111	78	433.13	377.34		
B	FIRST	430.64	355.11	307.88	301.49	9.83	7.08	incl	incl	105	65	41	40	3	2	incl	incl	149	107	748.35	663.68		
B	SECOND	436.49	366.28	307.88	307.92	9.83	5	incl	incl	106	57	41	41	3	2	incl	incl	150	100	754.2	679.2		
B	THIRD	430.72	259.62	307.88	213.22	9.83	0	incl	incl	105	38	41	25	3	0	incl	incl	149	63	748.43	472.84	1 DAY RECORDING MISSING FOR FLOOR & VIEW OBSCURED	
B	FOURTH	434.52	338.98	307.88	286.58	9.83	2.75	incl	incl	105	59	41	38	3	1	incl	incl	149	98	752.23	628.31	VIEW PARTLY OBSTRUCTED	
B	FIFTH	428.53	191.47	307.88	285.91	7.355	4.33	incl	incl	103	30	41	38	3	1	incl	incl	147	69	743.765	481.71	VIEW PARTLY OBSTRUCTED	
B	SIXTH	523.99	252.29	308.39	293.19	0		incl	incl	171	78	42	39	0		incl	incl	213	117	832.38	545.48	VIEW PARTLY OBSTRUCTED	
	ROOF			44.27	44.27							4	4					4	0	44.27	0	%age Area Capture/ Measured	%age Panels Captured/Measured
TOTALS TOWER B		3105.47	2131.31	1847.79	1732.58	59.225	28.94	incl	incl	802	402	251	225	19	9	incl	incl	1072	632	5056.755	3848.56	76.11%	58.96%
TOWER C																			0				
C	GROUND	623.77	540.84			20.776	10.14	12.71	incl	114	74			6	3	28	incl	148	77	657.256	550.98		
C	FIRST	642.1	623.09	513.75	449.53	20.6	2.87	8.82	incl	119	111	55	48	6	1	26	incl	206	160	1185.27	1075.494		
C	SECOND	648.06	417.09	513.75	513.75	20.952	0	11.46	incl	118	41	55	55	6	0	27	incl	206	96	1194.222	930.84		
C	THIRD*	657.26		513.75	287.41	20.6		9.09		118		55	32			25		55	32	513.75	287.41		
C	FOURTH*	657		513.75		20.6		8.64		120		55				18				1199.99	0	*FLOORS IN RED UNABLE ABLE TO MEASURE DUE TO VIEW OBSTRUCTED	
C	FIFTH*	648.15		513.75		20.6		5.49		120		55				16				1187.99	0		
C	SIXTH*	673.17		513.75		20.6		9.27		166		55				20				1216.79	0		
C	SEVENTH*	656.89		347.29				4.82		189		31				9				1009	0	%age Area Capture/ Measured	%age Panels Captured/Measured
TOTALS TOWER C (UP TO LEVEL 3)		1913.93	1581.024	1541.25	1250.69	62.328	13.01	32.99	0	351	226	110	103	18	4	81	0	615	365	3550.498	2844.724	80.12%	59.35%
																O/A TOTAL # PANELS		2610	1631				62.49%
																O/A TOTAL M2 CLT				13719.663	11328.584	82.57%	

HIGH LEVEL (MACRO) PRODUCTIVITY SUMMARY ANALYSIS FROM FIELD STUDY VIDEO REVIEW — R. Brisland

BLOCK	COMMENCE	COMPLETE	TOTAL OF BUILDING LEVELS RECORDED	DAYS (BASED ON 5.5 DAY /WK)	NO OF LEVELS RECORDED	AVE. #DAYS/FLR	GROSS PRODUCTION (M2/DAY)	GROSS PRODUCTION (M2/HR) (BASED ON 7.5HR DAY)	AVE. # PANELS PER SITE DAY (PRODUCTIVE FLOOR CYCLES/ DAY)
BLOCK A	4/7/16	31/8/16	TOTAL(NOT ROOF)	46	6	7.67	111.14	14.82	20.07
BLOCK B	29/8/16	4/11/16	TOTAL (NOT ROOF)	54.5	7	7.79	92.78	12.37	19.67
BLOCK C	20/9/16	9/12/16	UP TO LV 3 FLOOR ONLY	63.5	3	21.17	55.91	7.46	9.69

Appendix 4: Case Studies Intermediate Level Review Worksheets

LEVEL 2 PRODUCTIVITY ANALYSIS SUMMARY OF CASE STUDY PROJECT -TOWERS A, B & C

R.Brisland

LEVEL 2 ANALYSIS SUMMARY - TOWER A

TOWER BLOCK	FLOOR #	WALL PANELS AREA/ M2	FLOOR PANELS AREA/ M2	STAIRS AREA / M2	COLUMNS/ BEAMS AREA/M2	WALL PANEL QUANTITY	FLOOR PANEL QUANTITY	STAIR PANEL QUANTITY	COLUMNS BEAM QUANTITIES	TOTAL # PANELS	TOTAL M2 PANELS	DAYS WORKED	GROSS CLT CRANE HOURS	PRODUCTIVITY M2/DAY	PRODUCTIVITY M2/ GROSS CLT CRANE HR	WORK DAY/FLOOR CYCLES	CLT CREW (NOT MAN) GROSS HR PER FLOOR CYCLE	PRODUCTIVITY M2/CREW GROSS HRS
A	GROUND	491.61		4.61	INCL.	102		2	INCL	104	496.22	4	14.96	122.90	32.86		24.72	20.07
	LV 1 FLOOR		381.89				44			44	381.89	1.5	5.93	254.59	64.40		10.01	38.15
1ST COMPLETE FLOORSUMMARY										148	878.11	5.5	20.89	158.82	41.81	5.5	34.73	25.28
A	FIRST	501.27		9.79	INCL.	100		3	INCL	103	511.06	6	27.91	83.55	17.96		35.09	14.56
	LV 2 FLOOR		381.29				43			43	381.29	3	10.11	127.10	37.71		17.01	22.42
2ND COMPLETE FLOOR										146	892.35	9	38.02	98.06	23.21	9	52.1	17.13
A	SECOND	504.96		9.83	INCL.	99		3	INCL	102	514.79	4.5	17.32	112.21	29.15		32.36	15.91
	LV 3 FLOOR		381.89				43			43	381.89	2.5	6.22	152.76	61.40		12.37	30.87
3RD COMPLETE FLOOR										145	896.68	7	23.54	126.69	37.67	7	44.73	20.05
A	THIRD	503.31		9.83	INCL.	98		3	INCL	101	513.14	5	15.88	100.66	31.69		26.39	19.44
	LV 4 FLOOR		381.89				43			43	381.89	3	12.99	127.30	29.40		20.27	18.84
4TH COMPLETE FLOOR										144	895.03	8	28.87	110.65	30.66	8	46.66	19.18
	FOURTH	507.68		9.83	INCL.	98		3	INCL	101	517.51	4.5	16.15	112.82	31.44		27.81	18.61
	LV 5 FLOOR		380.66				43			43	380.66	4	11.3	95.17	33.69		23.41	16.26
5TH COMPLETE FLOOR										144	898.17	8.5	27.45	104.51	32.36	8.5	51.22	17.54
A	FIFTH	601.64		5.5	INCL.	192		2	INCL	194	607.14	7	30.47	85.95	19.75		48.97	12.40
	ROOF		33.93				4			4	33.93	2	4.48	16.97	7.57		13.03	2.60
6TH COMPLETE FLOOR										198	641.07	9	34.95	70.62	18.19	9	62	10.34
TOTALS TOWER A SUMMARY		3110.47	1941.55	49.39		689	220	16		925	5101.41							
				TOWER A PRODUCTION AVERAGE								6.7	24.8	95.6	26.3	6.7	41.6	18.25

LEVEL 2 ANALYSIS SUMMARY - TOWER B

TOWER BLOCK	FLOOR #	WALL PANELS AREA/ M2	FLOOR PANELS AREA/ M2	STAIRS AREA / M2	COLUMNS/ BEAMS AREA/M2	WALL PANEL QUANTITY	FLOOR PANEL QUANTITY	STAIR PANEL QUANTITY	COLUMNS BEAM QUANTITIES	TOTAL # PANELS	TOTAL M2 PANELS	DAYS WORKED	GROSS CLT CRANE HOURS	PRODUCTIVITY M2/DAY	PRODUCTIVITY M2/ GROSS CLT CRANE HR	WORK DAY/FLOOR CYCLES	CLT CREW (NOT MAN) GROSS HR PER FLOOR CYCLE	PRODUCTIVITY M2/CREW GROSS HRS
B	GROUND	420.58		12.55	INCL.	107		4	INCL.	111	433.13	5	31.39	84.12	13.40		35.85	12.08
	LV 1 FLOOR		307.88				41			41	307.88	2	9.7	153.94	31.74		10	30.79
1ST COMPLETE FLOORSUMMARY										152	741.01	7	41.09	104.07	17.73	7	45.85	16.16
B	LV 1 WALLS	430.64		9.83	INCL.	105		3	INCL.	108	440.47	4	22.07	107.66	19.51		26.02	16.93
	LV 2 FLOOR		307.88				41			41	307.88	2	10.09	153.94	30.51		13.98	22.02
2ND COMPLETE FLOOR										149	748.35	6	32.16	123.09	22.96	6	40	18.71
B	LV 2 WALLS	436.49		9.83	INCL.	106		3	INCL.	109	446.32	3.5	17.22	124.71	25.35		24.16	18.47
	LV 3 FLOOR		307.88				41			41	307.88	2.5	10.31	123.15	29.86		16.69	18.45
3RD COMPLETE FLOOR										150	754.2	6	27.53	124.06	27.04	6	40.85	18.46
B	LV 3 WALLS	430.72		9.83	INCL.	105		3	INCL.	108	440.55	6.5	15.3	66.26	28.15		32.21	13.68
	LV 4 FLOOR		307.88				41			41	307.88	2.5	9.95	123.15	30.94		19.81	15.54
4TH COMPLETE FLOOR										149	748.43	9	25.25	82.07	29.25	9	52.02	14.39
B	LV 4 WALLS	434.52		9.83	INCL.	105		3	INCL.	108	444.35	4.5	13.53	96.56	32.12		24.86	17.87
	LV 5 FLOOR		307.88				41			41	307.88	2.5	12.79	123.15	24.07		31.73	9.70
5TH COMPLETE FLOOR										149	752.23	7	26.32	106.06	28.21	7	56.59	13.29
B	LV 5 WALLS	428.53		7.355	INCL.	103		3	INCL.	106	435.89	3	13.55	142.84	31.63		28.18	15.47
	L6 FLOOR		308.39				42			42	308.39	3	12.52	102.80	24.63		34.27	9.00
6TH COMPLETE FLOOR										148	744.28	6	26.07	122.82	28.27	6	62.45	11.92
B	LV 6 WALLS	523.99			INCL.	171			INCL.			L6 VIEW OBSTRUCTED						
TOTALS TOWER B		3105.47	1847.79	59.225		802	247	19		897	4488.50							
				TOWER A PRODUCTION AVERAGE					TOWER B PRODUCTION AVERAGE			6.8	29.7	110.4	25.6	6.8	49.6	15.49

LEVEL 2 ANALYSIS SUMMARY - TOWER C

TOWER BLOCK	FLOOR #	WALL PANELS AREA/ M2	FLOOR PANELS AREA/ M2	STAIRS AREA / M2	COLUMNS/ BEAMS AREA/M2	WALL PANEL QUANTITY	FLOOR PANEL QUANTITY	STAIR PANEL QUANTITY	COLUMNS BEAM QUANTITIES	TOTAL # PANELS	TOTAL M2 PANELS	DAYS WORKED	GROSS CLT CRANE HOURS	PRODUCTIVITY M2/DAY	PRODUCTIVITY M2/ GROSS CLT CRANE HR	WORK DAY/FLOOR CYCLES	CLT CREW (NOT MAN) GROSS HR PER FLOOR CYCLE	PRODUCTIVITY M2/CREW GROSS HRS
C	GROUND	623.77			12.71	114			28	142	636.48	6.5	22.2	95.96	28.10		34.45	18.48
	LV 1 FLOOR		513.75				55			55	513.75	3.5	14.01	146.79	36.67		15.34	33.49
1ST COMPLETE FLOORSUMMARY										197	1150.23	10	36.21	113.75	31.41	10	49.79	23.102
C	FIRST	642.1			8.82	119			26	145	650.92	9	26.52	71.34	24.21		45.75	14.23
	LV 2 FLOOR		513.75				55			55	513.75	3.5	9.1	146.79	56.46		15.3	33.58
2ND COMPLETE FLOOR										200	1164.67	12.5	35.62	92.47	32.45	12.5	61.05	19.077
C	SECOND	648.06			11.46	118			27	145	659.52	7	ONLY PART	OBSERVED			30.02	
	LV 3 FLOOR		513.75				55			55	513.75	1	ONLY PART	OBSERVED			6.96	
3RD COMPLETE FLOOR										200	1173.27	8	Excl	145.23	Excl	8	36.98	Excl
TOTALS TOWER C		1913.93	1541.25	.	32.99	351	165	.	81	597	3488.17							
				TOWER A PRODUCTION AVERAGE					TOWER C PRODUCTION AVERAGE			10.17	35.92	103.11	31.93	11.25	49.27	21.089
				TOTAL # PANELS FOR ALL TOWERS =						2419	PANELS							
				TOTAL M2 CLT =							13078.08							

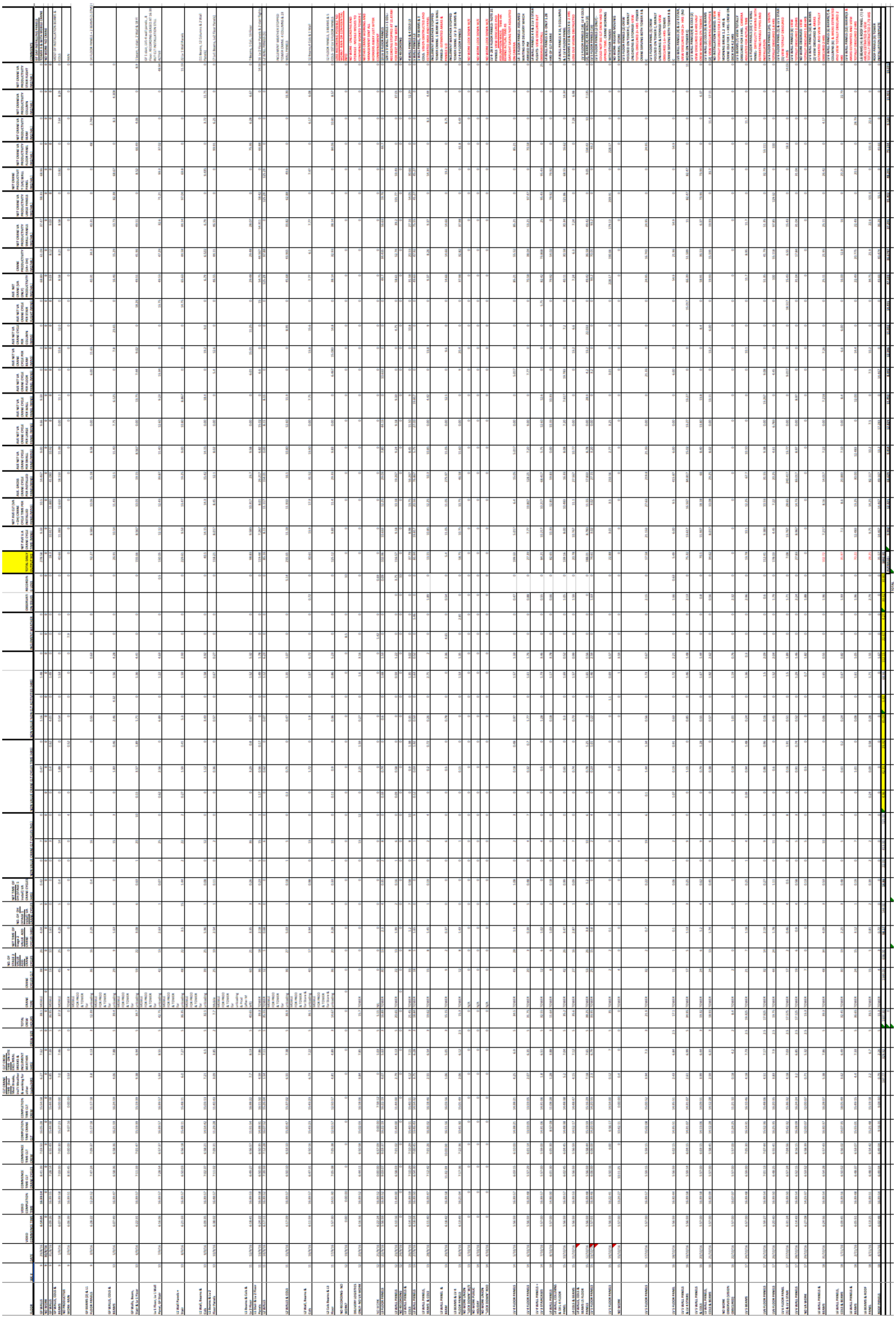
Overall Intermediate Level Floor level Analysis of Productivity by Panel Type

Tower A Detailed Intermediate Level Worksheet

Tower B Detailed Intermediate Level Worksheet

LOOR	WK #	DATE	VIDEO COMMENCE TIME	VIDEO COMPLETION TIME	COMMENCE TIME CLT CRANE CYCLES	COMMENCE TIME CLT CREW	COMPLETION TIME CRANE CLT	COMPLETION TIME CLT CREW	CLT CRANE TIME (Excl Meal Breaks, Incl't Weather & working for other trades)(HRS)	CLT CREW TIME ON SITE EXCL MEAL BREAKS & INCLEMENT WEATHER (HRS)	CREW SIZE	TOTAL CREW HOURS	CRANE TYPE	TOTAL CRANE CYCLES CLT #	NO. OF VALUE ADD Stage 2 CRANE CYCLES #	NET TIME OF VALUE ADD Stage 2 CRANE CYCLES (HRS) INSTALL	NO. OF DH (STAGE 1 install) VA CRANE CYCLES # WORKING (DOUBLE HANDLING) (from Store to installation location)	NET TIME OF DH (STAGE 1 install) VA CRANE CYCLES (HRS) WORKING (DOUBLE HANDLING) (from Store to installation location)	NON VALUE CRANE CLT CYCLES (NO.) REWORK	DELIVERY LOGISTICS - STORAGE & SORTING OUT PANELS	DELIVERY LOGISTICS - UNLOADING	NON VALUE CRANE CLT CYCLES TIME (HRS) REWORK	DELIVERY LOGISTICS - SORTING OUT IN STORAGE AREA	DELIVERY LOGISTICS - UNLOADING	NON VALUE NON CLT ACTIVITIES (HRS) CRANE(S) WAITING DURING CLT WORK	STOPPAGE DUE TO TOWER CRANE OR OTHER ACTIVITY ADJACENT TO WORK AREA	MEAL BREAKS	CRANE USED FOR OTHER TRADES	INCLEMENT WEATHER RAIN (HRS)	WIND (HRS)	RECORDING AND OBSERVATION ISSUES RECORDING LOSS (HRS.)	VISION BLOCKED (HRS.)	TOTAL DAILY OUTPUT M2
GF WALLS,COLS & BEAMS (WEST 1/2)	13	26/9/16	6:14:12	16:39:10	9:11:09	9:05:24	16:09:42	16:05:12	4.67	5.46	2	10.92	MOBILE	26	17	3.35	1	0.1	1	7	0	0.3	0.92	0	0.45	0.36	1.54	0	0	0	0	0	59.12
GF WALLS,COLS & BEAMS & LV 1 FLOOR (WEST 1/2)	13	27/9/16	6:18:04	16:39:10	7:06:15	7:00:45	15:16:17	15:10:17	4.06	6.78	2	13.56	MOBILE	32	19	2.56	0	0	0	11	0	0.64	0.86	0	1.47	0.24	1.71	1.06	0	0	0	0	153.4
GF WALLS & BEAMS & LV 1 FLOOR (WEST 2)	13	28/9/16	6:11:40	16:39:47	7:18:17	7:03:26	16:06:00	16:18:46	4.37	7.93	2	15.86	MOBILE & TOWER	35	10	1.61	2	0.37	0	23	0	0	2.35	0	1.93	0.3	1.36	1.23	0	0	0	0	104.31
GF WALLS & COLS (WEST 2)	13	29/9/16	6:18:42	16:39:18	13:54:35	11:30:55	15:54:10	15:56:56	1.61	3.57	2	7.14	MOBILE	9	4	0.86	1	0.08	0	0	0	0	0.67	0	1.36	0	0.86	0	5.38	0	0	0	25.88
GF WALL & LV 1 FLOOR PANELS (WEST 1/2)	13	30/9/16	6:13:49	16:21:04	7:36:22	7:32:37	14:06:01	14:06:49	5.06	5.23	2.5	13.075	MOBILE	44	15	1.61	7	0.83	2	20	0	0.54	1.85	0	0.42	0	1.34	0.18	0	0.33	0	0	101.18
NO WORK	13	1/10/16	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK	14	3/10/16	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK	14	4/10/16	5:56:59	16:39:44	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK ON TOWER C	14-16	5-17/10/16							0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GF BEAM & LV 1 FLOOR PANELS (WEST 2)	16	18/10/16	5:56:59	16:30:44	6:25:00	5:56:59	14:35:52	8:53:00	2.85	2.85	2	5.7	TOWER	14	3	0.31	1	0.28	1	4	5	1.07	0.3	0.91	0.63	0	1.72	3.41	0	0	0.84	0	26.15
NO WORK ON TOWER C	16	19/10/16	5:56:59	16:39:18	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LV 1 WALLS (WEST 1/2)	16	20/10/16	5:57:00	16:39:18	6:33:02	5:57:00	14:18:38	16:20:38	4.07	7.93	2	15.9	MOBILE	25	9	1.9	0	0	0	16	0	0	2.16	0	2.29	1.01	1.13	0.58	0	0	0	0	104.9
LV 1 & GF WALLS & LV 1 FLOOR	16	21/10/16	5:57:00	16:30:03	5:57:00	5:57:00	14:20:23	14:29:29	4.93	7.25	2.5	18.125	MOBILE	23	10	2.03	1	0.33	1	11	0	0.23	1.36	0	1.15	0	1.29	0.21	0	0	0	0.94	156.21
LV 1 WALLS & GF STAIR	16	22/10/16	5:57:00	16:00:37	6:13:01	5:57:00	18:02:36	18:02:36	2.7	4.09	2.5	10.225	MOBILE	12	5	1.36	1	0.24	0	6	0	0	0.91	0	1.02	0	0	0	0	0	0	0.37	31.29
LV 1 COLS & GF STAIR FLIGHT	17	24/10/16	6:57:00	16:39:48	8:40:20	8:45:05	14:47:23	14:47:23	1.92	4.82	2.5	12.05	MOBILE	13	4	0.55	2	0.33	2	5	0	0.26	0.78	0	2.93	1.48	1.22	0.29	0	0	0	0	8.31
LV 1 WALLS, COLS & BEAMS	17	25/10/16	5:59:27	16:39:14	6:33:02	6:51:13	15:09:50	15:21:05	5.14	7.3	2.5	18.25	MOBILE	34	24	4.04	7	0.65	0	3	0	0	0.45	0	0.9	0	1.2	0.84	0	0	0	0.31	41.6
LV 1 WALLS, COLS & BEAMS	17	26/10/16	6:20:40	16:39:53	7:21:27	6:57:11	14:21:00	14:21:00	4.33	6.23	2.5	15.575	MOBILE	29	13	2.66	10	0.71	1	5	0	0.17	0.96	0	1.06	0	1.23	0.06	0	0	0	0.47	33.91
LV 1 WALLS, COLS & BEAMS & L2 FLOORS	17	27/10/16	6:31:24	16:39:50	7:07:11	13:07:11	14:53:15	15:27:47	3.27	2.34	3	7.02	MOBILE	49	11	1.37	1	0.1	0	37	0	0	1.65	0	2.92	0	1.49	0.46	0	0	0	0	77.2
L2 FLOOR PANELS (WEST END)	17	28/10/16	6:14:43	16:39:54	8:30:09	8:30:09	13:53:47	15:28:06	3.62	5.7	2.5	14.25	MOBILE & TOWER AFTER MOBILE LEAVES SITE	34	18	2.1	1	0.13	0	15	0	0	1.03	0	0.73	0.28	1.27	1.51	1.04	0	0	0	163.39
NO WORK	17	29/10/16	6:27:03	14:11:12	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK	18	31/10/16	6:24:16	16:39:54	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK	18	1/11/16	6:09:45	16:39:56	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK	18	2/11/16	6:05:51	16:39:48	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK	18	3/11/16	6:13:25	16:39:51	0	0	0	0	0	0	0	0	N/A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GF & LV 1 WALLS, COLS & BEAM (EAST SIDE)	18	4/11/16	6:02:48	16:39:54	9:16:35	9:16:35	15:11:50	15:26:20	2.57	4.86	5	24.3	TOWER	20	9	1.33	3	0.34	0	8	0	0	0.9	0	0.36	0	1.3	1.19	0	0	0	0.75	54.85
NO WORK-HIGH WINDS	18	5/11/16	6:27:40	15:53:02	0:00:00				0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.05	0	4.8	0	0	0
NO WORK ON TOWER C-RECORDING LOSS	19	7/11/16	5:59:20	10:35:31	0:00:00		0:00:00	0:00:00	0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0.66	3.13	0	0	5	0	0
GF WALLS & COLS & LV 1 FLOOR PANELS (EAST SIDE)	19	8/11/16	9:01:20	16:39:54	9:01:20	9:01:20	16:39:54	16:39:54	3.22	6.26	5	31.3	TOWER	33	18	1.81	5	0.52	0	8	2	0	0.58	0.31	0.15	0	1.38	1.69	0	0	3.00	1.2	186.29
LV 1 FLOOR AND WALL PANELS (EAST SIDE)	19	9/11/16	6:05:59	16:39:56	6:50:30	6:57:59	16:38:41	16:38:41	3.36	6.09	8	48.45	TOWER	25	12	1.86	4	0.45	0	10	0	0	1.05	0	0	0	1.61	4.72	0	0	0	0.14	157.73
LV 1 WALLS, COLS & BEAMS (EAST SIDE)	19	10/11/16	6:02:55	16:39:55	6:46:11	6:53:11	15:44:35	15:40:04	3.52	7.37	5	36.85	TOWER	35	28	3.29	1	0.09	0	6	0	0	0.55	0		0	1.4	2.4	0	0	0	1.16	67.39
NO WORK	19	11/11/16	6:02:16	16:39:52					0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NO WORK	19	12/11/16	6:28:36	15:12:06					0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LV 1 WALLS, BEAM, FLOOR & STAIR FLIGHT & LEVEL 2 FLOOR PANELS	20	14/11/16	6:25:41	16:39:53	6:56:41	6:56:41	15:40:20	15:52:21	4.1	7.51	5	37.55	TOWER	44	29	3.14	1	0.21	0	13	1	0	0.88	0.28	1.19	0	1.42	1.74	0	0	0	0.07	239.15
LV 2 FLOOR PANELS	20	15/11/16	5:57:00	16:39:56	9:14:38	6:57:47	15:48:10	15:45:54	3.88	7.26	5	36.3	TOWER	22	7	0.72	5	0.49	4	6	3	1.41	0.49	0.78	0.07	0	1.54	3.22	0	0	0	0.13	77.08
LV 2 WALL PANELS	20	16/11/16	6:00:02	16:39:47	6:49:12	7:02:07	16:39:47	16:39:47	3.27	8.01	5	40.05	TOWER	23	11	1.4	2	0.46	1	4	5	0.22	0.42	0.78	0.55	0	1.62	4.31	0	0	0	0.08	177.56
LV 2 WALL & BEAM PANELS	20	17/11/16	6:07:31	16:39:58	6:51:33	6:51:33	15:49:41	15:42:41	4.68	7.14	5	35.7	TOWER	31	19	2.67	4	0.68	1	7	0	0.19	1.13	0	0.12	0	1.64	1.99	0	0	0	0.54	148
LV 2 WALL PANELS	20	18/11/16	6:12:23	16:39:50	6:46:05	6:46:05	14:31:23	14:28:44	1.61	6.96	5	34.8	TOWER	15	2	0.21	1	0.13	0	12	0	0	1.26	0	0.08	0	0.64	5.43	0	0	0	0	22.38
NO WORK	20	19/11/16	6:23:05	15:02:32					0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.81	0	0	0	0	0
LV 2 WALL, COLS & BEAMS - ACTIVITY IDENTIFIED/ BLOCKED	21	21/11/16	6:04:31	16:39:57	6:51:17	6:55:17	16:15:26	16:15:26	2.87	7.91	5	39.55	TOWER	22	9	1.35	6	0.57	0	7	0	0	0.96	0	0.05	0	1.43	2.79	0	0	0	2.27	57.69
NO ACTIVITY IDENTIFIED/ BLOCKED	21	22/11/16	6:19:41	16:39:52					0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0
NO ACTIVITY IDENTIFIED/ BLOCKED	21	23/11/16	5:57:00	16:39:45					0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.66	0	0	9	0
NO ACTIVITY IDENTIFIED/ BLOCKED	21	24/11/16	6:33:38	16:39:50					0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0
LV 3 FLOOR PANELS	21	25/11/16	6:23:08	16:39:50	6:48:35	7:03:09	15:48:32	15:44:47	5.85	6.96	5	34.8	TOWER	53	32	5.29	9	1.29	0	12	0	0	1.11	0	0	0	1.73	0.43	0	0	0	1.15	287.41
NO WORK- NO CREW	21	26/11/16	6:20:41	14:07:31	6:20:41	14:07:31			0	0	0	0	TOWER	0	0	0	0	0	0	0	0	0	0	0	0	0.83	1.27	4.75	0	0	0	0	0
									99.19	185.69		589.02		743.00	365.00	52.29	85.00	10.15	16.00	267.00	21.00	5.03	26.44	3.75	25.05	6.57	37.57	59.81	7.08	5.13	8.84	36.58	2816.48

DATE	NET AVE VA CRANE CYCLE TIME (MINS)	NET AVE CLT (VA + DH) CRANE CYCLE TIME PER INSTALLED PANEL(MINS)	AVE. GROSS CRANE CYCLE PER INSTALLED PANEL(MINS)	AVE NET VA CRANE CYCLE PER SMALL PANEL(MINS)	AVE NET VA CRANE CYCLE PER LARGE PANEL (MINS)	AVE NET VA CRANE CYCLE PER WALL PANEL (MINS)	AVE NET VA CRANE CYCLE PER FLOOR PANEL (MINS)	AVE NET VA CRANE CYCLE PER BEAM (MINS)	AVE NET VA CRANE CYCLE PER COLUMN (MINS)	AVE NET VA CRANE CYCLE PER STAIR FLIGHT (MINS)	AVE NET CRANE (VA ONLY) PRODUCTIVITY (M2/HR.)	CRANE PRODUCTIVITY (VA+DH) (M2/HR.)	NET CRANE VA PRODUCTIVITY SMALL PANELS (M2/HR.)	NET CRANE VA PRODUCTIVITY LARGE PANELS (M2/HR.)	NET CRANE PRODUCTIVITY (VA) WALL PANEL (M2/HR.)	NET CRANE VA PRODUCTIVITY FLOOR PANEL (M2/HR.)	NET CRANE VA PRODUCTIVITY BEAM (M2/HR.)	NET CRANEVA PRODUCTIVITY COLUMN (M2/HR.)	NET CRANE VA PRODUCTIVITY STAIR FLIGHT (M2/HR.)	COMMENTS
26/9/16	11.817	12.15	19.167	11.817	0	11.4	0	11.4	11.00	0	17.67	17.136	17.67	0	70.9	0	7.47	11.786	0	GF WALL PANELS (5) BEAMS(10) & COLS (2)
27/9/16	8.083	8.083	21.583	9.00	7.2	12.617	6.12	12.24	8.5	0	59.88	59.88	35.19	108.94	50.93	113.35	5.23	4.09	0	GF WALL PANELS (1) BEAMS(5) & COLS (1) & LV 1 FLOOR PANELS(12)
28/9/16	9.66	11.867	45.8	6.6	16.19	16.19	5.75	9.62	0	0	64.8	52.68	67.22	64.05	64.05	96.98	17.82	0	0	GF WALL PANELS (3) BEAMS (2) &LV1 FLOOR PANELS (5)
29/9/16	12.883	14.067	124.23	11.4	16.8	13.6	0	0	10.75	0	30.13	27.53	23.4	44.79	38.06	0	0	9.82	0	GF WALL PANELS (3) & COL (1) (5.38HRS. RAIN)
30/9/16	6.45	9.783	23.267	6.6	4.267	20.183	5.46	0	0	0	62.7	41.47	58.69	151.87	7.13	77.188	0	0	0	GF WALL PANEL(1) & LV 1 FLOOR PANELS (14)
1/10/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	LOCK DOWN WEEKEND
3/10/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	PUBLIC HOLIDAY
4/10/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	UNION RDO
5-17/10/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK ON TOWER C CREW FOCUSED ON TOWER B
18/10/16	6.167	11.767	138.617	7.25	4.017	0	5.367	7.75	0	0	84.81	44.32	43.7	233.93	0	134.56	14.93	0	0	LV 1 FLOOR PANELS (2) AND GF BEAM (1) TOWER CRANE FOCUSED ON TOWER B
19/10/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	WORK ONLY ON TOWER B
20/10/16	12.683	12.683	52.967	9.6	14.4	12.683	0	0	0	0	55.17	55.17	51.32	56.1	55.17	0	0	0	0	LV 1 WALL PANELS (9) TO WEST SIDE (NEAREST CAMERA -PARTLY BLOCKING VIEW)
21/10/16	17.583	19.583	43.5	20.4	16.2	17.067	19.65	0	0	0	53.3	47.92	20.78	70.21	59.2	32.68	0	0	0	L1 WALL PANELS (7) GF WALL PANEL (1) LV 1 FLOOR PANELS (2)
22/10/16	18.7	21.55	49.117	19.00	17.017	17.4	0	0	0	21.00	20.17	17.38	14.44	45.17	27.58	0	0	0	10.97	L1 WALL PANELS (2) & STAIR FLIGHTS (2)
24/10/16	8.183	13.2	107.967	8.183	0	0	0	0	7.5	10.267	15.22	9.443	15.22	0	0	0	0	14.42	16.54	L1 COLS (3) AND STAIR FLIGHT (1) (MOBILE CRANE LEFT IDLE FOR 4.5HRS)
25/10/16	10.083	11.7	17.583	10.083	0	8.683	0	15.00	9.00	0	10.31	8.87	10.31	0	13.59	0	7.86	9.1	0	Lv 1 WALLS (10), COLS (9) & BEAMS (5)
26/10/16	12.3	15.55	27.33	12.3	0	21.60	0	6.617	10.8	13.633	12.73	10.06	12.73	0	16.92	0	21.773	9.1	11.735	L1 WALL (2) BEAMS (2) COLS (7) & 2 GF STAIR FLIGHTS
27/10/16	7.483	8.00	35.467	7.12	11.017	8.767	6.00	8.63	13.00	0	56.3	52.52	55.05	63.67	59.52	95.36	4.84	14.91	0	L1 WALL (2), BEAMS (2) COLS (1) & LV 2 FLOOR (6)
28/10/16	6.983	7.417	22.683	5.4	9.6	0	6.983	0	0	0	77.9	73.69	72.5	83.98	0	77.9	0	0	0	L2 FLOOR PANELS (18) MOBILE CRANE LEAVES SITE DUE UNABLE TO REACH FAR SIDE OF TOWER C
29/10/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK
31/10/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK
1/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK
2/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK
3/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK
4/11/16	8.867	11.117	32.4	8.4	10.8	9.583	0	4.783	8.75	0	41.22	32.84	32.01	66.17	53.58	0	14.3	7.567	0	GF WALL (3) COLS (1) BEAM (1) - LV 1 WALL (3) COL (1)
5/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK HIGH WINDS
7/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORKON TOWER C- RECORDING LOSS
8/11/16	6.033	7.75	20.867	5.4	6.6	7.017	5.167	0	9.75	0	102.94	79.95	58.03	131.9	120.37	104.64	0	16.12	0	GF WALLS (6) & COL (1) & LV 1 FLOOR PANELS (11) - NOTE RECORDING LOSS ACTIVITY BEFORE 9.00 AND AFTER 16.39
9/11/16	9.32	11.567	41.05	6.00	10.8	8.367	22.017	0	0	0	84.62	68.28	56.97	87.71	96.11	42.68	0	0	0	LV 1 WALL (11) & FLOOR (1) PANELS
10/11/16	7.033	7.217	16.217	6.8	10.1	8.95	0	6.35	7.317	0	20.53	19.997	13.37	82.53	57.15	0	11.63	11.96	0	LV 1 WALLS (4) BEAMS (15) & COLS (9)
11/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK- CONCRETE CREW INSTALLING PERIMETER CONCRETE SLAB TO TOWER C AND TOWER CRANE WORKING ON FAÇADE INSTALL TO TOWER B
12/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK- CONCRETE CREW INSTALLING PERIMETER CONCRETE SLAB TO TOWER C AND TOWER CRANE WORKING ON FAÇADE INSTALL TO TOWER B
14/11/16	6.5	6.933	15.533	6.00	7.8	12.5	5.333	19.033	0	11.017	76.16	73.58	66.58	81.46	26.63	100.81	1.71	0	15.63	LV 1 WALL (2) BEAM(1) STAIR (1) & FLOOR (1) & LV 2 FLOOR (24) PANELS
15/11/16	6.15	10.19	62.617	10.2	3.25	0	6.15	0	0	0	107.51	63.7	43.47	261.48	0	107.51	0	0	0	LV 2 FLOOR PANELS (7)
16/11/16	7.617	10.117	44.783	6.6	8.4	7.617	0	0	0	0	127.13	95.46	57.77	159.08	127.13	0	0	0	0	LV 2 WALL PANELS (11) SOME PANELS INSTALLED OBSCURE REMAINING TOWER AREA
17/11/16	8.43	10.58	23.15	8.76	9.00	8.63	0	0	7.683	0	55.44	44.18	27.91	79.44	60.86	0	0	16.94	0	LV 2 WALL (15) & BEAM (4) PANELS VIEW OBSCURED & SOME PANELS ESTIMATED
18/11/16	6.383	10.383	213.517	9.017	3.75	6.383	0	0	0	0	105.18	65.82	32.07	281.12	105.18	0	0	0	0	LV 2 WALL (2) PANELS- CRANE MAINLY DUTIES ON OTHER TRADES
19/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO CLT WORK NO CLT CREW- PROBABLY WAITING FOR CLT DELIVERY
21/11/16	8.983	12.783	62.683	8.22	11.64	11.88	0	5.88	7.2	0	42.84	30.05	19.24	101.09	61.865	0	8.858	19.19	0	LV 2 WALL (4) & BEAM (2) & COLS (3) PANELS -VIEW OBSCURED WITH ALMOST 3 HRS UNABLE TO OBSERVE
22/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	VIEW OBSCURED
23/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	VIEW OBSCURED
24/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	VIEW OBSCURED
25/11/16	6.183	8.6	13.617	5.1	8.52	0	6.183	0	0	0	87.26	62.75	81.2	96.04	0	87.26	0	0	0	LV 3 FLOOR PANELS (32)- LEVEL 3 FLOOR COMPLETED
26/11/16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NO WORK- NO CREW
AVERAGE=	9.237	11.378	43.834	9.046	9.862	11.649	8.348	9.492	9.049	13.979	56.241	45.135	37.507	111.483	58.449	89.244	10.515	13.164	13.719	



Tower C Detailed Intermediate Level Worksheet

Appendix 5: Questionnaire for Interview with Project Manager

Interview with Project Manager
Date of interview: 9/03/2017
Place: Contractor's site office, Campbelltown
Time: 11.55 Am –12.18 pm
Interviewee: 1. Project Manager (AM)
Pre–Interview (not recorded): 1. AS Ceo.2, (SS) & AM
Interviewer: Richard Brisland (R.B.), UTS HDR student

	Questions
1	Regarding [XXX] Project, from your experience, how does prefabricated timber construction compare with traditional construction in terms of site productivity?
2	What was your floor-to-floor cycle time? And what would from your experience the floor cycle be if it was a traditional concrete structure?
3	Do you believe that there are additional productivity benefits other than the improved floor to floor cycle time?
4	What are the main constraints in the overall process of CLT delivery and erection that affect productivity?
5	You had planned for "Just in Time" delivery and erection, but this was not delivered. Was there a problem with CLT delivery logistics? Did you sometimes have deliveries, which weren't for the floor you wanted or needed?
6	Can you suggest any improvements to make it a better result on-site in regards to the overall CLT process?
7	What about the jointing of the panels? Was there any improvement in jointing that you believed might improve productivity or not?
8	Describe how much design complexity affects the productivity of installing prefabricated panels on-site?
9	You had several columns of two storeys high in specific locations. Did that slow you down?
10	What do you believe is the best crew size and composition to provide the best productivity? (If required) Can you explain the logic behind your thinking?
11	And what crew size did you have?
12	So when you did divide the team, was it one supervisor between two or three workers on each team?
13	What do you think are the main variables that affect productivity on-site? (prompts) weather, design changes, deliveries, storage, jointing, planning?
14	So you are saying that the requirements for other things on site, was the variable that delayed the craneage being fully utilised on the CLT?

15	Did the weather affect you, and how? Did you experience weather affected your productivity on high levels as well as the low levels, or was it more predominantly high?
16	Did delivery logistics and storage (or lack of) affect your CLT productivity? Did you plan for CLT panel on-site storage?
17	How does prefabricated panel construction compare with traditional construction regarding safety on-site? How much of an improvement did you or did you not achieve with the use of CLT?
18	Did you experience any reduction in on-site waste due to the adoption of CLT? Can you quantify any experienced reduction in waste?