INVESTIGATING THE PERFORMANCE OF THE CONSTRUCTION PROCESS OF AN 18-STOREY MASS-TIMBER HYBRID BUILDING

by

Mohamed Kasbar

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Abstract

The use of mass timber in high rise construction is an innovation. Mass timber construction has influential benefits including a lower overall construction time, a lower environmental impact, the use of renewable resource and an improved aesthetics. Despite the mentioned benefits, mass timber is not the traditional material for low to mid-rise commercial, institutional and residential construction in Canada. This is partially due to the need to explore the efficiency of mass timber construction relative to traditional construction. Detailed quantitative documentation of successful construction projects assists organisations planning mass timber high-rise projects by understanding and quantifying the advantages to ensure the viability of the construction process.

This research project aims to understand the performance of mass-timber construction in the context of a construction manager, particularly the time saved due to completion of structural and envelope systems early. The case study chosen for this thesis is the tallest mass timber hybrid building in the world: Tallwood House. The research team studied the project in a macro-level perspective to investigate the building elements as single entities. Moreover, a micro-level study focuses on the performance of every level of the following elements: mass timber structure, envelope cladding systems and cross-laminated timber drywall encapsulation. The macro-level study investigates: (1) The production rate of the various building elements, (2) The coordination between structural trades to build a heavily pre-fabricated building using a single crane, and (3) The labor efforts per discipline. Moreover, the micro-level study investigates: (4) The variability of productivity of all levels, (5) A statistical investigation of three factors on cross-laminated timber installation, (6) Schedule reliability of preliminary planned schedule relative to the construction schedule (actual progress), (7) Earned value analysis, and (8) Planned percent complete to study the reliability of weekly work plans relative to construction schedules.

All metrics were validated by the senior project manager through a discussion and confirmation of the inputs, findings and conclusions drawn. The claimed contribution of this research is an advanced state of knowledge about mass timber by exploring the efficiency of the construction process.

Preface

A condensed, modified version of the findings presented in this research thesis, particularly the findings in Chapter 5, is intended to be submitted for possible future publications. The observations and interactions described in this document were approved by the Behavioural Research Ethics Board at UBC [H15-02907]. The author is responsible for the data collection and analysis presented in this manuscript with direct supervision and input by Dr. Poirier, the research associate on the research project, and research supervisor Dr. Staub-French.

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List of Abbreviations

BIM	Building Information Modelling
VDC	Virtual Design in Construction
TWH	Tallwood House
CLT	Cross-Laminated Timber
GLT	Glue Laminated Timber
PSL	Parallel Strand Lumber
CPM	Critical Path Method
CM	Construction Manager
BAC	Budgeted Cost at Completion
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
ACWP	Actual (Construction) Cost of Work Performed
SV	Schedule Variance
CV	Cost Variance
SPI	Schedule Performance Index
CPI	Cost Performance Index
PPC	Percentage Planned Work Completed
JIT	Just in Time
LCI	Lean Construction Institute
SI	Site Instruction

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with love to Nadia and Ashraf

with love to Nada and Rana

Chapter 1: Introduction

The use of mass timber as structural components, relative to reinforced concrete, steel and/ or light-frame timber, has influential benefits: lower carbon footprint, lower overall construction time, improved aesthetics, higher strength to weight ratio, high fire resistance due to charring, high support for local industry, as well as higher flexibility for de-construction, re-use and recycling (Forsythe and Sepasgozar 2016, Karsh 2014). However, mass timber is not the traditional material for low to mid-rise commercial, institutional and residential construction in Canada given the regulatory constraints (Poirer et al. 2016). This is partially due to the need to explore the efficiency of mass timber construction relative to traditional construction (Forsythe and Sepasgozar 2016). Detailed quantitative documentation of successful construction projects assists organisations planning mass timber high-rise projects by understanding and quantifying the advantages to ensure the viability of the construction process. To fulfill this need, this research project aims to understand the performance of mass-timber construction in the context of a construction manager. To allow the research findings to be applicable to a wide geographical context, the research team divided the construction process into details, particularly the installation of mass timber structure.[1]

The objective of this research project to study the performance of the construction phase of the Brock Common's Tallwood House project (TWH), located on the University of British Columbia's (UBC) Vancouver campus. Upon completion, TWH will be the tallest building of its kind in the world. A shortened floor cycle is the primary reported advantage of using mass timber as a structural element in high rise construction (Forsythe and Sepasgozar 2016, FMI Corporation 2013, Construction 2013). The research team studied the project in a macro perspective to investigate the building elements from TWH as a single entity. Moreover, a micro-level study focuses on the performance of every level of

[1] As discussed in Chapter 5, the installation of TWH included fixing drag-straps for lateral supports; however, regulatory codes in other countries do not have this requirement due to less seismic activities. To broaden the applicable geographical context, a detailed analysis of hook time is included in the findings.

the following elements: mass timber structure, envelope cladding systems and Cross-laminated Timber (CLT) drywall encapsulation.

As discussed in Chapter 3, this thesis presents a combination of metrics that allows organizations to assess the performance of their construction process. A macro-level study examines the following metrics for building elements:

1. Macro-level production rate at the element level in terms of number of working days (input) per level (output).
2. Hook time in crane days.
3. Total labor hours and daily counts.

Moreover, a micro-level study focuses on mass timber structure and envelope cladding systems to study the performance of every level in the building:

4. Variability of productivity of all levels at the activity level in m^2 (output)/ crane-hour (input).
5. Statistical Investigation of CLT Installation,
6. Schedule reliability in variance (days).
7. Earned value reliability analysis in Canadian Dollars.
8. Planned Percent Complete (PPC).

Understanding the process develops from the understanding of all relevant metrics; one metric cannot represent the full process. The macro-level study allowed the research team to understand the performance of the building elements as a single unit through understanding (1) The progress and learning curve in a macro-perspective, (2) The coordination between trades in building a heavily pre-fabricated building using a single crane, (3) The labor efforts corresponding to the building elements. Moreover, the micro-level study allowed the research team to further interpret the productivity of the structural elements by understanding: (4) The variability of productivity of installation of all levels, (5) The reliability of planned preliminary schedule, planned lookahead schedules, an earned value analysis and percentage of planned work completed (PPC), and (6) The effect of three factors on installation of a sample of six levels of CLT installation in a more detailed analysis.

Project data was collected through time-lapse images, videos, notes from site-visits, interviews with team representatives and studies of project specifications, structural, architectural drawings, preliminary and lookahead schedules and labor count reports. Regarding the macro-level study, data was collected for every building element as a single unit. Whereas, in the micro-level study, the data sample included all CLT panels (464 panels) and 378 out of 396 envelope panels[2] studied for every level separately. Furthermore, the research team studied the installation of every CLT panel separately for a sample of six levels to perform a fine productivity study. A matrix is provided in Chapter 3 matching the data collected to building elements. Data analysis and findings, of macro and micro studies, are presented in Chapter 5.

This thesis consists of seven Chapters. Chapter 1 introduces the research by demonstrating the research team's motivation and discussing the research objectives and approach. Chapter 2 provides a research background on several aspects differentiating tall wood buildings from traditional construction, as well as, a literature review on factors affecting construction labor productivity and how to measure them. Chapter 3 discusses the research methodology, how the research team collected and analyzed data. Chapter 4 contains all relevant information about the TWH case study project. Chapter 5 discusses the project performance study findings. Chapter 6 is a discussion to validate the findings. Finally, Chapter 7 is a conclusion providing lessons learned, limitations and future work for this research project. All quantitative calculations are duplicated in a complied table in Appendix D, for the reader's reference.

[2] 1 envelope panel per level was installed later in the project to allow for an outrigger system for material and equipment handling, as planned.

Chapter 2: Background

As discussed in Chapter 1, there exists a need to explore the efficiency of mass timber construction. This thesis aims to understand the performance of the tallest timber hybrid building in the world, Brock Common's TWH. Section 2.1 discuses previous literature on performance assessment in the construction context and the reasoning behind the chosen metrics in Chapter 5. Section 2.2 provides a background on the use of mass timber in the construction context.

2.1 Construction Performance Assessment

Performance assessment in construction can be approached from various perspectives. Amongst them, construction labor productivity, a subset of construction productivity, can be defined as the ratio of work performed in m^2 (output) to labor hours or crane hours (input) as well as the inverse to this ratio. It has been studied for decades by various academics (e.g. El-Gohary & Aziz, 2014; Grau, Caldas, Haas, Goodrum, & Gong, 2009; Shehata & El-Gohary, 2011; H. Thomas, 2012; H. R. Thomas et al., 1990). Efforts, in this field, are divided into two groups. One group focuses on describing factors affecting construction labor productivity, while the second focuses on measuring labor productivity (Figure 1). There exists a need to understand the performance of mass-timber construction to justify its use. Mass timber is not the traditional material for low to mid-rise commercial, institutional and residential construction given the regulatory constraints despite its benefits. Its benefits include: lower carbon footprint, lower overall construction time, improved aesthetics, higher strength to weight ratio, high fire resistance due to charring, high support for the local industry, as well as higher flexibility for de-construction, re-use and recycling (Poirer et al. 2016, Karsh 2014, Forsythe and Sepasgozar 2016).

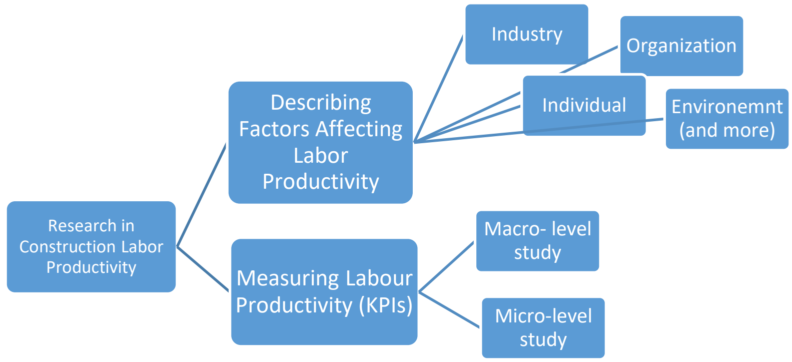


Figure 1: Literature review on construction productivity

Factors affecting labor productivity include labor-related factors (age, experience and motivation) as well as environmental, organizational and project-related factors. (Poirier, Staub-French, and Forgues 2015b) have gathered factors and categories in Table 1. Efforts in measuring labor productivity can be further divided into two categories: macro, referring to industry or regional trends, and micro, referring to an organization or a project. The main difference is level of data aggregation (Chau, 1988). Factors applicable to this case study are discussed in this section.

Researchers have established key performance indicators (KPIs) to measure the complexity of schedule, productivity, scope, quality, safety, organizational domains and more. A selected a series of KPIs is provided from the literature (Table 2). As discussed before, labor productivity has been studied for decades (El-Gohary & Aziz, 2014). It can be calculated through the ratio of input to output (Equation 1) or vice versa (Equation 2). Equation 1was utilised in the macro-level study of productivity (Section 5.1.1) because it follows the same logic as the conventional term: average working days required to finish a typical level. Thus, this ratio allows a general overview of the project's performance. However, Equation 2 was utilised in the micro-level study of variability of productivity between levels because it allows a better comprehension of productivity gained through the learning curve as the construction team progress with the typical levels, discussed in Chapter 3.

$$Productivity = \frac{Working\ Days\ Required\ [input]}{\#\ of\ Levels\ Completed\ [output]} \qquad \text{Equation 1}$$

$$Productivity = \frac{Area\ Installed\ (m^2)[output]}{Time\ Required\ (seconds)[input]} \qquad \text{Equation 2}$$

Labor efforts conveys all work in a single unit. It allows construction managers to determine progress without the bias of studying budgeted costs. Some contractors prefer to express work in terms of labor hours rather than construction costs because costs can be distorted with lump sum payments and front-loaded schedules (Hinze, 2008).

Statistical tests, such as the Kolmogorov-Smirnov (KS) test, can be used to investigate the correlation of factors on a project's performance. This is done by comparing the distributions of test and control samples. A probability value (P value) that is lower than the significance level (alpha) confirms that the samples follow different distributions with the specified confidence interval (1- P Value). As discussed, it is important to study net hook time because it is on the critical path of installing an element and it uses a critical resource. Reducing it has the potential to reduce the entire process's duration (Forsythe and Sepasgozar 2016).

Reliability, also known as growth, of schedule and/ or cost is a means to assess project performance to study the predictability of projects. This is performed through studying the reliability of plans made by the construction management team by comparing them to the actual construction schedule. Koskela has introduced this concept in 1992; Howell and Thomas have done further research and decided statistical research needed to be conducted to find if a correlation exists between work flow (the difference between planned and actual) and labor productivity (Ballard et al. 2005). Min Liu, investigated further and found no statistical significance (Liu et al. 2011). Nonetheless, "the true measure of performance lies in its predictability over time" (Poirier, Staub-French, and Forgues 2015a). Meaning, if a project is exceedingly complex but builders have predicted and accounted for all complexities during the pre-construction planning phase, it will be a successful project. This concept is utilised in this thesis through the following metrics: schedule reliability, earned value analysis, plan percent complete (5.2.3, 5.2.4 and 5.2.5). Plan percent complete (PPC) was developed by the Lean Construction Institute (LCI).

Table 1: Factors affecting labor productivity- adapted from (Poirier, Staub-French, and Forgues 2015b)

Factor	**Source**
Industry	
Adversarial relations	(Durdyev and Mbachu 2011)
Availability of skilled labor	(H. R. Thomas and Napolitan 1995),(Donald F. Mcdonald 2004)
Economy	(Pekuri, Haapasalo, and Herrala 2011), (Durdyev and Mbachu 2011), (Rojas and Aramvareekul 2003)
Organization	
Frim reputation	(Kazaz, Manisali, and Ulubeyli 2008)
Information technologies	(Rivas et al. 2011), (Rojas and Aramvareekul 2003)
Research and development	(Pekuri, Haapasalo, and Herrala 2011), (Rojas and Aramvareekul 2003)
Individual- Management	
Flow, coordination of work	(H. R. Thomas and Napolitan 1995), (Dai, Goodrum, and Maloney 2009), (Donald F. Mcdonald 2004), (Rivas et al. 2011)
communication	(Dai, Goodrum, and Maloney 2009)
change management	(Donald F. Mcdonald 2004)

Table 1(Cont.): Factors affecting labor productivity- adapted from (Poirier, Staub-French, and Forgues 2015b)

Factor	**Source**
Individual- Labor	
Absenteeism	(H. R. Thomas and Napolitan 1995), (Dai, Goodrum, and Maloney 2009), (Durdyev and Mbachu 2011), (Enshassi et al. 2007), (Donald F. Mcdonald 2004), (Rivas et al. 2011)
Learning Curve	(Pekuri, Haapasalo, and Herrala 2011), (H. R. Thomas and Napolitan 1995), (Donald F. Mcdonald 2004)
Benefits	(Enshassi et al. 2007)
Incentives	(Dai, Goodrum, and Maloney 2009), (Enshassi et al. 2007), (Rivas et al. 2011)
Experience	(Dai, Goodrum, and Maloney 2009), (Enshassi et al. 2007), (Rojas and Aramvareekul 2003)

Table 2: Summary of KPIs from selected literature

KPI	Description (Qualitative/ Quantitative)	Source
Schedule		
Speed (Productivity)	Output/ Input	(Hanna, Peterson, and Lee 2002), (CII 2014), (Poirier, Staub-French, and Forgues 2015b)
	Input/ Output	(H. Park 2005)
Schedule Reliability	Comparison of preliminary planned and construction (actual) schedules	(Staub-French and Khanzode 2007)
Plan Percent Complete (PPC)	Comparison of weekly work plans (WWPs) and construction (actual) schedule	(Hamzeh, Ballard, and Tommelein 2012), (Limon 2015)
Performance Index by Earned Value Analysis	Budgeted Cost of Work Performed (BCWP)/ Budgeted Cost of Work Scheduled (BCWS)	(Hinze 2008), (Yi and Chan 2014), (Poirier et al. 2015b)
	Budgeted Cost of Work Scheduled (BCWS)/ Budgeted Cost of Work Performed (BCWP)	(B. H. R. Thomas et al. 1991), (Poirier et al. 2015b)
Labor Efforts	Labor hours/ Gross Square Foot	(Ated, Gy, and Architec 2015)
Scaffolding Work Hours	Scaffold Hours (on-site transportation+ installation+ disassembly)/ Area	(CII 2014)
Direct Work	Shows percentage of time spent per laborer in value-adding activities	(Hanna, Peterson, and Lee 2002)

Table 2 (Cont.): Summary of KPIs from selected literature

KPI	Description (Qualitative/ Quantitative)	Source
Scope	Request for Information Logs: Logs the (a) number and (b) date of all RFIs	(Hanna, Peterson, and Lee 2002)
Change Orders	Logs the (a) number, (b) date and (c) quantity of work of all COs	(Hanna, Peterson, and Lee 2002), (Ated, Gy, and Architec 2015)
Quality	Logs the quantity and time of deficiency/ punch lists	(Hanna, Peterson, and Lee 2002)
Safety	Logs reported incidents, severity and time wasted due to incident	(Hanna, Peterson, and Lee 2002)
Organization		
Client Satisfaction	Collects information of how satisfied every trade by previous trade's work	(Hanna, Peterson, and Lee 2002)
GC Satisfaction	Collects information of how satisfied the general contractor is by every trade's performance	(Hanna, Peterson, and Lee 2002)
Project Management Teams	Number of full-time personnel dedicated for this project	(CII 2014)

2.2 Mass Timber in Construction

The use of mass timber as structural components has influential benefits, relative to reinforced concrete, steel and/ or light-frame timber. The research team assists in advancing the state of knowledge about mass timber by exploring the efficiency of the construction process (Chapter 5). This section provides a background on the use of mass timber in construction.

As discussed, a shortened floor cycle is one of the primary reported advantages of using mass timber as a structural element in high rise construction. Therefore, the research team studied the productivity of the installation of typical floors, amongst other metrics. To allow the research findings to be applicable to a wide geographical context, the research team divided the construction process into details. A detailed analysis of hook time is included in the study of installation of the mass timber structure. As discussed in Chapter 5, the installation of TWH included fixing drag-straps for lateral supports; however, regulatory codes in other countries do not have this requirement due to less seismic activities (Forsythe and Sepasgozar 2016). Other benefits include: a lower carbon footprint, lower overall construction time, improved aesthetics, higher strength to weight ratio, high fire resistance due to charring, high support for the local industry, as well as higher flexibility for de-construction, re-use and recycling (Karsh 2014).

Moreover, the construction process has the potential to require less skilled labor. A CLT system can be assembled using only two trades, whereas a post-tensioned concrete system requires approximately 12 trades. This results in a better flow of work on site, a shorter time construction time for the structure, and a shorter overall construction time (Schmidt and Griffin 2013, Crespell & Gagnon 2010). Moreover, it results in higher precision; using computer aided design (CAD) programs and precision cutting and routeing are able to model and fabricate mass timber panels with great accuracy (Kremer and Symmons 2015).

The manufacturing and installation processes allows the construction management team to follow more sustainable practices. Choosing mass timber as the structural element results in a lower carbon footprint, a significant reduction in waste and a sequester of substantial amounts CO_2 (Green, Sustainability 2014). The use of local industry is a sustainable practice because it results in lower delivery travels (Callisortkl 2016). Moreover, in the Grizzly Paw case study, the design and construction teams saved costs and resulted in a building that better suits the end customer's needs because they decided use mass timber as a structural element as opposed to concrete or steel (Woodworks 2013).

The National Building Code of Canada (NBCC) limits the height of wood buildings to six storeys wood frame residential buildings (NRC Canada 2010). Moreover, the British Columbia Building Code (BCBC) article 3.2.2.50 restricts the heights of buildings with

Group C (residential) and combustible construction to 6 storeys and/or 18m high. Special approvals would be required to build higher, thus the design of tall mass timber buildings in Canada is based on Site-Specific Regulations (SSR) (The National Research Council 2012). Wood buildings can be as structurally safe, resistant to fire and user-comfortable acoustically as a typical concrete or steel building if designed correctly (Karsh 2014). Previous research has provided technical guidance in the design and construction of mass timber systems, particularly cross-laminated timber (CLT), as alternative solutions in building codes (FPInnovations 2011).

Several decisions are required early in the design phase; this section will discuss a non-exclusive list. Firstly, the team will decide whether the wood will be exposed, partially exposed or concealed. Exposed wood structures protect the building against fire due to charring and eliminate the cost of extra finishing. However, it will require additional care in detailing to maintain fire separations, smoke separation, exposure risks, acoustic design and integration of building services for a unified aesthetic. An example of a partially exposed wood structure is exposed columns and concealed floors and ceilings. Partially exposed wood structures do not require a full-systems-integration approach because most services can hang below the structure and be concealed by a false ceiling, similar to a typical concrete building. However, it will require additional care in detailing for fire and acoustics. A concealed wood structure allows for a high performance of acoustics and fire. However, it deprives the users from the aesthetic features of (partial) exposed wood structures. Secondly, the team will decide whether the timber elements are fully integrated into the structural design, partially integrated or not at all. This is another example of coordination of early coordination with services that would not occur in a typical concrete building. Thirdly, the team will decide on the mass timber product to be used. This decision is particularly relevant in exposed and structural mass timber buildings. Coordination is required herein to consider the following factors: architectural aesthetic intents, panel dimensions, material handling and exposure to weather, material cost, material availability and sustainability objectives (Green, The Building as a System 2014).

The design, fabrication and installation teams combine efforts to assure that the design and codes are well-implemented in construction. Coordination meetings are set prior to the fabrication phase to review panels' connections for constructability and sequencing, confirm schedule and personnel's responsibilities, allow access to 3D model and review safety. Moreover, a clear strategy of transportation and storage should be agreed upon. Typically, the Engineer of Record would have to approve it. Just-in-time delivery of all prefabricated parts to the site is preferred (Ballard and Howell 1995). Minimizing material storage on site reduces site logistic issues, the negative impact of weather and handling on the prefabricated parts and the risk of site accidents. A plan should be created by the Architect, Engineer and Supporting Engineer of Record to develop the required quality assurance strategies and divide responsibilities. Logs should also be kept to document following, preferably with visuals: (1) Environmental conditions, (2) Site deliveries, (3) Quality control sign-off on hardware installations, (4) Site modifications, (5) Site inspections (Epp 2014).

Erection methods are typically designed by the Supporting Registered Professional Structural Engineer and followed by the Construction Manager. This is because rigging prefabricated panels into location causes structural stresses that differs from those experienced by the element as part of the building structure (Gagnon and Pirvu 2011). Moreover, the Engineer of Record records the method of protection of wood elements during installation as well as after installation in the specifications. Some of the potential risks are: (1) Fire, (2) Weather due to excessive water and UV exposure, (3) Rapid moisture change, (4) Contamination of wood with other construction materials such as steel welding, (5) Wood damage due to other trades by handling and moving of materials or equipment. Examples of wood protection are coating, as a final step in the factory, and a parameter starting finishing work as early as possible on site.

Where possible, site modifications should be pre-planned and pre-approved by the Architect and Engineer of Record. Unforeseen site modifications should be approved by the Architect, Engineer and Supporting Engineer of Record before any action on site (Epp 2014).

Chapter 3: Research Methodology

The research team aimed to study the performance of the construction phase of the Brock Common's Tallwood House project (TWH) to advance the state of knowledge about construction performance of mass timber buildings. To understand and document the construction process, the research team collected the following data: time-lapse images and videos of exterior façade, site-visits images and notes on progress and methods, interviews with team representatives, structural and architectural drawings, site-instructions, project specifications, preliminary and lookahead schedules (Section 3.1). Consequently, the research team analyzed the data to understand the performance of the construction process (Section 3.2).

A macro-level study examines the following metrics to investigate the building elements from TWH as a single entity:

1. Macro-level production rate at the element level in terms of number of working days (input) per level (output).
2. Hook time in crane days.
3. Labor efforts in labor hours per discipline.

Moreover, a micro-level study focuses on the performance of every level of the following elements: mass timber structure, envelope cladding systems and CLT drywall encapsulation. The following metrics were utilized:

Micro-level productivity of all levels at the activity level in m^2 (output) / crane-hour (input).

4. Variability of productivity of all levels at the activity level in m^2 (output) / crane-hour (input).
5. Statistical investigation of CLT installation.
6. Schedule reliability in lead days between preliminary and construction schedules.
7. Earned value reliability analysis in Canadian Dollars.
8. Planned Percent Complete (PPC).

3.1 Data Collection

The necessary data was collected depending on the building element in question, as discussed in Table 3. The research team's scope included all building elements in a macro-level; additionally, for the micro-level study, the scope included all CLT panels in all levels and 21 out of 22 envelope panels per level for all levels. One envelope panel per level has been excluded because a vertical strip was left open to place temporary outriggers for material rigging.[3] 842 crane cycles were studied,[4] covering the full 11,553 m^2 of floor area and 6,235 m^2 out of 6,472 m^2 of cladding area, and a perimeter of 2,244 m. Daily weather and number of laborers on site served to complement the analysis.

Time-lapse images and videos were collected using a series of cameras. The research team installed a site camera on a roof of a neighboring building to capture 1 image-frame/ 10 seconds. The research team had access to three additional site-cameras on different roof-tops location around the site. Furthermore, a camera was mounted every day on the ground floor to record trucks at a rate of 1 image-frame/ 5 seconds. Three additional cameras were mounted on the crane and/ or equipment carts to record progress on deck at a rate of 1 frame/ 5 seconds or a continuous video (30 frames/ second), depending on the need. Placing a camera on a mobile object, requires capturing a video. A video runs out the camera's battery after 1-2 hours while a series of time-lapse images can record for approximately 5 hours. A correlation of the data utilised for every metric is discussed in Section 3.2.

[3] As planned, the remaining strip of envelope panels was later installed by the same trade.

[4]A crane cycle is the duration of time required to hook a pre-fabricated part to crane, transport it from truck to location, fasten it in place, unhook it from crane and an empty return trip by the crane back to the truck.

Table 3: Data collection methodology and scope

Building Elements	Time-lapse at 1 frame/ 10 seconds	Time-lapse at 1 frame/ 5 seconds	Interviews & Site Visits	Structural and Architectural Drawings	Site Instru-ctions	Preliminary Schedule	Lookahead Schedules	Daily Site Weather	Daily Crew Size	Labor Count
Site work										
Excavation			X			X	X			X
Concrete structure										
Foundation	X		X			X	X			X
Podium	X		X			X	X			X
East Core	X		X			X	X			X
West Core	X		X			X	X			X
Mass-timber structure										
CLT Panels	X	X	X	X	X	X	X	X	X	X
Glulam Columns	X	X	X	X	X	X	X	X	X	X
Envelope Panels										
Flat Panel	X	X	X	X	X	X	X	X	X	X
Corner Panels	X	X	X	X	X	X	X	X	X	X
Other Structural Elements										
Perimeter L-angles	X	X	X	X	X	X	X	X	X	X
Water sealer on CLT	X		X		X	X	X			X
Concrete Floor Topping	X		X		X	X	X			X
Steel Roof	X		X			X	X			X

Table 3 (Cont.): Data collection methodology and scope

Building Elements	Time-lapse at 1 frame/ 10 seconds	Time-lapse at 1 frame/ 5 seconds	Interviews & Site Visits	Structural and Architectural Drawings	Site Instru-ctions	Preliminary Schedule	Lookahead Schedules	Daily Site Weather	Daily Crew Size	Labor Count
Interior finishing										
Encapsulation	X		X	X	X	X				X
Framing			X			X				X
Mechanical+ Electrical rough-ins			X			X				X
Insulation, boarding, mudding, taping, vapor barrier			X			X				X
Paint (prime + patch)			X			X				X
Flooring			X			X				X
Cabinets			X			X				X
Doors, hardware, accessories, fixtures			X			X				X
Final Paint			X			X				X

3.2 Data Analysis

As discussed above, the research team focused on studying the performance of the construction phase of TWH. Building elements were studied at different levels of details, contributing to different levels of performance assessments. The research scope included all building elements in a macro level; additionally, it included all CLT panels, most envelope panels and CLT encapsulation in a micro level. All metrics discussed below are defined and referenced in Chapter 2 and organised in Table 4 for the reader's convenience.

At the macro-level, building elements of the TWH were studied as an entity. The macro-level metrics were:

1. **Macro-level production rate in terms of number of working days (input)/ number of levels completed (output).** The data utilized herein are: time-lapse images and videos at a rate of 1 image-frame/ 10 seconds as well as site-visits pictures and notes on construction progress. For this metric, total durations, number of working days and number of levels completed were studied for the following elements: concrete foundation, levels 1 and 2 concrete slabs, concrete core stairs, mass timber structure, envelope cladding system, steel roof, application of on-site water sealer, preparations for and pouring of concrete floor toppings and interior finishing work. This metric provides an overview of the learning curve for every building element as an entity.
2. **Hook time is presented in crane days.** The data utilized herein are: time-lapse images, videos and interviews with team representatives to understand the installation processes. Two aspects were studied: (a) the coordination between installers and (b) learning curve in a macro-level in the construction of a heavily pre-fabricated building using a single crane. Crane days were linked to location, number of installed pre-fabricated parts and type of pre-fabricated part for the following structural elements: CLT panels, glulam columns and envelope panels. This metrics studies the coordination between different trades to build a heavily pre-fabricated structure using a single crane and presents an overview of the learning curve in a macro-level.

3. **Labor Efforts in total labor hours per discipline**. The data utilized herein are site-visit notes and labor-count records. For this metric, the research team studied the labor efforts for the following elements: concrete stair cores, mass timber structure, envelope cladding, civil work, drywall, MEP and contributory work by general contractor labors. This metric covey all work in a single unit to allow the reader to determine progress without the bias of studying budgeted costs.

At the micro-level, the study focused on the following building elements: mass timber structure, envelope cladding systems and CLT encapsulation with drywall. The performance of every level was studied separately and contrasted against other levels. The micro-level metrics were:

4. **Variability of productivity of all levels in m^2 (output)/ hour (input).** The data utilized herein are time-lapse videos, site-visit notes, interviews with team representatives and project specifications and structural and fabrication drawings. For this metric, hook times for CLT floor panels and envelope panels cladding systems were analyzed for all levels at the activity level. Net hook time is the duration, in hours, needed to install prefabricated parts excluding any stoppages to accommodate other trades. Productivity rates in terms of crane time (m^2/ crane-hours) and labor time (m^2/ labor-hours) were calculated and compared within all levels of project to deduce the variability in productivity (learning curve). Stoppages, miscellaneous rigging, crane operational times and rework have been subtracted and studied separately for a fair comparison between different levels. Rain, wind and temperature were recorded to complement the study. The site camera with an image rate of 1 picture-frame/ 10 seconds was the primary source of input. Footage for the fine analysis (metric #5) was utilized during blind spots, fog and bright sunlight. Important take-aways that come from this level of analysis are: crane time needed for installation activities, crane productivity and crew productivity. This section discusses the learning curve established in installation productivity in more detail than Section 5.1.2 Crane Days.

5. **Statistical investigation of CLT installation in hook time (minutes and seconds).** The data utilized herein are time-lapse images, interviews with team representatives and studies of project specifications, structural and architectural drawings. The mobile cameras with an image rate of 1 picture-frame/ 5 seconds, sometimes 30 picture-frames/ 1 second, were the primary source of input. The effect of three factors on hook time was investigated for a scope of six levels of CLT panels. The installation of CLT panels is divided into seven sub-activities, three of which constitute net hook time.
6. **Schedule reliability in lead days between planned and construction schedules.** The data utilized herein are time-lapse videos, site-visit notes, interviews with team representatives and preliminary schedules. The research team investigated a comparison between planned preliminary schedule and construction schedule for the mass-timber structure and envelope cladding system. The planned schedule, finished in March 2015, was overlaid with the construction schedule, finished in August 2016, to understand schedule reliability for the mass timber structure and envelope cladding systems.
7. **Earned value analysis.** The data utilized herein are time-lapse videos, site-visit notes, interviews with team representatives and preliminary schedules. The Budgeted Cost of Work Scheduled (BCWS, the planned cost and schedule) from March 2015, the Actual Cost of Work Performed (ACWP, the actual cost and schedule) from August 2016, and the Budgeted Cost of Work Performed (BCWP, the earned value) were compared. The objective is to understand the reliability of schedule and cost estimate for the mass timber structure and envelope cladding system. This analysis was conducted by the research team post-mortem.
8. **Plan Percent Complete (PPC).** The data utilized herein are time-lapse videos, site-visit notes, interviews with team representatives and lookahead schedules. Weekly work plans (WWPs) were produced and compared with the actual construction schedules to calculate the percent of work completed. PPC was developed by the Lean Construction Institute (LCI). For this investigation, the research team's scope was: CLT installation, flat envelope panels installation and the first layer of CLT ceiling encapsulation with drywall.

Table 4: Data analysis and scope

Building Elements	Macro level production rate (working days/ level)	Crane Days	Labor Efforts (labor hours/ discipline)	Variability of Productivity (m²/hour)	Statistical Study (seconds)	Schedule Reliability (lead days)	Earned Value Analysis ($)	PPC (%)	Comparative Case Analysis (m²/hour)
Site work									
Excavation	X								
Concrete structure									
Foundation	X								
Podium	X								
East Core	X								
West Core	X								
Mass-timber structure									
CLT Panels	X	X	X	X	X	X	X	X	X
Glulam Columns	X	X	X			X	X	X	
Building envelope									
Flat Panel	X	X	X	X		X	X	X	X
Corner Panels	X	X	X	X		X	X	X	X
Other Structural Elements									
Perimeter L-angles			X						
Water sealer on CLT	X		X						
Concrete Floor Topping	X		X						
Steel Roof	X		X						

Table 4 (Cont.): Data Analysis and Scope

Building Elements	Macro level production rate (working days/ level)	Crane Days	Labor Efforts (labor hours/ discipline)	Variability of Productivity (m^2/hour)	Statistical Study (seconds)	Schedule Reliability (lead days)	Earned Value Analysis ($)	PPC (%)	Comparative Case Analysis (m^2/hour)
Interior finishing									
Encapsulation	X		X						
Framing	X		X						
Mechanical+ Electrical rough-ins	X		X						
Insulation, boarding, mudding, taping, vapor barrier	X		X						
Paint (prime + patch)	X		X						
Flooring	X		X						
Cabinets	X		X						
Doors, hardware, accessories, fixtures	X		X						
Final Paint	X		X						

3.3 Validation

This research project aims to investigate the performance of the construction process of the TWH. The findings from the chosen metrics allowed the required understanding of the performance of the construction process, particularly the innovative mass timber structure and envelope cladding systems; therefore, fulfilling the research objectives. All metrics were validated by the senior project manager. The inputs, findings and conclusions drawn have been discussed and confirmed with the project manager.

Furthermore, the outcomes were justified through design, fabrication, construction and weather events in Chapter 5. For example, the considerable reduction of CLT installation productivity experienced in level 16 was justified by the rain event and the introduction of four skilled workers to new positions. Justification of quantitative outcomes was done for the following metrics: crane days, variability of productivity, statistical investigation of CLT installation. PPC was calculated using weekly work plans and construction schedules made by the research team from lookahead schedules and site visits, respectively. It was validated through site pictures showing the weekly construction progress of prefabricated structural elements (Appendix C). The validation pictures solidify the authenticity of the quantitative findings.

Lastly, the research team compared the productivity of installation of CLT and envelope panels in TWH to installation of mass timber as floor and wall panels in previous productivity case studies by University of Technology Sydney, Table 4 (Forsythe and Sepasgozar 2016). Due to the originality of every construction project, particularly this case study, several challenges and solutions were experienced by the research team in the comparison process. Case study comparisons' findings, challenges and solutions are documented in Chapter 6.

Chapter 4: Case Study

This chapter provides a background for the chosen case study project. Brock Common's Tallwood House (TWH) will be the tallest building of its kind in the world upon completion. The building is 18-storey high, composed of a hybrid of mass-timber, concrete and steel.

4.1 Project Description

The University of British Columbia's Brock Common's, TWH is a student residence with a capacity of 404 beds. It provides single-bed studios as well as four-bed shared units for upper year undergraduate and graduate students. It is aims for a LEED Gold certification. Detailed project information is provided below (Table 5).

While the project is a unique and innovative, project participants intended to "keep it simple" by using tested and certified solutions where possible (Acton 2017). The structural system is a hybrid of three elements: concrete, steel and mass timber (Figure 2). The foundations, cores, level 1 slab and columns and level 2 slab are made of concrete. Mass timber constitutes the remaining super structure, level 2 columns to level 18 columns. Steel is utilised in connections, roof and building cladding system.

The building is estimated to be 7,648 tonnes lighter relative to a similar concrete building (Poirer et al. 2016). Thus, the team saved budgeted costs by using smaller-sized foundations, 2.8m x 2.8m x 0.7m spread footings. The lighter weight reduces the building's inertia needed to aid the resistance to lateral loads. The concrete cores and steel connections provide excellent lateral support.

Levels 2 to 18 utilizes 29 cross-laminated timber (CLT) panels and 78 glulam columns per level. CLT was used in a two-way spanning capability. The panels are joined together using 25 mm wide splines; fixed using nails and screws. The primary lateral support system consists of two concrete cores and steel straps (Appendix E). The project meets the fire rating standards for its type. This was achieved through three layers of fire-rated Type X gypsum board encapsulation as well as back-up water and power supplies.

Table 5: UBC TWH project information (Poirer et al. 2016)

Project Information		
Building Address	6088 Walter Gage Road	
Building Type	Residential (Group C) with assembly spaces (Group A-2)	
Sustainability target	LEED Gold/ ASHRAE 90.1-2010	
Gross Floor Area	15,120 m²	
Building Footprint	840 m²	
Number of stories	18 (17 in mass timber)	
Building height	54.81m (T.O.P.)	
Typical floor height	2.81m	
Project Costs		
Design	$2,411,000	160$/m²
Construction	$39,437,000	2,608$/m²
Estimated premium for mass timber	$4,452,000	294$/m²
Total project cost	$51,525,000	3,390$/m²
Project Schedule		
Start Date	October 15, 2015	
Finish Date	May 30, 2017	
Duration	593 Days	
Building Elements		
CLT Panels- volume	1973 m^3	
CLT Panels- quantity	464 panels	
CLT Panels- weight	954 tons	
Columns- volume	260 m^3	
Columns- quantity	1,298 columns	
Volume concrete saved	2,650 m^3	
Volume of Concrete used	2,740 m^3	
Reduction in Emissions of CO_2	500 tons relative to a similar concrete building	

Table 5 (Cont.): UBC TWH Project Information (Poirer et al. 2016)

Team Participants	
Owner/ Client	UBC Student and Hospitality Services& UBC Properties Trust
Construction Manager	Urban One Builders
3D Coordination Consultant	CadMakers Virtual Construction
Timber Manufacturer	Structurlam Products
Concrete/ Rebar	Seagate Structures

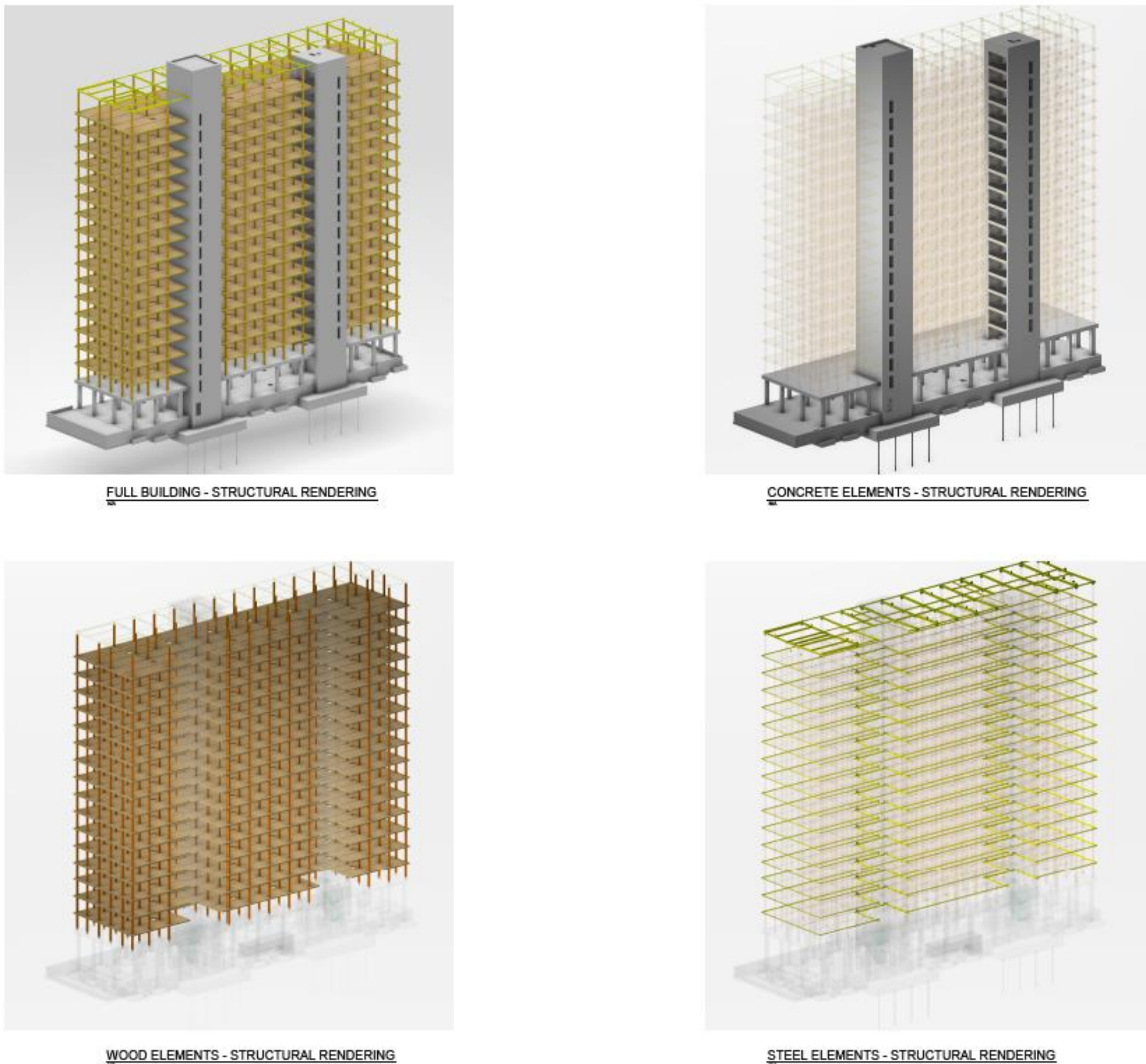


Figure 2: UBC TWH hybrid structural system (© Fast+ Epp)

4.2 Project Context

The UBC Student Housing and Hospitality Services (SHHS) has developed the Student Housing Growth Strategy to add 2,000+ beds by 2017 (UBC Housing Plans & Policy 2015). The design utilizes Cross-Laminated Timber (CLT) in floor panels and Glue laminated timber (GLT) and Parallel Strand Lumber (PSL) in columns. They are manufactured by binding strands, veneers or boards of with adhesives. It will house 404 graduate/ upper year undergraduate students in studio and quad units. The project was initiated in November 2014 with design beginning in January 2015. Construction of the building began in November 2015 and the building is expected to be ready for move in by early May 2017. The building was designed using an integrative design approach and involved heavy use of virtual design & construction tools and methods. The project is also characterized by considerable prefabrication of structural components and building envelope, early trade buy-in, early detailed design and a mock-up to test the constructability of structural components' connections.

UBC follows the British Columbia Building Code 2012 (BCBC), The British Columbia Fire Code (BCFC), UBC Policy #92- Land Use and Permitting, and The BC Building Act. BCBC article 3.2.2.50 restricts the heights of buildings with Group C (residential) and combustible construction to 6 storeys and/or 18m high. Brock Common's, Tallwood House (TWH) does not conform with the current requirements of BCBC (Poirer et al. 2016). A Site-Specific Regulation (SSR) was proposed based performance by Province of British Columbia's Building Standards and Safety Branch (BSSB), authorized under the Building Standards and Safety Act and authorized by the Minister as well as UBC. The NRCan Tall Wood initiative offered a funding to drive the use of wood as a structural element in this project. This was the key factor in choosing mass timber as a structural element, as opposed to the traditional material: reinforced concrete (E. Poirier, A. Fallahi, et al. 2016).

4.3 Pre-Construction Planning Process

The installation process proved to be a success. Virtual design in construction (VDC), early detailed design, early trade buy-in, fabrication and a mock-up were factors that assisted in the success of the Tallwood House project (Figure 3). This section summarizes the planning efforts. A detailed description of the pre-construction planning phase is referenced (E. Poirier, et al. 2016).

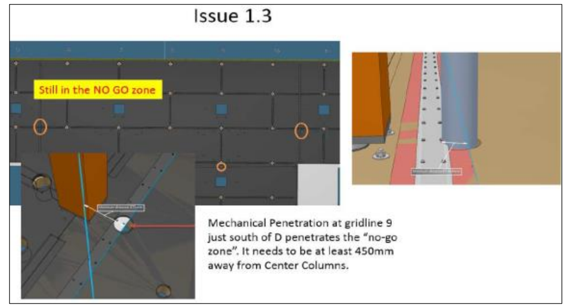
Virtual design in construction (VDC) was used for visualization, multi-disciplinary coordination, clash detection, constructability review, quantity takeoffs, 4D planning and sequencing, digital fabrication of prefabricated mock-up elements and, in some instances, structural analysis. Typically, the spatial layout of mechanical, electrical and plumbing (MEP) systems is the performed on-site by the construction manager and trades.

Fabrication creates the need for an earlier spatial layout; engineers collaborated with VDC modelers and design-assist trades to layout the MEP systems within the building. The VDC model was used as an input to the computer numerical control (CNC) machine in the fabrication process of the timber structure. This allowed the fabrication and construction teams to achieve the challenging tolerances of ±2 mm. This includes the steel connection components in the columns.

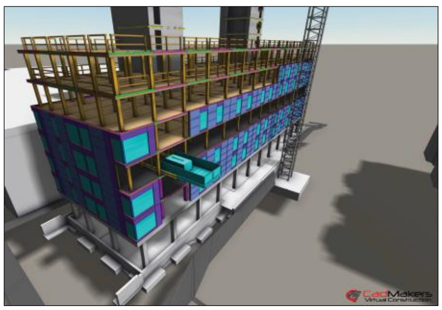
The design process was initiated more than a year prior to the construction of mass timber structure. Schematic design was initiated in November 2014, Detailed design was finished in May 2015 and the design process was completed in September 2015. The concrete and wood structures were initiated in February and May 2016, respectively. An integrated design workshop was held in January 2015. A collaboration of the following teams was held for three days: the owner representative, architect of record, advisory architect, structural, mechanical and electrical engineers, code consultants, VDC integrators, pre-construction manager and the timber installing trade. Outcomes of the workshop includes: the structural, mechanical and electrical systems, the a more understanding of the envelope cladding system, and a comprehensive cost model of all design solution alternatives. Early decisions minimize the need to design, seek approvals and estimate costs for alternatives.

The use of a mock-up provided insightful feedback to structural, mechanical and electrical design teams, VDC integrators and construction management team. A full-scale mock-up of a portion of the building was constructed. It is two storeys high and 8m x 12m in plan. Three different column-to-column connections were tested. The design-assist trades were responsible for the construction. It assisted in the choice of structural, mechanical and electrical systems, such as: column-to-slab connection, slab-to-concrete core connections, steel assembly and design for fabrication of the envelope cladding system. More importantly, the column-to-column connection was modified from welding the threaded rods and hollow structural section (HSS) to the steel plate to drilling and tapping them using a CNC machine (Fast et al. 2016). Moreover, it assisted the trades in refining their process, equipment and validate their proposed speed of installation. The construction management team planned the installation process accurately. Concrete toppings and wood sealers were tested for a decision on the material to be used in construction. VDC integrators tested the exchange of data with the manufacturer (E. Poirier, et al. 2016).

Prefabrication- Structurlam ©



Early detailed design- CadMakers ©



VDC- CadMakers ©

Early trade buy-in – (E. Poirier, A. Fallahi and M. Kasbar, et al. 2017)

Mockup- Fast+ Epp ©

Figure 3: Pre-construction planning process

The schedule was developed and the following risks were identified and mitigation strategies put in place:

- construction schedule prepared with involvement through buy-in process from major trade contractors; specialized methods required to achieve structure erection timeline will likely involve 6-day work weeks to ensure one-floor per week;
- proactive procurement process of major materials, systems, and equipment; tracked for availability of items well in advance of construction timing requirements;
- wood structure and building envelope materials prefabricated and stored offsite;
- computerized design models and physical mock-ups analyzed in advance of mass production to ensure correctness and approval;
- concrete work scheduled for construction through winter; mass wood structure erection to take place in Spring/Summer for reduced weather-related stoppages;

- erection of wood structure after concrete structure will ensure sufficient tower crane time for prefabricated building envelope erection to keep pace with erection of wood structure.

4.4 Construction Process Strategy

This section discusses the installation strategy of structural elements. The construction management team planned 3 days/ level for the mass timber structure and 3 days/ level for the envelope cladding system. The team planned to do the following five activities simultaneously (Figure 4). For the reader's convenience, this is discussed through an example showing a snapshot on a day chosen at random, July 14th:

- encapsulate ceiling and columns in level n (level 6 on July 14th);
- pour concrete floor topping in level n+1 (level 7 on July 14th);
- install envelope panels in level n+2 (level 8 on July 14th);
- line columns in level n+4 (level 10 on July 14th);
- install CLT panels in level n+5 (level 11 on July 14th).

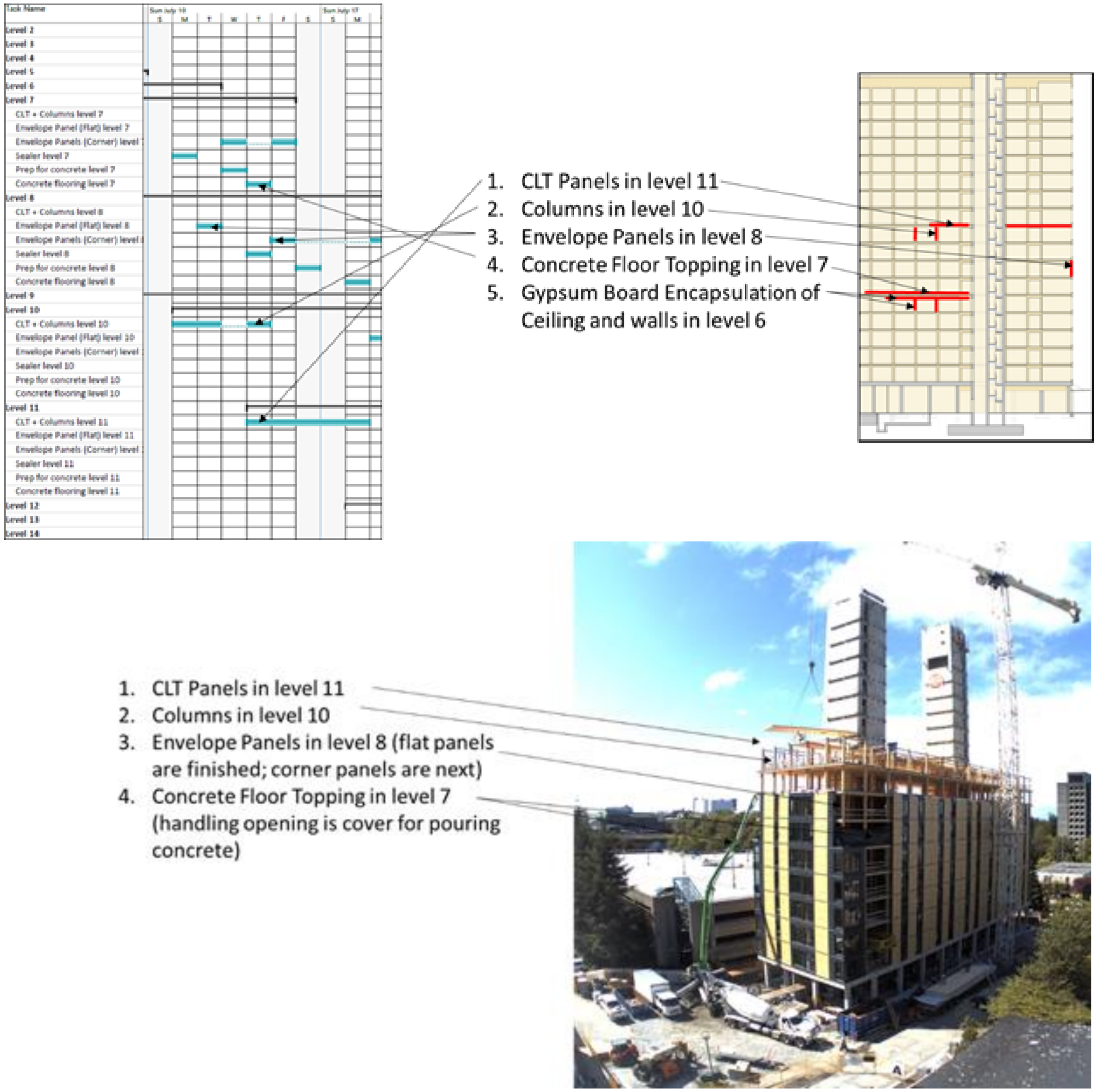


Figure 4: Sequence of structural elements- snapshot on July 14th

This is explained through the sequence of activities that occur for every level (Figure 5):

1. CLT Trucks #1 and 2 are allowed on site;
2. CLT panels #14 to 29 are installed;
3. Equipment and materials are rigged to active level;
4. Trucks #1 and 2 exit the site;

5. Truck #3 is allowed on-site;
6. CLT Panels #1 to 13 are installed;
7. Guard rails are installed;
8. Column washers, splines, drag straps and water-proofing tapes are installed;
9. Perimeter L-angles are installed;
10. Columns are installed;
11. Envelope panels are installed;
12. Water sealer is applied;
13. MEP holes are covered to prepare of concrete pouring;
14. Concrete floor topping is poured;
15. Envelope panels' joints are sealed using baker-rods and caulking;
16. Drywall, mechanical, electrical and plumbing trades start;

A detailed description in the context of installation trades is provided with visual aids in Appendix F Installation Methods.

Figure 5: Sequence of structural elements

Chapter 5: Productivity Study Findings

This section presents the performance assessment of the construction phase of the Brock Common's Tallwood House (TWH). To support the performance assessment process, eight metrics were considered, as discussed in Chapter 3. A macro-level study examines the following metrics for building elements: (1) Macro-level production rate at the element level in number of working days (input)/ level (output), (2) Hook time in crane days, and (3) Labor efforts per discipline. A micro-level study focuses on mass timber structure and envelope cladding systems to study the performance of every level in the building: (4) Variability of installation at the activity level in m^2 (output)/ crane-hour (input), (5) Statistical investigation of CLT installation in minutes and seconds, (6) Schedule reliability in lead days between planned and construction schedule, (7) Earned value analysis in Canadian Dollars, and (8) Percent Plan Complete (PPC).

5.1 Macro-level Study

The macro-level study investigates building elements from TWH as a single entity. As an overview, the concrete substructure and levels 1 and 2 (1,467 m^3) were finished in 3.5 months. Both concrete cores (1,546 m^3) were finished in 3.5 months at a productivity average rate of 6.7 days per 2 levels. The mass timber structure, majority of envelope cladding system, on-site water sealer, majority of concrete floor toppings, roof and majority of first layer of encapsulation were finished in 2.5 months. Their average productivity rates were 2.4, 2.5, 1.0, 1.0, 16.0 working days/ level, respectively[5]. Encapsulation and concrete floor topping work for level 18 was not scheduled directly after level 17 to avoid over-crowding level 18. Construction cost of completion of the mass-timber structure was \$3.4M; resulting in savings of \$100,000 relative to budgeted cost. The general contractor issued 351 requests for information (RFIs) during the period of April 2016 to February 2017, compared to 1000+ in a smaller concrete building (Fraser, Senior Project Manager, Brock Common's Tallwood House Project, Urban One Builders 2017).

[5] Encapsulation was out of scope of macro-level study. It has been studied in the micro-level study section 5.2.5 Percent Plan Complete (PPC).

5.1.1 Macro-level Production Rate

Macro-level production rate is measured through the ratio of input to output as seen in Equation 3, below. This ratio is applicable in macro-level studies because it follows the same logic as the conventional term: average working days required to finish a typical level, allowing a general overview of the project's performance. However, for other sections of the report, the reciprocal of this equation is more applicable, Section 5.2 Micro-level Study, below.

$$Macro\ Level\ Productivity = \frac{Working\ Days\ Required\ (input)}{\#\ of\ Levels\ Completed\ (output)} \quad \text{Equation 3}$$

Various building elements are investigated to support the assessment of this measure: excavation, concrete foundations, slabs, concrete cores, mass-timber structure, structural steel roof, envelope cladding system, on-site water sealer, preparations and concrete floor toppings and interior finishing work. Start and finish dates, levels completed and time required have been used to calculate the production rate as shown in Table 6. The most productive structural element on site was the mass timber structure because it required an average of 2.4 days/ level, compared to: 2.5 days/ level for envelope cladding, 6.7 days/2 levels for concrete cores, 16 days for structural steel roof, 28.5 days/ level for concrete slabs and 59 days for concrete foundations. This is due to the high continuity nature of prefabricated structural systems. The timber installers had the ability to work 52 days out of 60 business days, as seen in Gantt charts in appendix A.

In 14 weeks, the following building elements were completed (Table 6 +appendix F).:

1. The full mass timber structure (17 levels) was assembled on site.
2. All lateral supports (drag-straps and splines).
3. 16 levels of envelope panels.
4. 15 levels of on-site water sealer.
5. 15 levels of preparations and pouring concrete floor topping.

6. 11 levels of encapsulation of timber structure by type X drywall for fire protection during construction,[6] and lastly.
7. The initiation of the following finishing activities: mechanical and electrical rough-in and interior wall framing.

More details on productivities of mass timber and cladding systems are discussed in Section 5.2 Variability of Installation Productivity.

Table 6: Summary of actual durations and productivity per building element

Building Element	Start Date	End Date	Number of Levels	Total Duration (Calendar Weeks)	Working Days	Production rate (Working Days/ Level)
Excavation	11/18/2015	11/23/2015	1	1	4	4.0
Concrete Foundation	11/20/2015	2/9/2016	1	12	59	59.0
Concrete Slabs (L1 and L2)	12/21/2015	3/8/2016	2	12	57	28.5
East Concrete Core (L2 to L18)	3/11/2016	6/4/2016	17	11	60[7]	6.7[7]
West Concrete Core (L2 to L19)	2/26/2016	6/4/2016	18	14		
Mass Timber Structure (L2 to L18)	6/6/2016	8/11/2016	17	10	41	2.4
Structural Steel Roof	8/11/2016	9/8/2016	1	5	16	16.0
Envelope Panels (L2 to L19 Parapet)	6/21/2016	9/8/2016	18	12	45	2.5
On-site Water Sealer (L3 to L18)	6/27/2016	8/19/2016	16	8	16	1.0

[6]As discussed in Chapter 4, the maximum allowable levels of exposed mass timber during construction is 7, as utilized.

[7]As discussed in Chapter 4, concrete core formworks are set to build 2 levels at a time. Therefore, the unit of output is 2 levels. The first level was not included in the study because a different formwork was used.

Table 6 (Cont.): Summary of durations and total productivities

Building Element	Start Date	End Date	Number of Levels	Total Duration (Calendar Weeks)	Working Days	Production rate (Working Days/ Level)
Prep. work for Concrete (L3 to L18)	6/30/2016	8/29/2016	16	9	16	1.0
Concrete Floor Topping (L3 to L18)	7/4/2016	11/8/2016	16	14	16	1.0
Interior Finishing (L1 to L18)	8/5/2016	Expected to complete in May 2017	18			20

5.1.2 Crane Days

Hook time, also known as crane time, is the duration where cranes are utilized for an activity. It is a subset of the total time, discussed in Section 5.1.1. Hook time is analyzed in detail in the micro-level study, Section 5.2.1. In this section of the report, hook time is purposely presented in a macro-level to link the installation of different types of pre-fabricated parts. This shows the coordination between trades to build a heavily pre-fabricated building using a single crane and presents an overview of the learning curve. Crane days were linked to location, type of pre-fabricated parts and number of installed parts for the following structural elements: CLT panels, columns and envelope panels.

Hook time is valuable to study because the crane portion is on the critical path of assembling prefabricated structures. Meaning, a delay in hook time while installing a panel, delays the total duration of installation. It is important to choose the number of riggers such that they are synchronized with the crane speed. Highlighting hook time assists builders in coordinating crane-time between trades for future projects. An optimum coordination is provided when trades are provided with the hook time required at the required time. Builders aim to minimize instants where trades are waiting for their crane time as well as minimize crane idle times. Total durations, number of working days, number of crane days and average hook time/ level are contrasted in Table 7.

Table 7: Crane days for mass timber and envelope cladding systems

Building Element	Start Date	End Date	Total Duration (Calendar Weeks)	Working Days	Total Crane Days
CLT Panels (L3 to L18)	6/10/2016	8/11/2016	10	19	19
Glulam Columns (L2 to L18)	6/7/2016	8/11/2016	10	47	17
Envelope Panels (L2 to L19 Parapet)	6/21/2016	9/8/2016	12	45	21

The number of columns installed by the crane (green bars in Figure 6) differs in level 2 compared to all other levels. 30 columns were installed using the crane on June 7th followed by 48 columns on June 8th; adding up to a total of 78 columns for level 2. This is because the steel pedestals supporting level 2 columns are elevated, forcing the installers to use the crane on all columns for this level, exclusively. However, the hollow structural steel (HSS) column-to-column connection in levels 3 to 18 are not elevated, allowing the installers to hand-lift non-perimeter columns into place and only use the crane on the 34 perimeter columns to ensure safety.[8] Installers chose to not use the crane for all columns in level 5 to test the practicality of the using the dolly to install perimeter columns.

Moreover, the result of the coordination between trades to share one crane to build a heavily pre-fabricated building can be observed in a macro-level in Figure 6. Section 5.2.1 discusses learning curves and hook time in a micro-level. Installation of CLT panels required 2 crane days in levels 3, 4 and 6; while the succeeding levels required only 1 crane day (timber bars). Installation of flat envelope panels required 2 crane days in level 2; while the remaining levels required only 1 crane day (blue bars).[9] Moreover, in level 17, 29 CLT panels and 34 columns, adding up to 63 pre-fabricated parts, were installed on August 5th.

[8] Perimeter columns can be installed by hand-dolly if it is anchored to an interior column or using the crane, as explained in Chapter 4: Construction Phase Description per Building Element.

[9] Installation process of 17 flat envelope panels and 4 corner panels is explained in detail in Chapter 4: Construction Phase Description per Building Element.

The installation process went exceedingly fast, proving the possibility of installing one complete level of mass-timber structure per day in succeeding projects.

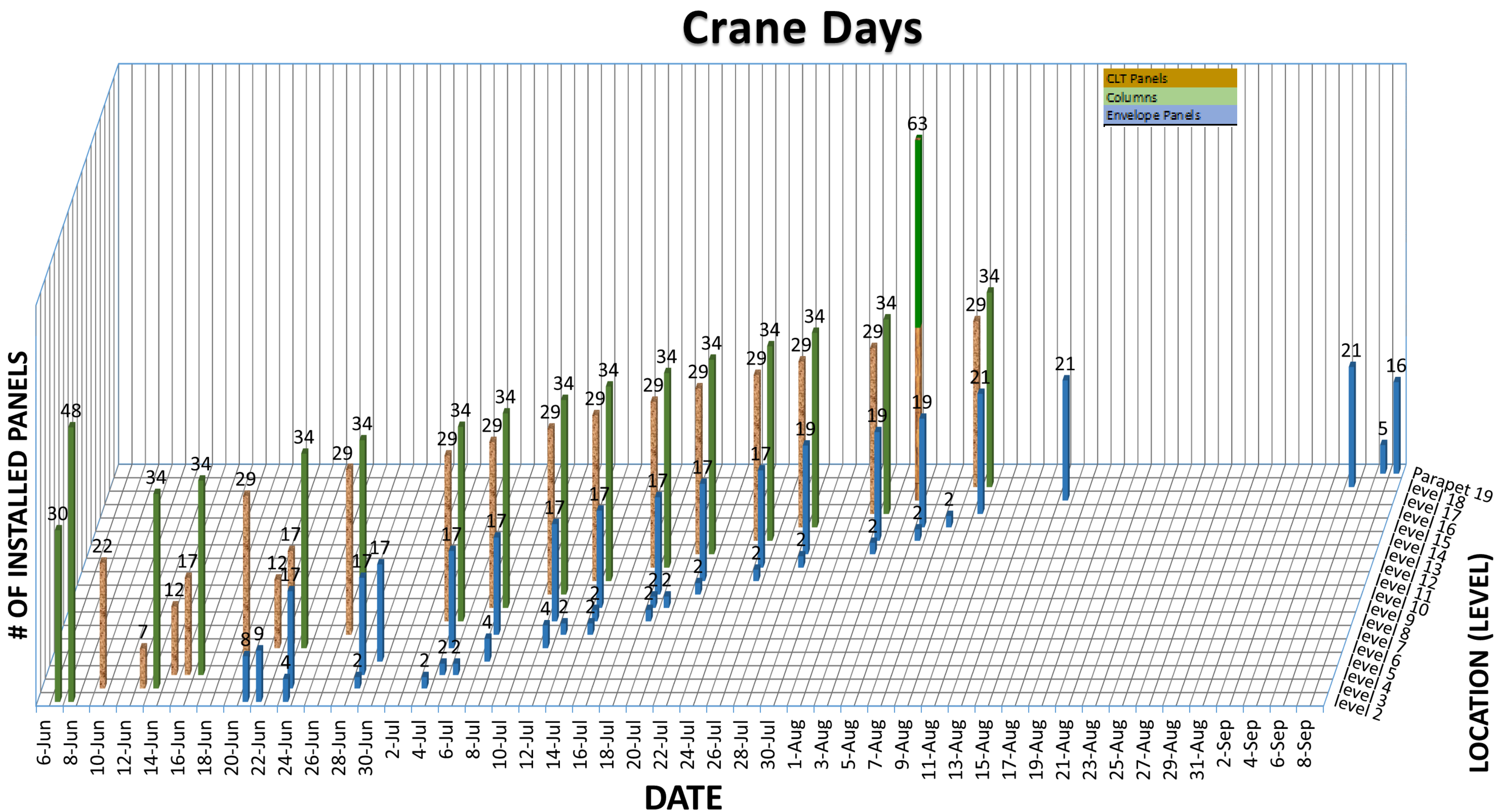


Figure 6: Overview of crane days for all prefabricated elements

5.1.3 Labor Efforts

Conveying all work in a single unit is useful because project managers can determine progress without the bias of studying budgeted costs. Some contractors prefer to express work in terms of labor hours rather than construction costs because costs can be distorted with lump sum payments and front-loaded schedules (Hinze, 2008). A breakdown of labor hours by building element since April 2016, is shown in Figure 7. The mass timber structure and envelope cladding systems required 3.0% and 3.3%, respectively, of the total labor hours.

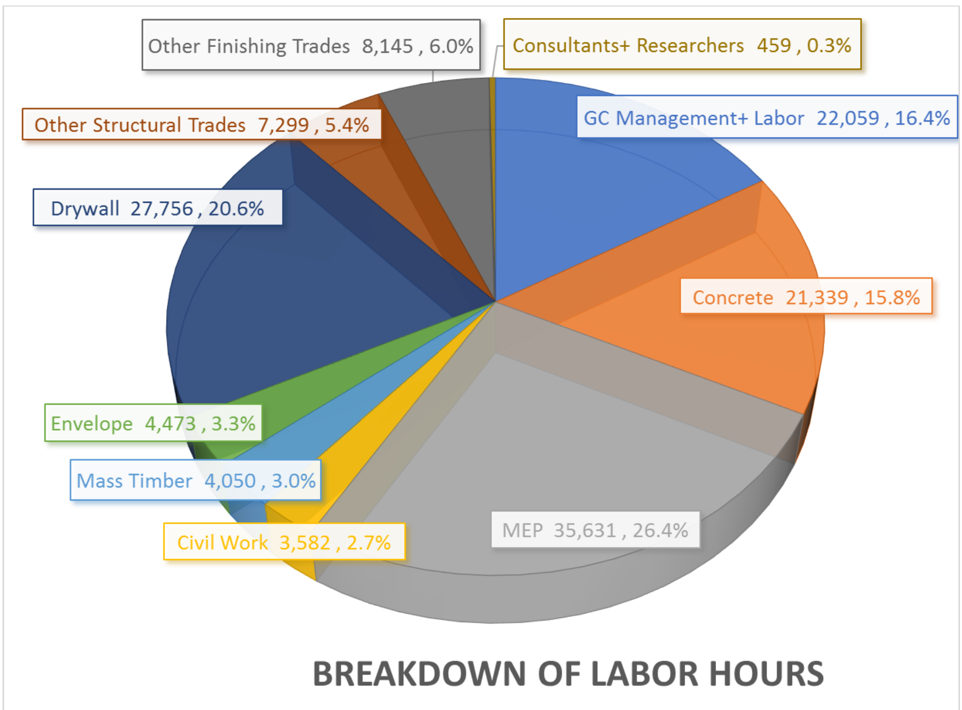


Figure 7: Breakdown of labor hours by building element

A second approach to study labor efforts is to investigate the labor count throughout the construction process. Labor count since April 2016 for all trades has been categorized to present labor effort for different building elements during the construction phase (Figure 8). Sub-contractors responsible for mass timber and envelope cladding systems were fewer in quantity and were required for a shorter time (June- August) in comparison to other trades.

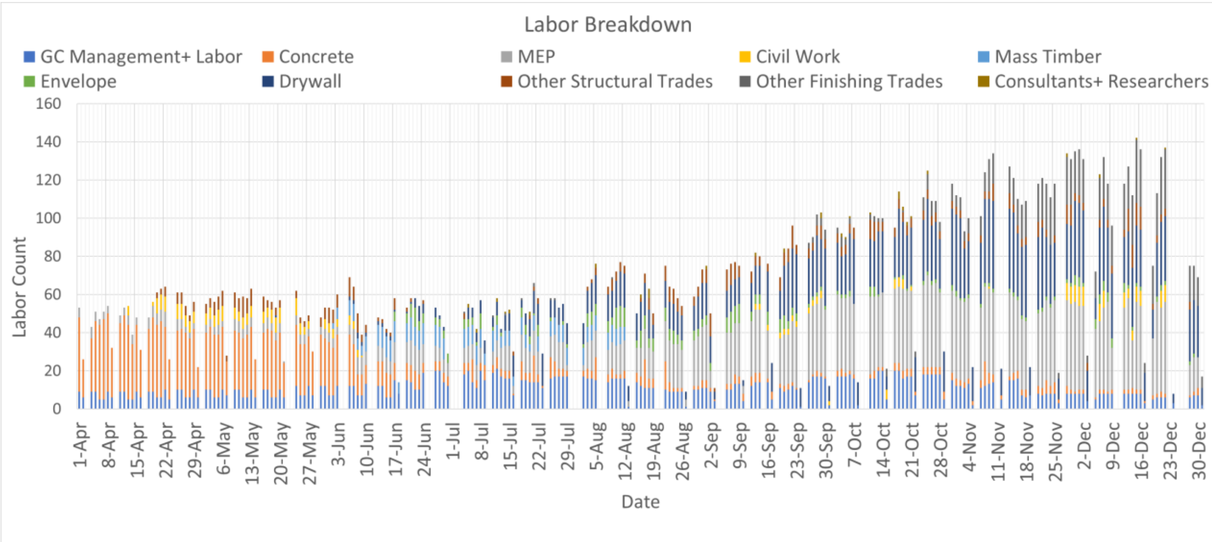


Figure 8: Labor count breakdown by building element

5.2 Micro-level Study

The micro-level study focuses primarily on two building elements: the mass timber structure and envelope cladding systems. CLT drywall encapsulation was studied with a lower extent. The performance of every level is studied for building elements. Results are summarised below:

1. Variability of productivity was investigated by studying 842 crane cycles covering 11,554 m^2 of floor area and 6,235 m^2 of cladding area.
    a. Regarding the mass-timber structure, net hook time for level 3 was 7 hours and 20 minutes. It continued to improve until it reached a duration of 3 hours and 5 minutes at levels 14 and again in 18. The impact of weather and number of labors were studied; the maximum net crane productivity of 234 m^2/ crane-hour at level 14 and a maximum net crew productivity of 29.3 m^2/ labor-hour at levels 14.
    b. Regarding envelope panel cladding system, net hook time started at 12 hours and 7 minutes for level 2. It continued to improve until it reached a duration of 4 hours and 24 minutes at level 15. The impact of weather and number of labors were studied; the maximum net crane productivity of 78 m^2/ crane-hour at level 15 and a maximum net crew productivity of 16 m^2/ labor-hour at level 15.
2. A detailed study of CLT installation resulted in insignificant influences of the following three factors on hook time, described below. Effects on installation durations are less than a minute with no statistical significance.

   a. the location of the CLT panel within the structural drawing,
   b. the location of deck riggers due access to short/ long edge of the flying panel
   c. Rigging circumference due to trucks being on the same/ different side of the crane as the end location of the panel deck.
3. The productivity rates discussed allowed the builders to finish the mass timber structural system 68 days ahead of planned schedule and envelope panels cladding system 58 days ahead of planned schedule.
4. The timber elements were constructed with a cost savings of $100,000 relative to planned budgets; the envelope cladding element experienced a design change resulting in an acceptable increase in cost.
5. CLT panels, envelope panels and encapsulation installation experienced exceptional planned work completed (PPC).

5.2.1 Variability of Installation Productivity

The research team investigates installation productivity at the activity level for building elements: CLT panels, glulam columns and prefabricated envelope panels. Important take-aways that come from this level of analysis are: crane time needed for installation activities, crane productivity and crew productivity. This section discusses the learning curve established in installation productivity in more detail than Section 5.1.2 Crane Days. Every level is studied separately in hours, minutes and seconds; whereas Section 5.1.2 studies every building element as a single unit in number of days to display the installation progress and coordination on-site.

In this investigation, hook time, also known as crane time, is used as the unit of analysis. Hook time is the duration of hooking pre-fabricated parts, rigging to location, fastening, unhooking from crane and empty crane return trips. Net hook times are calculated by measuring the total (gross) hook time, then subtracting: stoppages, crane operational time, miscellaneous rigging and rework. Hook Times have been found to be a useful method of analysis in prior research (Forsythe and Sepasgozar 2016).

It is valuable to study hook time because it is usually on the critical path of installing an element and uses valuable resources: cranes. Reducing the duration of hook time, has the potential of reducing the total durations. Highlighting hook time assists builders in coordinating crane-time between trades for future projects. An optimum coordination is provided when trades are provided with the hook time required at the required time. Builders aim to minimize instances where trades are waiting for their crane time and crane idle times.

As an overview, the total number of crane days for the installation of CLT panels is 19 days with an average hook time of 3.98 hours/ level. The total number of crane days for the installation of glulam columns is 17 days with an average hook time of 0.86 hours/ level. The total number of crane days for the installation of envelope panels is 21 days with an average hook time of 7.10 hours/ level.

Table 8: Average hook time/ level for mass timber and envelope cladding systems

Building Element	Start Date	End Date	Total Duration (Calendar Weeks)	#of Working Days	Total Crane Days	Average Hook Time/ level (hours)
CLT Panels (L3 to L18)	6/10/2016	8/11/2016	10	19	19	3.98
Glulam Columns (L2 to L18)	6/7/2016	8/11/2016	10	47	17	0.86
Envelope Panels (L2 to L19 Parapet)	6/21/2016	9/8/2016	12	45	21	7.10

5.2.1.1 CLT Floor Panels

To study the productivity of the mass timber structure on a micro-level, the time needed by the crane to install all levels of CLT floor panels was measured: levels 3 to 18. Table 15, in Appendix B, presents the data set, which includes measurements from 29 crane cycles per level, a total of 464 crane cycles for the mass timber structure were collected. To compare the productivity of different levels, it was necessary to subtract stoppages, miscellaneous rigging, crane operational times and rework durations. The result is the net hook duration. Net hook duration of all levels was compared to understand the learning curve. This was complemented with daily weather descriptions and crew sizes.

Gross hook duration is the total duration from the start to the end of installation. Net hook duration consists of gross hook duration minus stoppages, miscellaneous rigging, crane operational times and rework (Figure 9). Stoppages are the typical coffee breaks, lunch breaks and pauses due to wind. Stoppages ranged between 6 minutes to 3 hours; depending on the starting time of timber installation. The duration of 3 hours includes coffee and lunch breaks. Miscellaneous rigging included the duration of transporting equipment and materials relating to the timber structure of other elements in the building. Miscellaneous rigging ranged between 30 minutes and 4.5 hours. An example of rework by timber installers would be rigging a CLT panel from a truck to ground, then from ground to location. The duration of rigging a panel from truck to ground is considered rework. The cause of rework is: the panels were shipped in the wrong order. Fortunately, there were only two incidents of rework in levels 3 and 16. Rework incidents were only 6 minutes and 7 minutes, respectively. The former because it is the first level of the mass timber structure and the latter because the ground riggers were new to that location. It is helpful to group miscellaneous rigging separately to show durations where the timber installers could share the crane resources while working on a level. Net hook duration is compared across all levels to highlight productivity and help understand elements such as the learning curve.

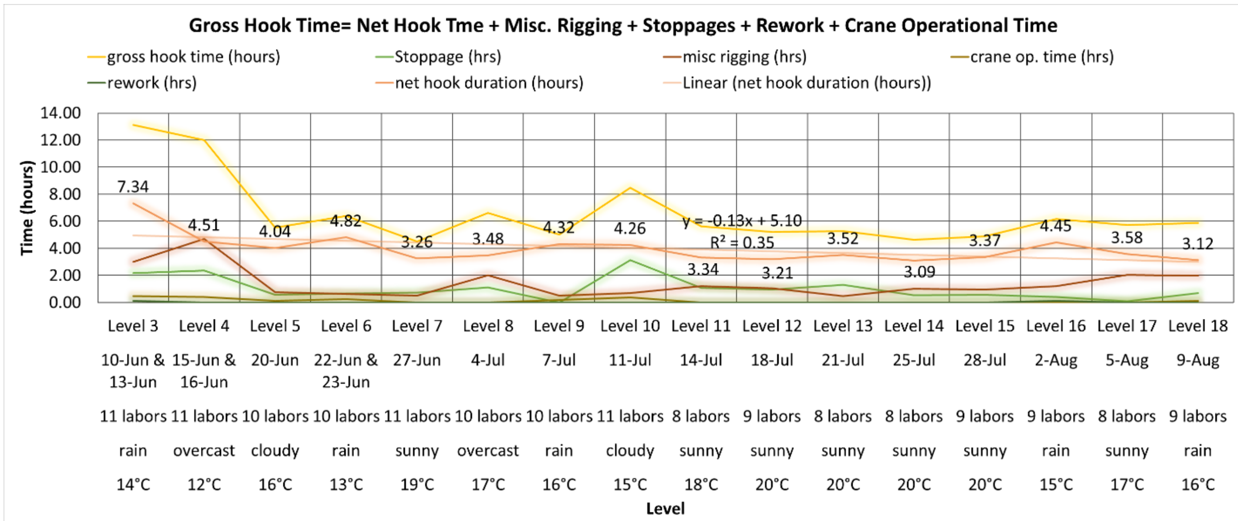


Figure 9: Gross Hook Time, Net Hook Time, Misc. Rigging, Stoppages, Rework and Crane Operational Time for CLT panels

Net hook time for each level has been extracted from Figure 9 to be shown separately in Figure 10 for clarity. This demonstrates a reduction in installation time for the mass timber structure. The longest duration needed was 7.3 hours in the first level of CLT panels (level 3). The shortest duration for installing the identical floor plan was 3.1 hours in levels 15 and 18. The learning curve is portrayed through a negative slope of the linear trend line.[10] The longest net duration was 7 hours and 20 minutes in first CLT level (level 3) and the shortest net duration was 3 hours and 5 minutes in level 14.

Three areas, levels 6, 9 and 16, show an increase in installation time. This is shown by a positive slope in the figure 43. The magnitudes of increase in time, shown by data labels, are: 48 minutes, 1 hour and 66 minutes, respectively. The causes of the increase in time needed to finish the same floor plan is: the tougher weather experienced on those days.

[10] The slope of trendline of CLT Hook time= -0.13 hours/ level.

Weather descriptions and temperatures are available on the x-axis of figure 43. In level 5, there was no rain event. Installation was finished in 4 hours and 2 minutes. In level 6, there was a rain event; installation was finished in 4 hours and 50 minutes. Similarly, in levels 9 and 16 the timber installers required more time than levels 8 and 15. This is because there was a rain event during the installation of levels 9 and 16 and absence of rain during the installation of levels 8 and 15.

The largest spike in time required was in level 16. This is because the builders experienced an additional obstacle during the installation of this level: two members of the crew were new to site and an additional two members were new to location. Meaning, their previous role on this project has been deck riggers but they were ground riggers on August 2nd. Combining the impacts of rain and four new members, the contractors experienced the largest spike in time required.

The crew completed installation of level 18 in a net duration of 3.1 hours regardless of adverse weather condition. This was amongst the quickest net durations of the whole structure. Levels 18 and 14 have the fastest installation time.

A good flow of work is achieved through a high consistency of productivity or consistent rate of productivity. Coefficient of correlation, R^2, goodness-of-fit, is a statistical measure that explains how well the real data (curve) is represented by a linear line and allows to understand the consistency of the rate productivity (Wang, Song and Zhu 2013). As seen in figure 43, net hook durations have a goodness-of-fit of 35%. This number includes all the data points.

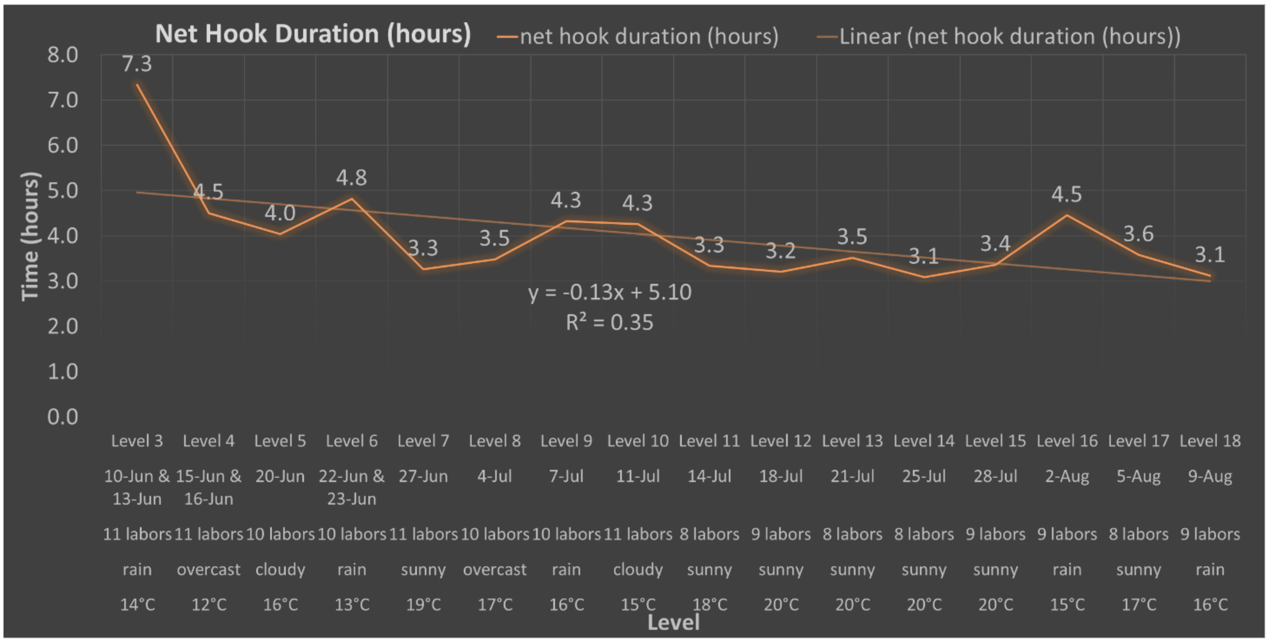


Figure 10: Net Hook duration for mass timber structure

Net crane productivity (Figure 11) is the ratio of total area of CLT panels in one level, 722 m^2, to the net hook time (Figure 10). Therefore, it shows an inverse trend in comparison to net hook duration because the output area completed is identical in all levels. Reductions in productivity in levels 6, 8, 13 and 16 are shown as peaks in Net Hook Duration but as troughs in Net Crane Productivity. The learning curve is portrayed through a positive slope of the linear trend line of 4.8 m^2/ crane-hour/ level.

This ranged between 98.4 m^2/ crane-hour at level 3 to 234 m^2/ crane-hour at level 14. All numbers are higher than the planned productivity rate of 90.3 m^2/ crane-hour. Planned productivity is calculated from the ratio of 722 m^2 of CLT floor area to 8 crane-hours estimated by the timber installing team in March 2016.

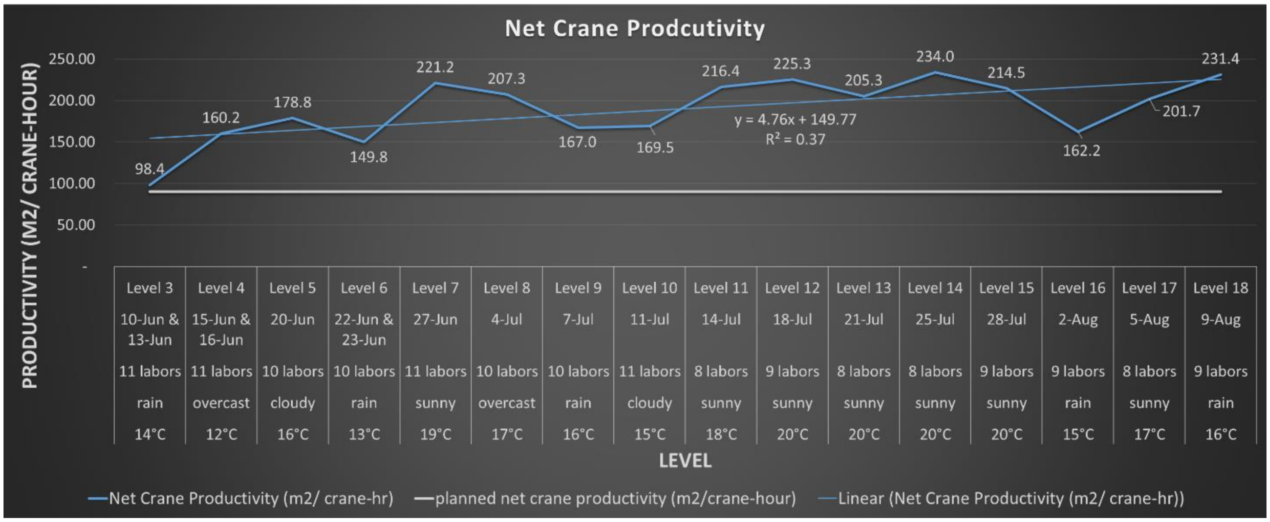


Figure 11: Net Crane Productivity for mass timber structure

Net Crew Productivity was calculated for the project (Figure 12). Net crew productivity is the ratio of total area of CLT panels in one level, 722 m^2, to the net crew time. Net crew time is the product of the crew size and the net hook time, therefore, net crew productivity curve has a similar trend to the net crane productivity. Level 8 showed an increase in crew productivity and a decrease in crane productivity because the crew number reduced by 1, shown by the secondary bar chart. A similar effect occurred in level 13 and an inverse effect occurred in levels 10 and 12. The minimum productivity was 9.0 m^2/labor-hour at level 3 and the maximum achieved was 29.3 m^2/labor-hour at level 14; which could be attributable to the learning curve and refinement in panel sequencing and placement techniques.

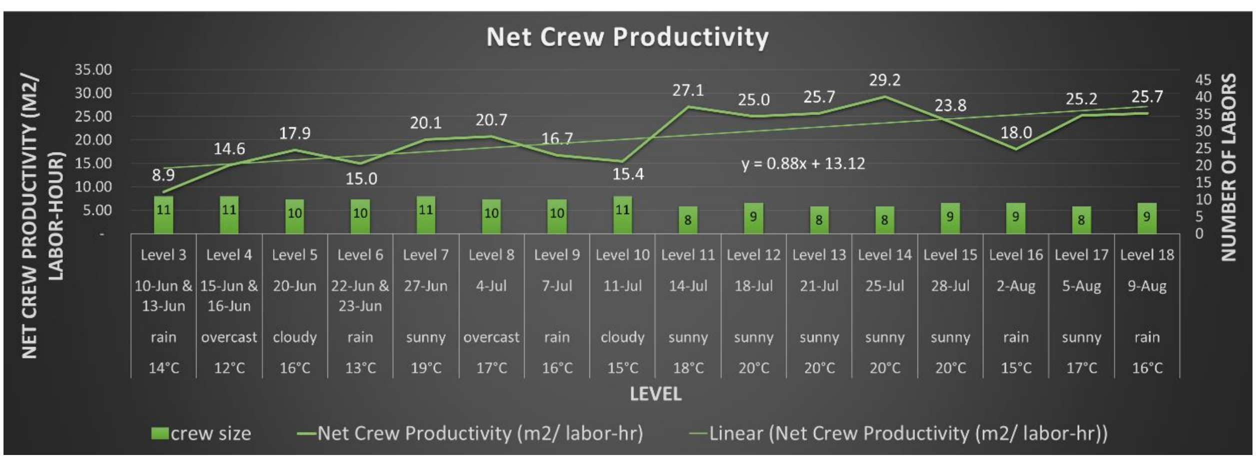


Figure 12: Net Crew Productivity for mass timber structure

5.2.1.2 Envelope Panels

Regarding micro-level productivity of the building envelope panels, the time needed by the crane to install all levels of envelop panels was measured. Table 16, in Appendix B shows the data set for the variability of installation productivity of envelope panels, which scopes measurements of 21 panels from all levels of the envelope cladding system for: levels 2 to 19 (parapet)[11]. This is a total of 399 crane cycles, covering an area of 6,302 m^2 spanning a linear perimeter of 2,244 m. Like the mass-timber structure, net hook durations were considered. This was complemented with daily weather descriptions and crew sizes.

Net hook durations, the corresponding wind speeds, weather descriptions and crew sizes are shown in Figure 13. A negative slope of the trend line of -0.2 hours/ level shows the learning curve: an overall reduction in time required to install the same surface area of cladding. The longest duration of 12.7 hours was required to install level 2, the first level of envelope cladding system. The shortest duration of 4.4 hours was required to install level 15.

There are two major increases in durations: 5 hours 48 minutes at level 12; as well as an increase of 2 hours and 6 minutes at level 18. This can be related to the increase in wind speeds. Smaller increases in duration were also observed at levels 4, 7, 9, 17 and 19 of magnitudes of 18 minutes, 36 minutes, 24 minutes, and 18 minutes and 12 minutes, respectively. This can be also explained by the smaller increases in wind speeds, as shown in figure 46. Levels 11, 14 and 16 are insignificant anomalies with magnitudes of approximately 20 minutes.

Increases in productivity on levels 3, 5, 6, 8, 10, 13 and 15 were observed. This resulted in the overall negative slope of trend line, as discussed above. Productivity rates on levels 8, 10 and 13 was also noted despite a small increase in wind speeds. To address the consistency of rate of productivity, the net hook durations have a goodness-of-fit of 24%. This number includes all the data points.

[11] The reason for not installing all 22 panels per level at once is to install outriggers for hauling materials into the building. The research team covered an area of 6,302m^2 out of 6,542m^2. This has been explained in Section 5.3: Methodology and Scope.

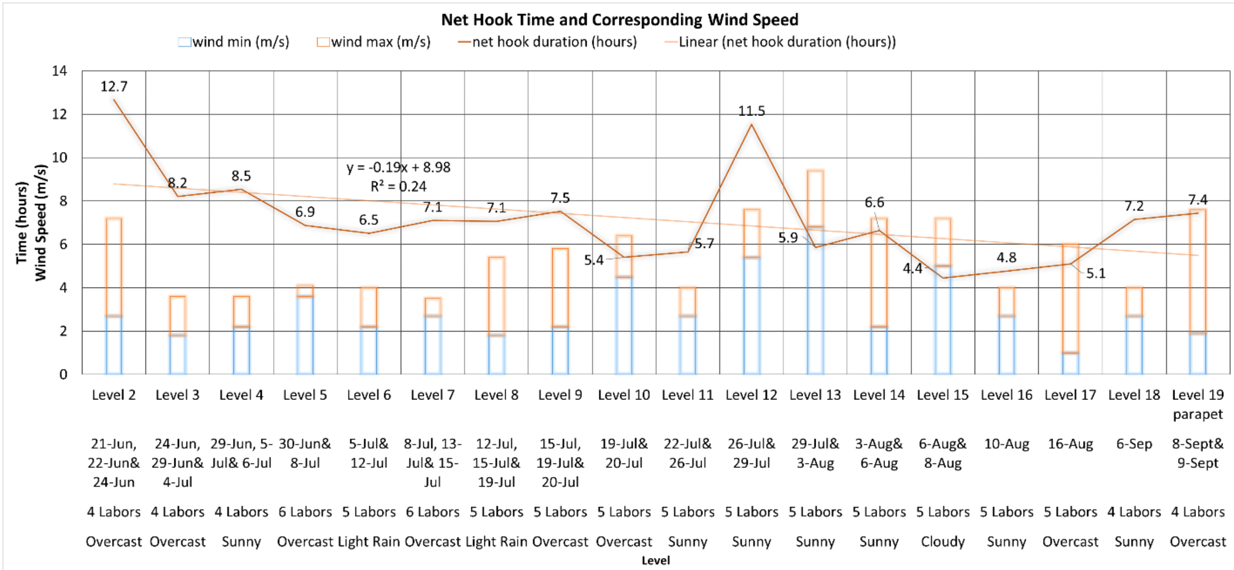


Figure 13: Net Hook time & wind speeds for envelope cladding system

Similar information is represented Net Crane Productivity (Figure 14). Productivity is the ratio of surface area of cladding installed (350 m^2/ level) to crane-time required. The learning curve is portrayed through a positive slope of the linear trend line.[12] This is achieved because overall increases in productivity outweigh decreases, as explained earlier. Increases in productivity occurred due to reduction in time required to install the same area of cladding, in levels 3, 5, 6, 8, 10 and 13. Reductions in productivity occurred in levels 4, 7, 9, 12, 17, 18 and 19. Causes of variations have been addressed in the discussion of net hook time. All levels experienced higher productivity than planned (22.4 m^2/crane-hour). This is calculated from the ratio of 346 m^2 of cladding area to 15.5 crane-hours predicted by the cladding system team in March 2016.

[12] The slope of envelope panels net crane productivity= 1.3 m^2/ crane-hours/ level.

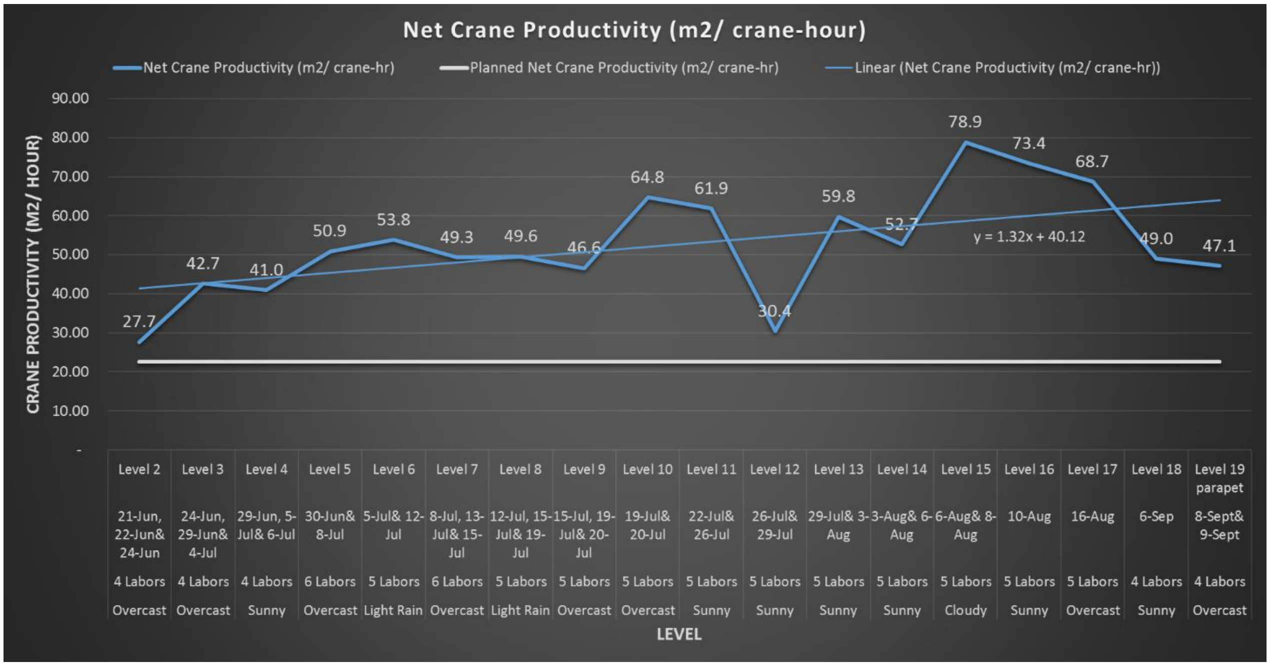


Figure 14: Net Crane Productivity for envelope cladding system

Net crew productivity is shown in Figure 15; it is the ratio of area installed in m^2 to the input in labor hours. The lowest crew productivity was 6 m^2/ labor-hour at level 12; and highest was 15.6 m^2/ labor-hour at level 15. Net crew productivity shows similar trends to net crane productivity. The only two deviations can be found in levels 5 and 8. In level 5, net crew productivity has reduced even though net crane productivity had increased. This is because the same surface area was installed using more skilled labors (2 extra installers) despite being finished in less time (1 hour 36 minutes less). Following the same logic, level 8 shows an increase in crew productivity and a relatively steady crane productivity. This is because the same output was installed by fewer skilled labors (1 fewer installer) despite being finished in relatively similar time.

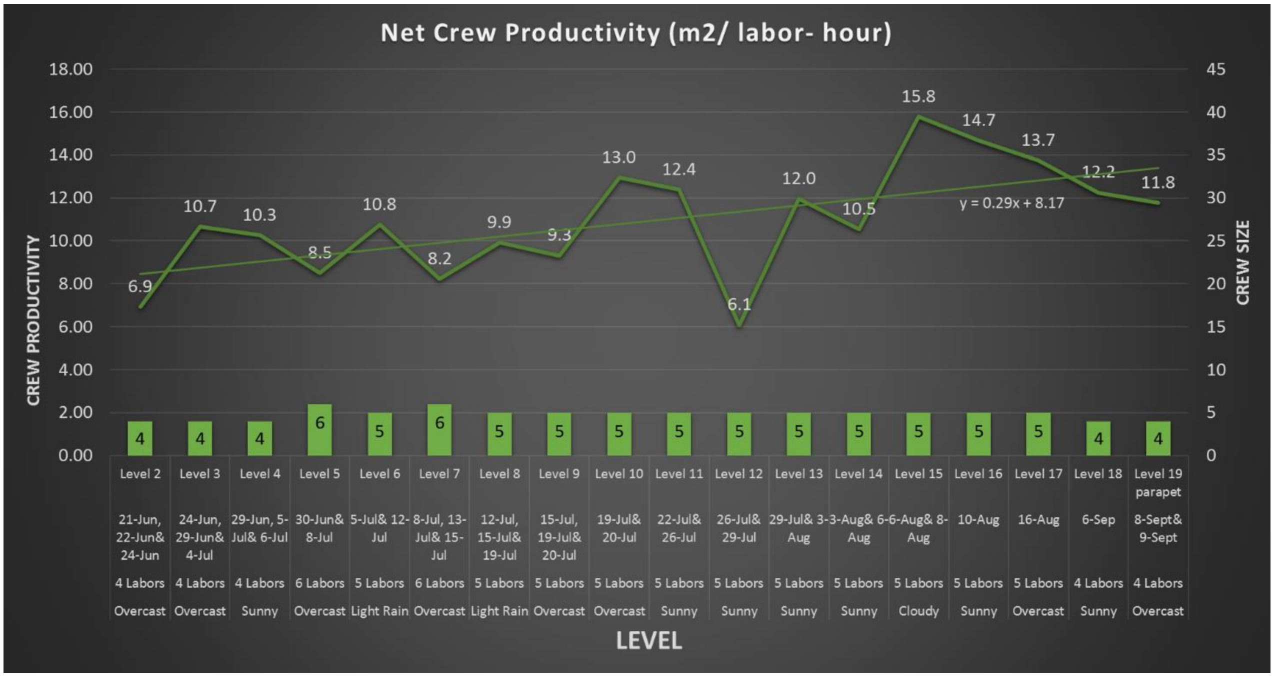


Figure 15: Net Crew Productivity for envelope cladding system

5.2.2 Statistical Investigation of CLT Installation

In this investigation, net hook time is studied in further detail for a smaller sample relative to Section 5.2.1. The effect of the following three minor factors on net hook time was investigated: (1) Location of CLT panels within plan, (2) Location of deck riggers relative to CLT panel and (3) Swing circumference by the crane (Table 9). This section investigates if the three factors hypothesized before construction affected the installation method. The Kolmogorov–Smirnov (KS) test was utilized to compare the distributions of test and control samples. Moreover, mean values for tests and control samples were compared for this investigation. The installation of 159 of CLT panels in levels 9, 11, 13, 16, 17 and 18 were recorded in detail; a total of 1078 sub-activities' durations were recorded. As a review of the results, minor differences between the mean durations of tests and control samples. Moreover, the probability values show a low significance level of correlation that does not prove cause and effect. "A project manager would know these [effects] but not have to plan for them" (Fraser, Senior Project Manager, Brock Common's Tallwood House Project, Urban One Builders 2017).

As discussed, it is important to study net hook time because it is on the critical path of installing an element and it uses a critical resource. Reducing it has the potential to reduce the entire process's duration. The reason for choosing the KS test is because it is a non-parametric test and, hence, does not require the population's distribution to be characterized by certain parameters (for example: the normal distribution). The population herein is the time data collected. A hypothesis is required for every test calculation stating that a factor affected the test sample and not the control sample. The KS test output is either a nullification of the stated hypothesis (H0) or an affirmation of the hypotheses (Ha). A nullification is done by proving the test and control samples follow the same distribution. An affirmation is done by proving the distributions of the two samples are different. To conclude, if a statistical significance exists, a factor is present affecting the test sample and is absent in the control sample. The significance value (alpha) is chosen to be 0.05. Meaning, the confidence level of tests being true is 95%.

Efforts were made to avoid bias. Every level was tested independently to avoid influence from weather. Net hook time was divided into three sub-activities, out of a total of seven subs-activities, to avoid influence from a different portion of net hook time.

The installation method has been divided into the following seven sub-activities detailing truck work, net hook time and other deck work (Figure 16):

1. Unwrap CLT Panel.
2. Install anchoring Bergin plates and tagline.
3. Attach the one-bolt swivel plate and rig CLT panel to level.
4. Fit CLT anchor holes into column rods.
5. Unhook CLT panel by unbolting swivel plate and hook previous CLT panel's Bergen plate.
6. Unscrew Bergin plates and align CLT panel if necessary.
7. Install splines.

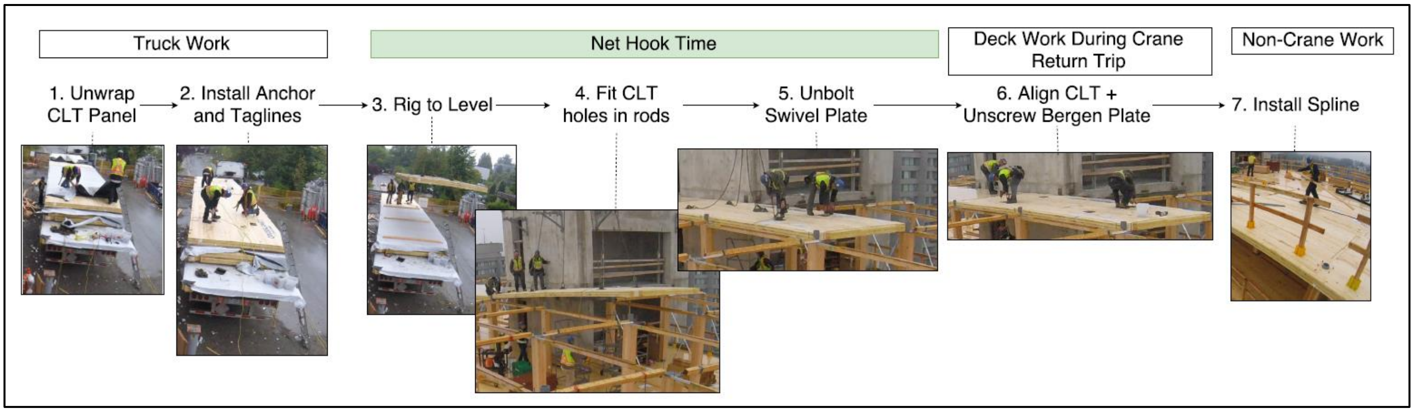


Figure 16: CLT installation method and sub-activities

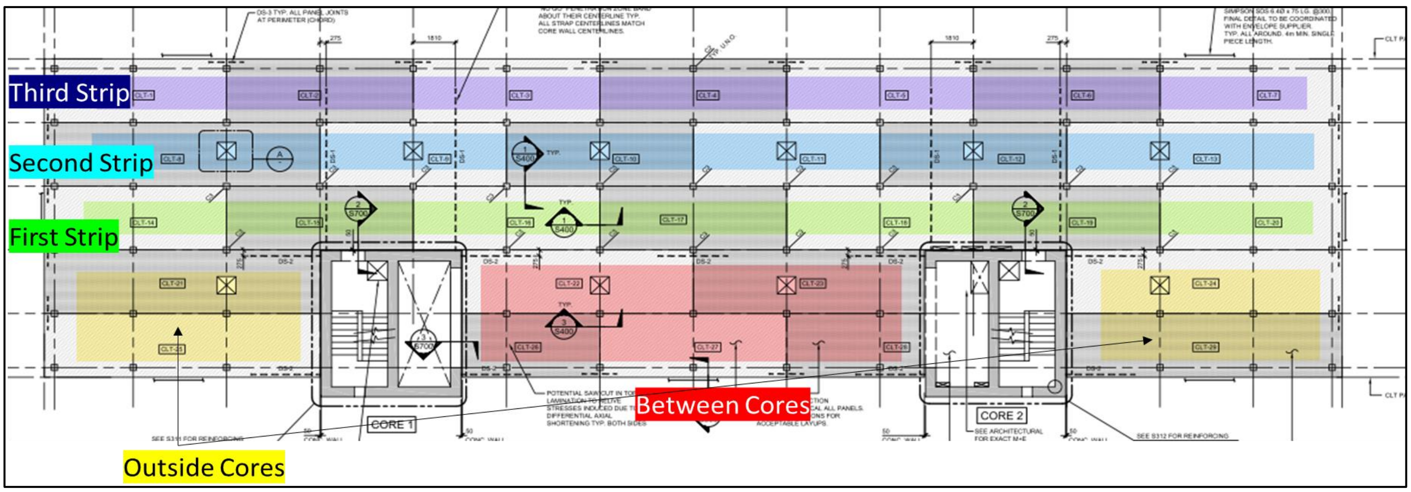


Figure 17: Typical CLT floor structural plan divided in four groups: between cores, outside cores, first strip, second strip and third strip (courtesy of Fast+ Epp)

Table 9: Kolmogorov–Smirnov test results and mean comparisons

Factor	Level	Test Sample Size	Test Mean (minutes)	Test Standard Deviation	Control Sample Size	Control Mean (minutes)	Control Standard Deviation	Group Containing Longer Duration	Difference= test mean-control mean (minutes)	Difference= test mean-control mean (seconds)	Probability (P-value)	Test interpretation
Location of CLT panels	9	5	1.633	0.298	20	1.646	0.317	control	-0.013	-1	1.000	H0
	11	4	1.688	0.229	14	1.589	0.401	test	0.099	6	0.822	H0
	13	5	1.050	0.095	23	1.402	0.365	control	-0.352	-21	0.038	H1
	16	5	1.733	0.273	23	1.681	0.601	test	0.052	3	0.703	H0
	17	5	1.767	0.532	23	1.764	0.684	test	0.003	0.2	0.999	H0
	18	5	1.767	0.465	22	1.648	0.402	test	0.119	7	0.990	H0
Location of deck riggers	9	4	1.854	0.336	21	1.603	0.293	test	0.251	15	0.714	H0
	11	5	1.850	0.525	13	1.519	0.255	test	0.331	20	0.610	H0
	13	6	1.472	0.352	22	1.303	0.36	test	0.169	10	0.364	H0
	16	6	2.319	0.620	21	1.532	0.402	test	0.787	47	0.056	H0
	17	6	2.292	1.085	22	1.621	0.404	test	0.671	40	0.364	H0
	18	6	1.986	0.343	21	1.579	0.384	test	0.407	24	0.095	H0

Table 9 (Cont.): Kolmogorov–Smirnov test results and mean comparisons

Factor	Level	Test Sample Size	Test Mean (minutes)	Test Standard Deviation	Control Sample Size	Control Mean (minutes)	Control Standard Deviation	Group Containing Longer Duration	Difference= test mean-control mean (minutes)	Difference= test mean-control mean (seconds)	Probability (P-value)	Test interpretation
Swing circumference	9	6	2.453	0.655	2	2.983	0.613	control	-0.530	-32	[redacted]	
	11	5	2.800	0.439	4	2.896	0.142	control	-0.096	-6		
	13	8	2.835	0.770	7	3.569	1.267	control	-0.734	-44		
	16	8	4.025	0.998	7	4.231	1.715	control	-0.206	-12		
	17	8	4.135	1.350	6	4.369	3.113	control	-0.234	-14	[redacted]	
	18	11	3.073	0.642	9	3.459	0.682	control	-0.386	-23		

5.2.2.1 Factor 1: Location of CLT Panel

The tested hypothesis (H_0) is: the location of CLT panels within the structural plan affects the duration of installation. The test sample hypothesized to require longer durations to install are between concrete cores: CLT# 22, 23, 26, 27 and 28, highlighted in red (Figure 17). The installation team believed this group of panels will be more difficult to install because the close-fitting nature of this space caused by the concrete cores. The sub-activity to be affected is step #4: fitting CLT holes in rods. The test sample was compared to all other panels, excluding CLT #19 because another factor might affect fitting CLT holes into rod, discussed in section 5.2.2.2.

The mean duration of the test sample was not consistently longer than that of the control sample. The test sample's mean duration was longer than the control sample in levels 11, 16, 17 and 18 by only 6, 3, 0.2 and 7 seconds, respectively (Table 9). Moreover, the test sample's mean duration was shorter than the control sample in levels 9 and 13 by 1 and 21 seconds. These are minor differences relative to other activities in the construction industry.

No statistical significance was found between the two distributions in most tested levels (Table 9). Meaning, statistical tests conclude there is no present factors affecting the test samples that are absent in the control samples. Moreover, alpha of 0.038 was achieved in level 13, indicating a statistical significance in distributions. Contrary to the discussion description of the KS test, this result continues to disprove the hypothesis (H_0) because the mean value of the test sample is shorter than the mean value of the control sample.

5.2.2.2 Factor 2: Location of Deck Riggers

The tested hypothesis is: the location of deck riggers affects the duration of installation. The test sample hypothesized to require longer durations to install is: the first panel to install (CLT #19) and the panels outside the cores (CLT #21, 25, 24, 19) and the first panels to install in second and third strip (#13 and 1 respectively). Installers believed this group will be difficult to install because deck riggers will access the flying panels from the long edge as opposed to the short edge. The sub-activity to be affected is step #4: fit CLT holes into rods. We compared the test sample to all other panels. We excluded the panels between the cores because another factor might affect the same step, discussed in 5.2.2.1.

All mean durations of the test sample are longer than mean durations of the control sample (Table 9). The means values of levels 9, 11, 13, 16, 17 and 18 exceeded the mean of control samples by 15, 20, 10, 47, 40 and 24 seconds, respectively (Table 9). These are minor differences relative to other activities in the construction industry.

No statistical significance was found between the two distributions in all tested levels. Meaning, statistical tests conclude there is no present factors affecting the test samples that are absent in the control samples.

5.2.2.3 Factor 3: Swing Circumference

The tested hypothesis is: the swing circumference affects the duration of installation. The test sample hypothesized to require shorter durations to install is: the panels where the truck is on the same side of the crane as the CLT final location. This is achieved in load 2: CLT #20, 19, 18, load 3: CLT #25, 21, 8, 9 and load 4: CLT #7, 6, 5. The CLT panels hypothesized to take longer are load 2: CLT #20, 19, 18, load 3: CLT #25, 21, 8, 9 and load 4: CLT #7, 6, 5. The installers believed this group will require short rigging durations due to lower crane circumferences. This is achieved when the truck is on the same side of the crane as the end location of the CLT panel on deck. The sub-activity to be affected is step #3: Rig to level.

All mean durations of the test sample are longer than mean durations of the control sample (Table 9). The mean values of levels 9, 11, 13, 16, 17 and 18 exceeded the mean of control samples by 32, 6, 44, 12, 14 and 23 seconds, respectively (Table 9). These are minor differences relative to other activities in the construction industry. Kolmogorov–Smirnov test does not apply in this section because the factor tested, crane circumference, is present in both samples. The researchers are not testing for presence/ absence but are simply highlighting the minor difference due to a longer circumference.

5.2.3 Schedule Reliability

Another measure of performance is schedule reliability. The aim is to quantitatively understand how reliable the planned schedule that was prepared by the builders on November 2015, was compared to the actual progress in May- August 2016. Planned and actual schedules are overlapped in one chart (Figure 19). Schedule variances are shown. A summary of the important aspects of planning efforts for both preliminary and construction schedules are explained below. As a review of the results, the maximum schedule variance of the mass timber structure was +68 days at level 18; the maximum schedule variance of the envelope cladding system was +67 days at level 17.

The schedule was developed and the following risks were identified and mitigation strategies put in place:

- construction schedule prepared with involvement through buy-in process from major trade contractors; specialized methods required to achieve structure erection timeline will likely involve 6-day work weeks to ensure one-floor per week;
- proactive procurement process of major materials, systems, and equipment; tracked for availability of items well in advance of construction timing requirements;
- wood structure and building envelope materials prefabricated and stored offsite;
- computerized design models and physical mock-ups analyzed in advance of mass production to ensure correctness and approval;
- concrete work scheduled for construction through winter; mass wood structure erection to take place in Spring/Summer for reduced weather-related stoppages; and
- erection of wood structure after concrete structure will ensure sufficient tower crane time for prefabricated building envelope erection to keep pace with erection of wood structure;

Thus, the construction management team planned 3 days/ level for the mass timber structure and 3 days/ level for the envelope cladding system. The team planned to do the following five activities simultaneously (Figure 18). For the reader's convenience, this is discussed through an example showing a snapshot on a day chosen at random, July 14th:

- encapsulate ceiling and columns in level n (level 6 on July 14th);
- pour concrete floor topping in level n+1 (level 7 on July 14th);
- install envelope panels in level n+2 (level 8 on July 14th);
- line columns in level n+4 (level 10 on July 14th);
- install CLT panels in level n+5 (level 11 on July 14th).

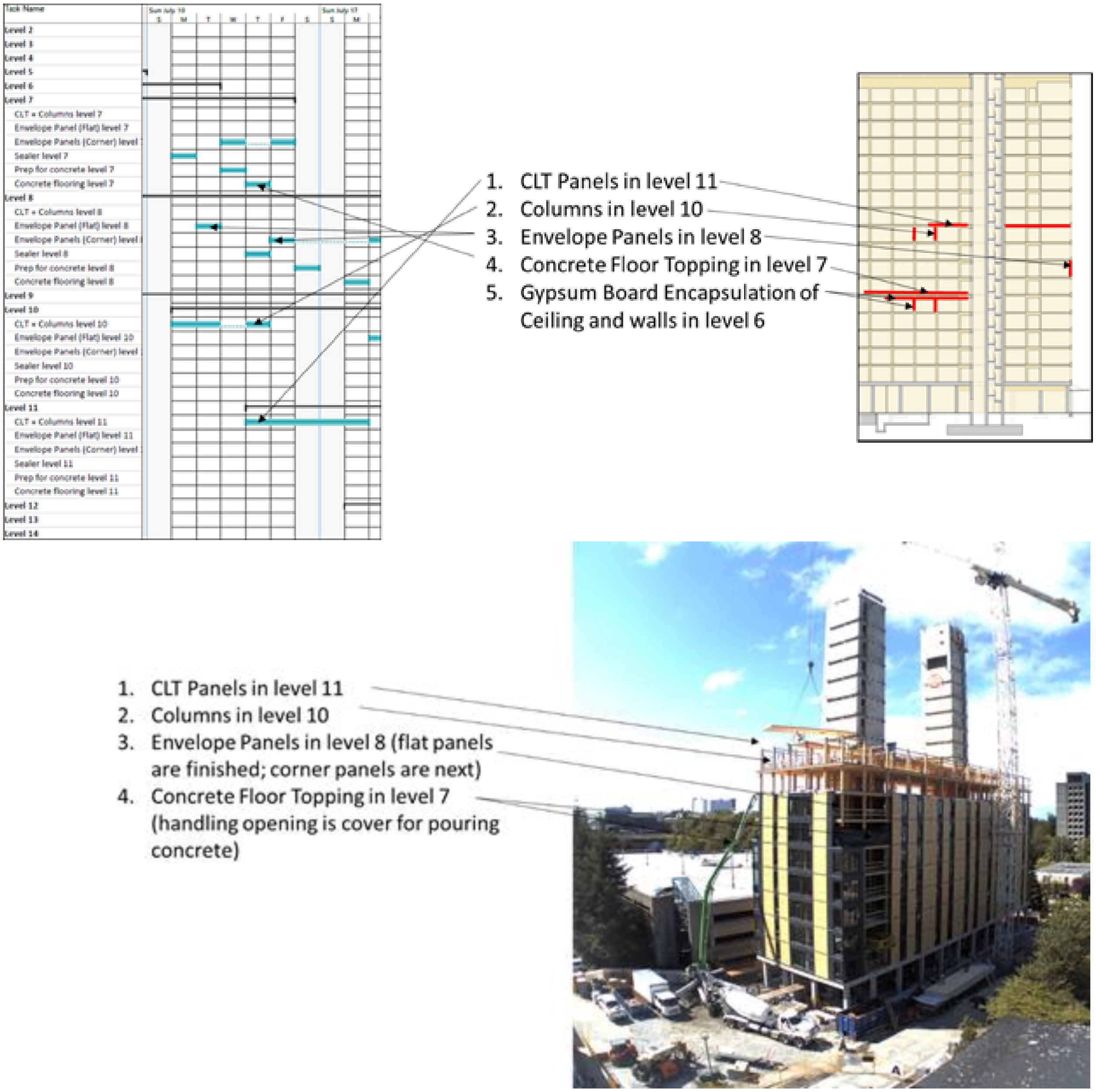


Figure 18: Sequence of structural elements- snapshot on July 14th.

Planned and actual schedules are overlaid and analyzed in Figure 19, Table 10 and Table 11 below.

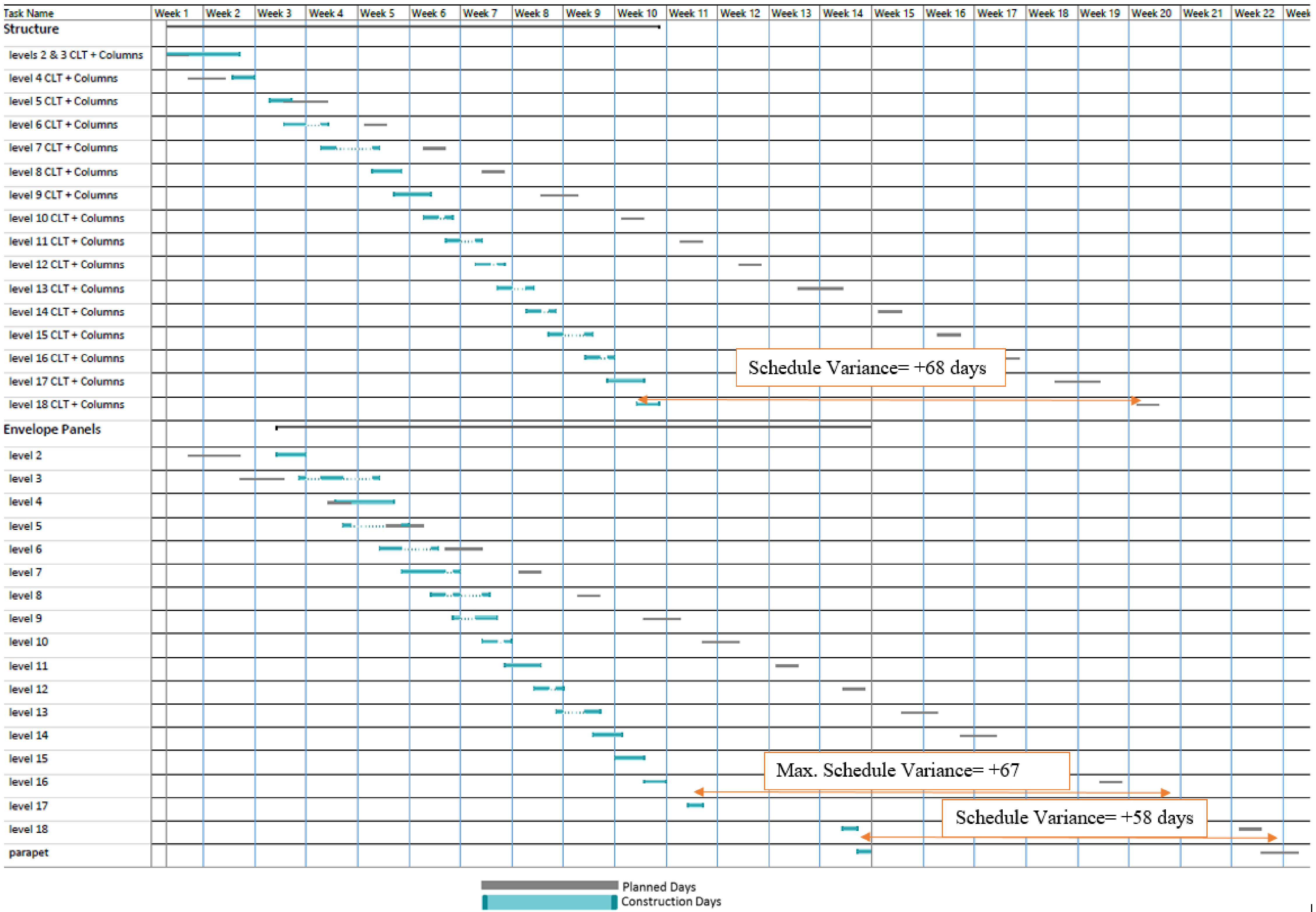


Figure 19: Construction and Planned Schedules overlaid for mass timber structure and envelope cladding system

Table 10: Planned and construction schedules for the mass timber structure

level	Timber Planned Dates					Timber Construction Dates					Schedule Variance (days)
	Start Date	Finish Date	Start Day#	End Day#	Duration	Start Date	Finish Date	Start Day#	End Day#	Duration	
18	12-Sep	14-Sep	133	135	3	9-Aug	11-Aug	65	67	3	68
17	1-Sep	6-Sep	122	127	6	5-Aug	9-Aug	61	65	5	62
16	24-Aug	26-Aug	114	116	3	2-Aug	5-Aug	58	61	4	55
15	16-Aug	18-Aug	106	108	3	28-Jul	2-Aug	53	58	6	50
14	8-Aug	10-Aug	98	100	3	25-Jul	28-Jul	50	53	4	47
13	28-Jul	2-Aug	87	92	6	21-Jul	25-Jul	46	50	5	42
12	20-Jul	22-Jul	79	81	3	18-Jul	21-Jul	43	46	4	35
11	12-Jul	14-Jul	71	73	3	14-Jul	18-Jun	39	43	5	30
10	4-Jul	6-Jul	63	65	3	11-Jul	14-Jul	36	39	4	26
9	23-Jun	27-Jun	52	56	5	7-Jul	11-Jul	32	36	5	20
8	15-Jun	17-Jun	44	46	3	4-Jul	7-Jul	29	32	4	14
7	7-Jun	9-Jun	36	38	3	27-Jun	4-Jul	22	29	8	9
6	30-May	1-Jun	28	30	3	22-Jun	27-Jun	17	22	6	8
5	19-May	24-May	17	22	6	20-Jun	22-Jun	15	17	3	5
4	6-May	10-May	4	8	5	15-Jun	17-Jun	10	12	3	-4
2 and 3	3-May	5-May	1	3	3	6-Jun	15-Jun	1	10	10	-7

Table 11: Planned and construction schedules for the envelope cladding system

level	Envelope Planned Dates					Envelope Construction Dates											Schedule Variance (days)
	start date	finish date	start day #	end day #	duration	[Date] Day #1	[Date] Day #2	[Date] Day #3	[Date] Day #4	[Date] Day #5	[Number] Day #1	[Number] Day #2	[Number] Day #3	[Number] Day #4	[Number] Day #5	duration	
19 (Parapet)	29-Sep	3-Oct	150	154	5	8-Sep	9-Sep				95	96				2	58
18	26-Sep	28-Sep	147	149	3	6-Sep	7-Sep				93	94				2	55
17	15-Sep	19-Sep	136	140	5	16-Aug	17-Aug				72	73				2	67
16	7-Sep	9-Sep	128	130	3	10-Aug	11-Aug	12-Aug			66	67	68			3	62
15	29-Aug	31-Aug	119	121	3	6-Aug	8-Aug	9-Aug			62	64	65			3	56
14	19-Aug	23-Aug	109	113	5	3-Aug	4-Aug	6-Aug			59	60	62			3	51
13	11-Aug	15-Aug	101	105	5	29-Jul	2-Aug	3-Aug			54	58	59			3	46
12	3-Aug	5-Aug	93	95	3	26-Jul	27-Jul	29-Jul			51	52	54			3	41
11	25-Jul	27-Jul	84	86	3	22-Jul	25-Jul	26-Jul			47	50	51			3	35
10	15-Jul	19-Jul	74	78	5	19-Jul	20-Jul	22-Jul			44	45	47			3	31
9	7-Jul	11-Jul	66	70	5	15-Jul	18-Jul	19-Jul	20-Jul		40	43	44	45		4	25
8	28-Jun	30-Jun	57	59	3	12-Jul	13-Jul	15-Jul	19-Jul		37	38	40	44		4	15
7	20-Jun	22-Jun	49	51	3	8-Jul	9-Jul	11-Jul	13-Jul	15-Jul	33	34	36	38	40	5	11
6	10-Jun	14-Jun	39	43	5	5-Jul	6-Jul	7-Jul	12-Jul		30	31	32	37		4	6
5	2-Jun	6-Jun	31	35	5	30-Jun	8-Jul				25	33				2	2
4	25-May	27-May	23	25	3	29-Jun	30-Jun	6-Jul			24	25	31			3	-6
3	13-May	18-May	11	16	6	24-Jun	27-Jun	28-Jun	29-Jun	4-Jul	19	22	23	24	29	5	-13
2	6-May	12-May	4	10	7	21-Jun	22-Jun	23-Jun	24-Jun		16	17	18	19		4	-9
prep work						*17-Jun*	*20-Jun*				*12*	*15*				*2*	

.

Reading from Table 10 and Figure 19, the mass timber structural system had a maximum lag of 7 days in level 3, the first level of CLT installation. The construction team caught up and lead the planned schedule by the level 5, third level of CLT installation. They continued to lead the planned schedule and finished construction 68 days ahead of planned schedule. Furthermore, reading from Table 11 and Figure 19, the envelope system experienced a maximum lag of 13 days in Level 3, the second level of envelope panels installation. The contractors caught up and lead the planned schedule by Level 5, the fourth level of envelope panels. They continued to lead the planned schedule and finished construction 58 days ahead of planned schedule.

5.2.4 Earned Value Analysis

The earned value concept obtains a visual understanding of the project status by comparing several metrics, described below (Hinze 2008). It was utilized in this section as a measure of schedule and cost reliability. This was done through studying the progression of budgeted and construction (actual) costs. "The integration of cost and schedule control systems is of natural interest to construction professionals, because the true status of a project can only be assed if both cost and schedule data are examined in conjunction with one another" (Hinze, 2008). This assessment of status is unbiased; as opposed to a negative cash flow or a front-end loaded schedule. The former is not necessarily a loss; the latter is a false indication of a positive cash flow position.

Budgeted cost of work scheduled (BCWS), budgeted cost of work performed (BCWP, Earned Value) and actual cost of work performed (ACWP) graphs are shown on the same chart for the mass timber structure (figure 53) and envelope panel cladding system (figure 54). Total budgeted and construction costs were provided by the builders for the mass timber and envelope cladding structure. The total costs were divided by the number of levels in each system for this study. The cost of a level is only applied once this level is complete. Therefore, in the figures below, a horizontal line (zero slope) refers to the duration needed to finish one level and an increase in cost (positive slope) refers to a finished level. The "steps" produced allows a comparison between planned and construction schedules *for every level of the building*.

Project managers can compare planned schedules to actual construction schedules by comparing BCWS to BCWP. Moreover, project managers can compare planned cost to construction cost by comparing BCWP to ACWP. Earned Value charts (figs. 53 and 54), Earned Value calculations and description of terms (tables 22 and 23) and Gantt charts used for reliability metric in section 6.2.3 are used simultaneously to perform the analysis.

The mass timber structure was behind schedule in the first and second levels (levels 3 and 4). The minimum schedule variance is -$440,000 on day #8 when construction had not finished levels 2 and 3 but was planned to finish level 4, resulting in a lag of 2 levels. This is because the count of mass-timber levels was initiated with level 3. This resulted in a percentage schedule variance of -100% because all items scheduled to be completed were not completed yet. Proceeding, construction progress caught up and lead the planned schedule, leading to a maximum schedule variance of $1.8M in day #67. This is when construction had finished level 18 and was planned to finish level 10, resulting in a lead of 9 levels. This is a percentage schedule variance of +100%; meaning, construction progress was double the planned schedule. This is observed through a peak in the schedule performance index (SPI) curve.

Installation of envelope cladding system lagged planned schedule for the first, second and third levels (levels 2, 3 and 4). The minimum schedule variance is -$460,000 on day #16 when construction had not started in level 2 and was planned to finish level 3. This resulted in a percentage schedule variance of -100% because all items scheduled to be completed were not completed. Then, construction progress caught up and lead the planned schedule leading to a maximum schedule variance of $1.8M in day 68. This is when construction had finished level 16 and planned schedule was to finish level 9. This is a percentage schedule variance of +114%. This is observed through a peak in the schedule performance index (SPI) curve.

The mass timber structure shows cost savings from the first level of construction (after finishing level 3). Cost savings continued to accumulate as progress continued reaching a maximum cost variance of $100,000 at day #67 when installation of mass timber was complete. This is a percentage cost variance of +2.8%. As expected, Cost Performance Index (CPI) curve is constant throughout the period of installation. This is because the ratio of BCWP to ACWP remains constant as per our method of calculations, explained earlier.

Envelope cladding system shows an increase in costs from the first level of construction (level 2). This is due to change in materials from steel to high-pressure compact laminate panels. Increases in costs continued to rise, reaching a cumulative cost variance of $4.8 million. In other words, a percentage cost variance of -117%. As expected, Cost Performance Index (CPI) curve is constant throughout the period of installation. This is because the ratio of BCWP to ACWP remains constant as per our method of calculations, explained earlier.

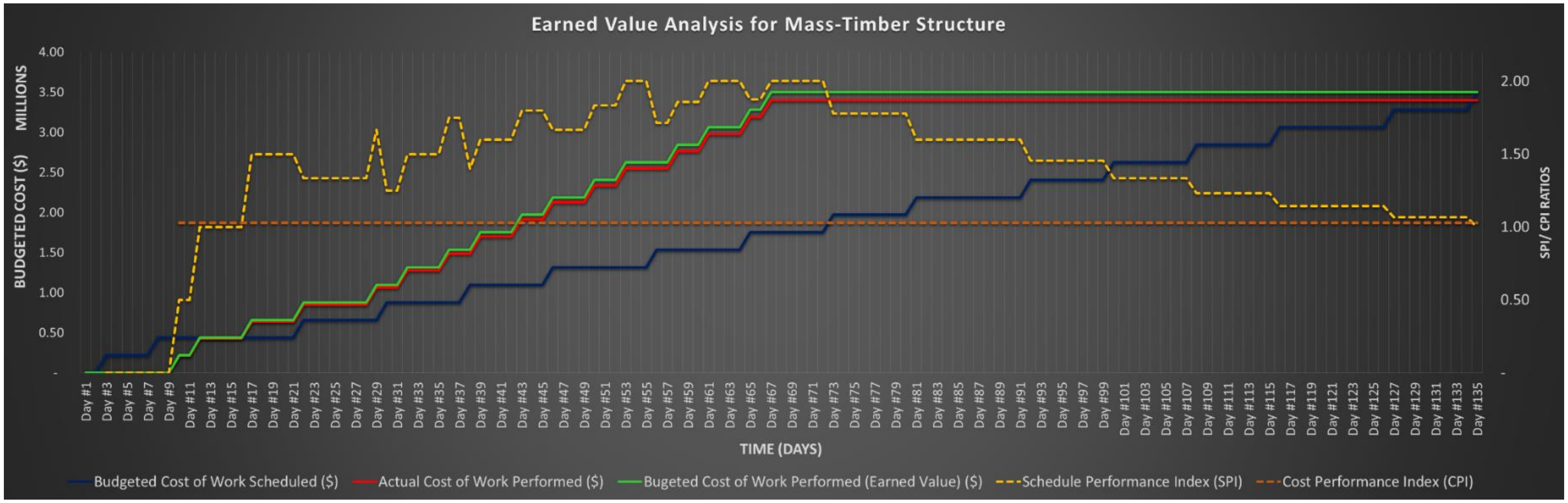


Figure 20: Budgeted Cost of Work Scheduled vs. Budgeted Cost of Work Performed for mass-timber structure

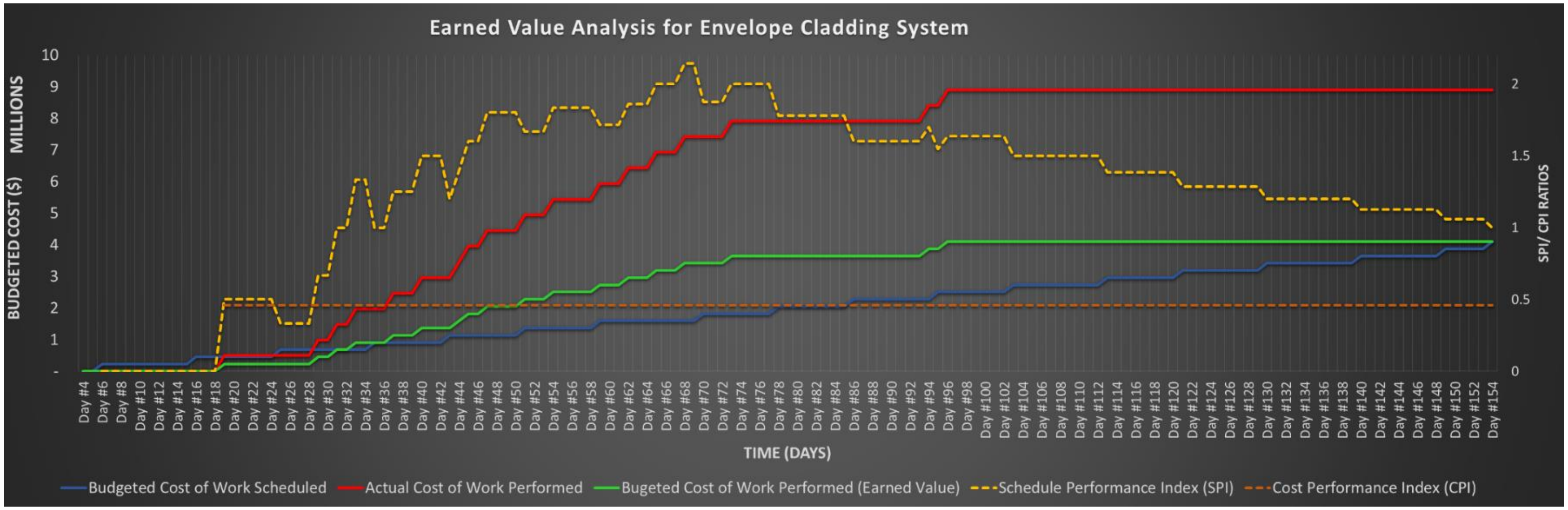


Figure 21: Budgeted Cost of Work Scheduled vs. Budgeted Cost of Work Performed for envelope cladding system

Table 12: Earned Value calculations of mass-timber structure

Term	Acronym + Formula	Value	Unit	Qualitative Description of Value
Budget Cost at Completion	BAC	3,500,000.00	$	
		218,750.00	$/ floor	
Construction Cost at Completion		3,400,000.00	$	
		212,500.00	$/ floor	
Schedule Variance	SV= BCWP - BCWS	(437,500.00)	$	at day 8. plan was to finish level 4. construction had not finished level 3. lag= 2 levels
		1,750,000.00		at day 67, construction finished level 18. planned to finish level 10. lead= 9 levels.
Cost Variance	CV= BCWP - ACWP	100,000.00	$	at day 67. when constructing had just finished, CV kept accumulating until progress is complete.
Percentage Schedule Variance	(SV/ BCWS) %	(100.00)	%	at day 8. everything that was planned was not completed.
		100.00	%	at day 67. construction progress was X2 planned.
Percentage Cost Variance	(CV/ BCWP) %	2.86	%	at day 67. The highest percentage at the highest CV
Schedule Performance Index	SPI = BCWP/ BCWS			
Cost Performance Index	CPI = BCWP/ ACWP			

Table 13: Earned Value calculation for envelope cladding system

Term	Acronym + Formula	Value	Unit	Qualitative Description of Value
Budget Cost at Completion	BAC	4,100,000.00	$	
		227,777.78	$/ floor	
Construction Cost at Completion		8,900,000.00	$	
		494,444.44	$/ floor	
Schedule Variance	SV= BCWP - BCWS	(455,555.56)	$	at day 16. construction was starting level 2, plan was finish level 3
		1,822,222.22	$	at day 68. construction was finished with level 16 and plan to finish level 9
Cost Variance	CV= BCWP - ACWP	(4,800,000.00)	$	at day 96. when constructing was finished. Change in mat,
Percentage Schedule Variance	(SV/ BCWS) %	(100.00)	%	at day 16. because everything that was schedules was not completed.
		114.29	%	at day 68.
Percentage Cost Variance	(CV/ BCWP) %	(117.07)	%	117% increase of cost. From 4.1M to 8.9M
Schedule Performance Index	SPI = BCWP/ BCWS			
Cost Performance Index	CPI = BCWP/ ACWP			

5.2.5 Planned Percent Complete (PPC)

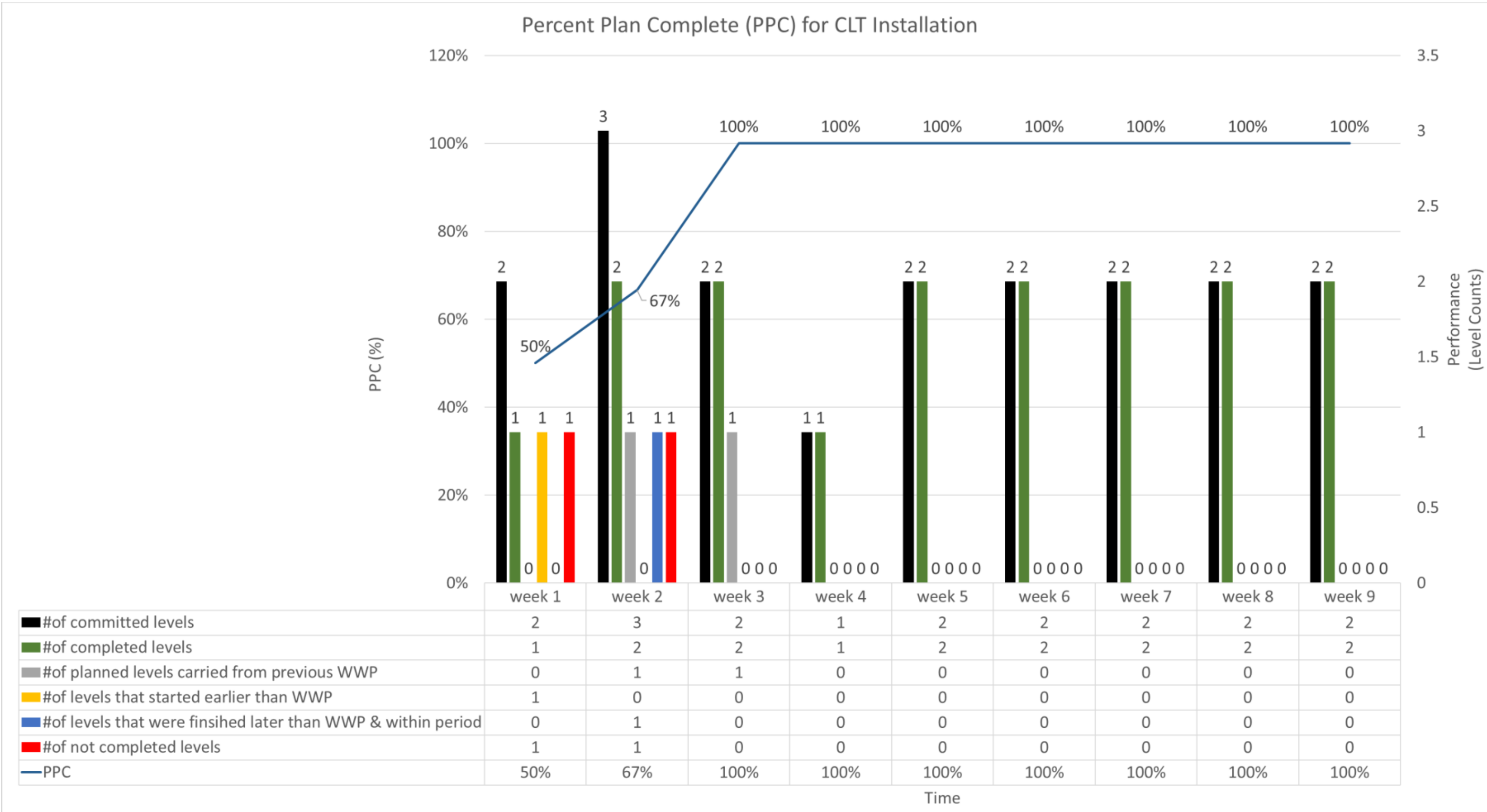
A measure of comparison of weekly work plans (WWPs) and actual construction schedules is the percentage of plan work completed (PPC) developed by the Lean Construction Institute (LCI). PPC is a measure of the extent to which promises are kept, as opposed to a direct measure of project progress (Hamzeh, Ballard, and Tommelein 2012).

Over the period of June 13th to September 10th, the construction management team issued 5 lookaheads plans. 14 weekly work plans were discussed in the weekly trades meetings. The research team studied the variation between on-site construction progress and WWPs for all CLT panels installation, flat envelope panels installations and the first layer of drywall encapsulation (Appendix C). For further understanding of progress beyond the PPC figures, the following information have been illustrated for every WWP: (1) number of committed levels, (2) number of completed levels, (3) number of planned levels carried from previous WWP, (4) number of levels that started earlier than WWP & within period, (5) number of levels that started later than WWP date & within period, (6) number of levels that finished earlier than WWP, (7) number of levels that finished later than WWP & within period, and (8) number of not completed levels during the lookahead plan. Ideally, the number of committed levels should equal the number of completed level and the remaining values to be zero. Meaning, all activities start and finish per the WWP. While an early start or finish is commonly perceived as a positive indicator, it is considered a negative mark in testing the reliability of WWP through the PPC metric. As a validation to the PPC metric, the research team provided construction snapshots proving the completion of CLT installation and envelope panels in the stated times (Appendix C). The research team provided a picture per week, not necessarily at the end of the WWP period.

5.2.5.1 CLT Panels

PPC for week 1 was 50%. It increased to 67% in week 2 and stabilized in weeks 3 to 9 to 100% (Figure 22 and Table 17 in Appendix C). The details provided further complemented the understanding of the learning curve shown in PPC values. Weeks 3 to 9 displayed a perfect overlay between the lookahead plan and on-site performance. All planned levels started and finished at the planned dates. This is a higher level of reliability than 100% PPC; a lookahead period can achieve a 100% PPC if an activity finishes late but within the lookahead duration. This was achieved despite one level being carried forward from lookahead period 1 (grey bar).

A lower PPC was experienced in weeks 1 and 2. In weeks 1, two levels were committed to (back bar). However, one were finished within the period (green bar) and one lagged to the next period (red bar). Furthermore, the installation of level 3 has started earlier than earlier than WWP date (yellow bar). In week 2, three levels were committed to, two were completed within the week, one level was finished later than WWP date but within the WWP duration.



	week 1	week 2	week 3	week 4	week 5	week 6	week 7	week 8	week 9
#of committed levels	2	3	2	1	2	2	2	2	2
#of completed levels	1	2	2	1	2	2	2	2	2
#of planned levels carried from previous WWP	0	1	1	0	0	0	0	0	0
#of levels that started earlier than WWP	1	0	0	0	0	0	0	0	0
#of levels that were finsihed later than WWP & within period	0	1	0	0	0	0	0	0	0
#of not completed levels	1	1	0	0	0	0	0	0	0
PPC	50%	67%	100%	100%	100%	100%	100%	100%	100%

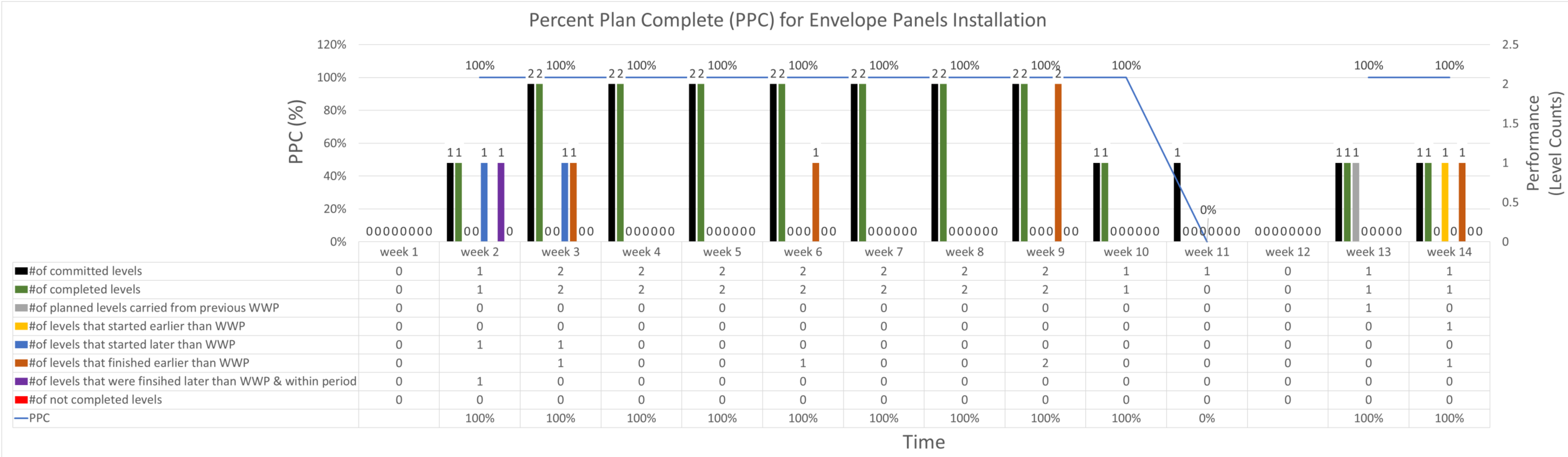
Figure 22: Percent Plan Complete (PPC) for CLT installation

5.2.5.2 Envelope Panels

The first WWP period for envelope panel installation is week 2. PPC for weeks 2 to 10, 13 and 14 were 100% (Figure 23 and Table 18 in Appendix C). [13] Meaning, all tasks that were committed to, were completed during the lookahead duration, except week 11. High PPC values are achieved because envelope panels have been in the industry for a long time. Therefore, construction managers can predict their performance accurately, hence, plan accordingly.

The research team found the current process to be insignificantly less reliable compared to the plans for CLT panels installation albeit the higher PPC values. In week 2, one level started and finished 1 day later than the WWP dates. In week 3, the construction team finished level 3 earlier than planned lookahead; while this is commonly perceived as a positive indicator, it is a negative mark in testing the reliability of lookahead plans. Furthermore, in week 3, level 4 started 1 day late but was finished in time. Furthermore, in week 6, level 10 was finished 1 day earlier. Weeks 4, 5, 7, 8 and 14 illustrated a perfect overlay; all levels started and finished on the planned dates. Furthermore, in week 9, level 15 started on the planned date but was finished 1 business day later.

[13] The research team's scope for this investigation is 18 flat envelope panels per level, a total of 324 envelope panels. Four corner panels per level were part of the construction process and lookahead plan but were excluded from this investigation. They required further design adjustments, hence were planned for installation at a later time as discussed in Section 5.1.2.



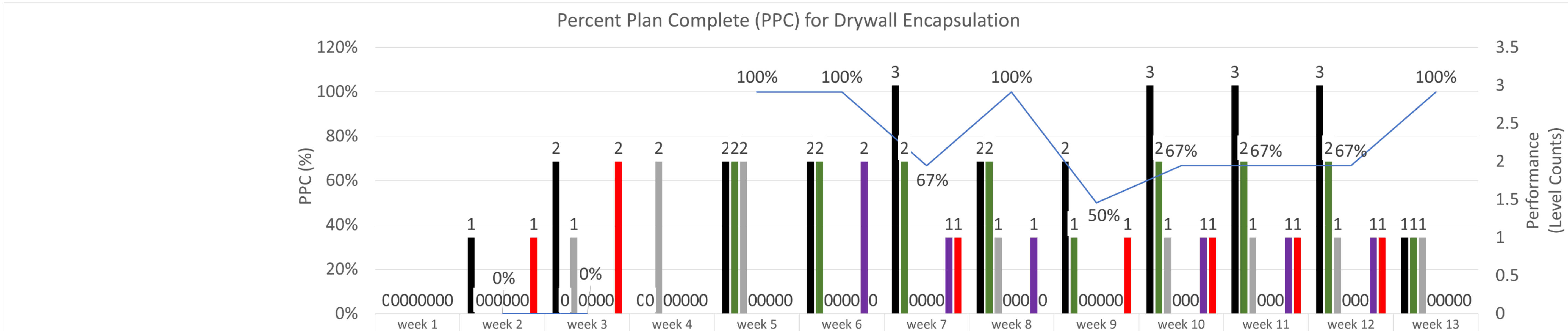
	week 1	week 2	week 3	week 4	week 5	week 6	week 7	week 8	week 9	week 10	week 11	week 12	week 13	week 14
#of committed levels	0	1	2	2	2	2	2	2	2	1	1	0	1	1
#of completed levels	0	1	2	2	2	2	2	2	2	1	0	0	1	1
#of planned levels carried from previous WWP	0	0	0	0	0	0	0	0	0	0	0	0	1	0
#of levels that started earlier than WWP	0	0	0	0	0	0	0	0	0	0	0	0	0	1
#of levels that started later than WWP	0	1	1	0	0	0	0	0	0	0	0	0	0	0
#of levels that finished earlier than WWP	0		1	0	0	1	0	0	2	0	0	0	0	1
#of levels that were finsihed later than WWP & within period	0	1	0	0	0	0	0	0	0	0	0	0	0	0
#of not completed levels	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PPC		100%	100%	100%	100%	100%	100%	100%	100%	100%	0%		100%	100%

Figure 23: Percent Plan Complete (PPC) for envelope panels' installation

5.2.5.3 Encapsulation

CLT ceiling encapsulation with drywall illustrated PPC values of 0% for weeks 2 and 3. 100% for weeks 5, 6, 8 and 13, 67% at weeks 7, 10, 11 and 12 and 50% at week 9 (Figure 24 and Table 19 in Appendix C). The reduction in PPC values in weeks 9 to 12 is because the WWP coincidently ends on the promised date of completion. A delay in progress of 1 day would count as a non-complete; whereas in other weeks, it would count was a "finished later than WWP & within WWP period."

Studying the reliability of the lookahead plans of envelope panels in further detail provided more insight of the construction performance. The cause of a significantly low PPC value in weeks 2 and 3 (0%) is because the construction management team committed to 1 and 3 levels, respectively, and were not completed. After further investigation, the construction management team decided to encapsulate one layer of drywall only to provide the fire safety needed during construction. This allows the structure to move forward. Later in the schedule, drywall installers finished the remaining two layers in all floors required for fire safety upon completion. This improved the productivity of structural installation by avoiding unnecessary stoppages. The purpose of this strategy is to maintain structural elements on the critical path of the construction schedule.



	week 1	week 2	week 3	week 4	week 5	week 6	week 7	week 8	week 9	week 10	week 11	week 12	week 13
#of committed levels	0	1	2	0	2	2	3	2	2	3	3	3	1
#of completed levels	0	0	0	0	2	2	2	2	1	2	2	2	1
#of planned levels carried from previous WWP	0	0	1	2	2	0	0	1	0	1	1	1	1
#of levels that started earlier than WWP	0	0	0	0	0	0	0	0	0	0	0	0	0
#of levels that started later than WWP	0	0	0	0	0	0	0	0	0	0	0	0	0
#of levels that finished earlier than WWP	0	0	0	0	0	0	0	0	0	0	0	0	0
#of levels that were finsihed later than WWP & within period	0	0	0	0	0	2	1	1	0	1	1	1	0
#of not completed levels	0	1	2	0	0	0	1	0	1	1	1	1	0
PPC		0%	0%		100%	100%	67%	100%	50%	67%	67%	67%	100%

Time

Figure 24: Percent Plan Complete (PPC) for encapsulation

Chapter 6: Validation and Lessons Learned

The research team validates the research objectives, findings and compares the outcomes to previous case studies in the literature. Lastly, lessons learned regarding productivity are discussed.

6.1 Validation

This research project aims to investigate the performance of the construction process of the Tallwood House (TWH). The findings from the chosen metrics allowed the required understanding of the performance of the construction process, particularly the innovative mass timber structure and envelope cladding systems, thereby, fulfilling the research objectives. All metrics were validated by the project senior project manager. The inputs, findings and conclusions drawn have been discussed and confirmed with the project manager.

Furthermore, the outcomes were justified through design, fabrication, construction and weather events in Chapter 5. For example, the considerable reduction of CLT installation productivity experienced in level 16 was justified by the rain event and the introduction of four skilled workers to new positions. Justification of quantitative outcomes was done for the following metrics: crane days, variability of productivity, statistical investigation of CLT installation. PPC was calculated using weekly work plans and construction schedules made by the research team from lookahead schedules and site visits, respectively. It was validated through site pictures showing the weekly construction progress of prefabricated structural elements (Appendix C). The validation pictures solidify the authenticity of the quantitative findings.

6.2 Case Study Comparison

The research team compared the productivity of installation of CLT and envelope panels in TWH to installation of mass timber as floor and wall panels in previous productivity case studies by University of Technology Sydney (Forsythe and Sepasgozar 2016). Eight productivity studies from other prefabricated projects were included to compare the productivity of installation of mass timber and envelope cladding systems in Brock Common's TWH, in a macro-level (Table 14). In efforts to achieve a fair comparison, net crane times were extracted from all projects and compared. This is the sum of hooking pre-fabricated parts, rigging to location, fastening, unhooking from crane and empty crane return trips. Net hook times are calculated by measuring the total (gross) hook time, then subtracting: stoppages, crane operational time, miscellaneous rigging and rework.[14]

Hook Time is valuable in prefabricated structures and directly affects the speed of installation. It is a subset of the total duration; it starts when ground riggers start hooking a prefabricated part to the crane. It ends when the prefabricated part is secured in its location in the building and the crane has finished the return trip. Proceeding to more detail in crane time, a subset of Total Hook Time is Net Hook Time. Other components of Total Hook Time include: stoppages, miscellaneous rigging, crane operational times and rework done. Such durations need to be subtracted for a fair comparison between the levels to understand the learning curve in installing the structure and envelope cladding systems. It is valuable to study hook time because it is usually on the critical path of installing an element and uses valuable resources: cranes. Reducing the duration of hook time, has the potential of reducing the total durations. Studying hook time assists builders in coordinating crane-time between trades for future projects. An optimum coordination is provided when trades are provided with the hook time required at the required time. Builders aim to minimize instants where trades are waiting for their crane time and crane idle times.

Challenges and solutions due to the originality of every project:

1. Installation periods for TWH included fixing drag-straps for lateral supports; however, case studies from Australia did not include drag-straps in their design, due to variation in seismic requirements between Vancouver and Australia. To overcome this challenge, only durations of installation mass timber panels were compared, Table 14 and Figure 25.
2. TWH utilized a tower crane; however, the other case studies utilized mobile crane. To overcome this challenge, crane start-up and cool-down durations were subtracted from other case studies and only compared net hook time, as shown in Table 14, Figure 25 and Figure 26.
3. CLT anchoring methods were different between TWH and Project 5 due to different rigging restrictions in Vancouver compared to Australia. TWH utilized a single bolt hook-unhook method at four anchor points; while Project 5 utilized tension force of a clip-on allowing a much faster hook-unhook method on-site, hence reducing net hook time. It is

[14] Section 5.2.1 explains the calculation of net hook time in detail.

important to note that TWH resulted in a more productive installation despite the difference.

4. Projects 1 to 4 utilized cassettes, which are lighter and require less temporary bracing compared to CLT panels. It is important to note that TWH resulted in a more productive installation despite not correcting for this difference.

Productivity is measured through the ratio of work completed (output) to net crane time (input) as seen in the Equation 4:

$$Productivity = \frac{Work\ Completed\ in\ Area\ (m^2)\ or\ Linear\ Length\ (m)\ [Output]}{Net\ Crane\ Time\ (hours)\ [Input]} \qquad \text{Equation 4}$$

A low-rise residential project utilizing CLT floor panels as well as four residential projects using floor/ roof cassettes have been included to compare CLT flooring used in TWH. TWH was found to have the highest overall productivity rate of 182 m^2/crane-hour. CLT floors and walls are heavier than cassettes and require greater attention to temporary bracing, wind and site rigging (Forsythe and Sepasgozar 2016).

To compare steel stud systems used for cladding the TWH, the following case studies have been included: a residential 3-level CLT wall cladding system, 2 residential buildings using OSB cladding for ground levels and fiber cement for upper levels and a residential 3-level project beams. OSB & fiber cement achieved the highest overall project productivity 25.6 m/crane-hour; TWH achieved the second highest productivity of 17.6 m/crane-hour.

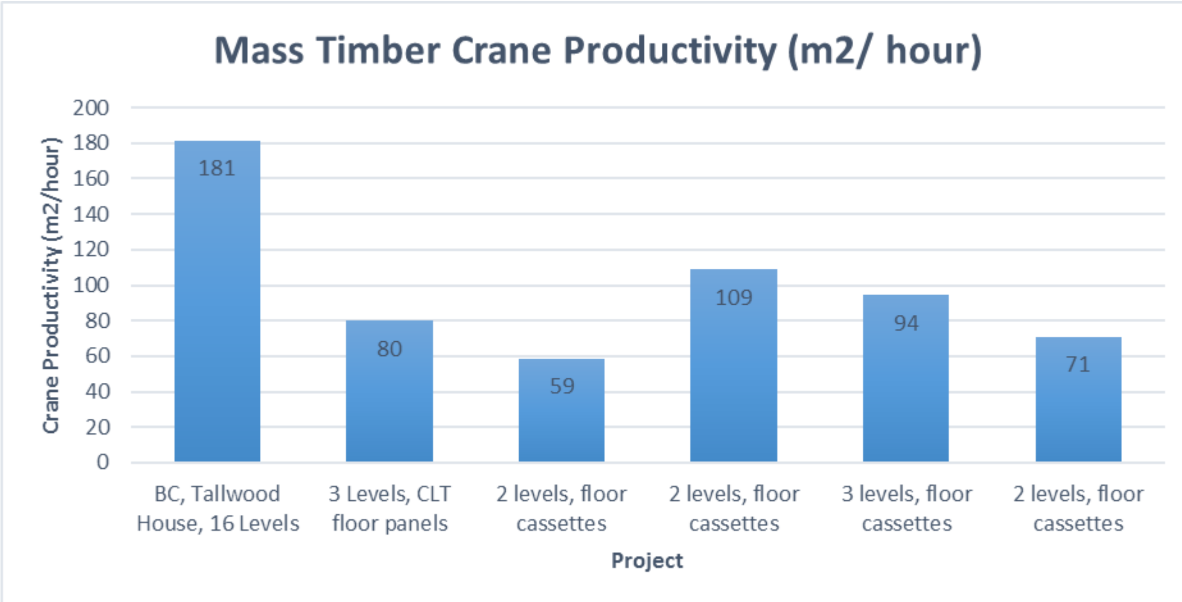


Figure 25:Comparison of TWH's productivity of installation of mass timber to previous case studies

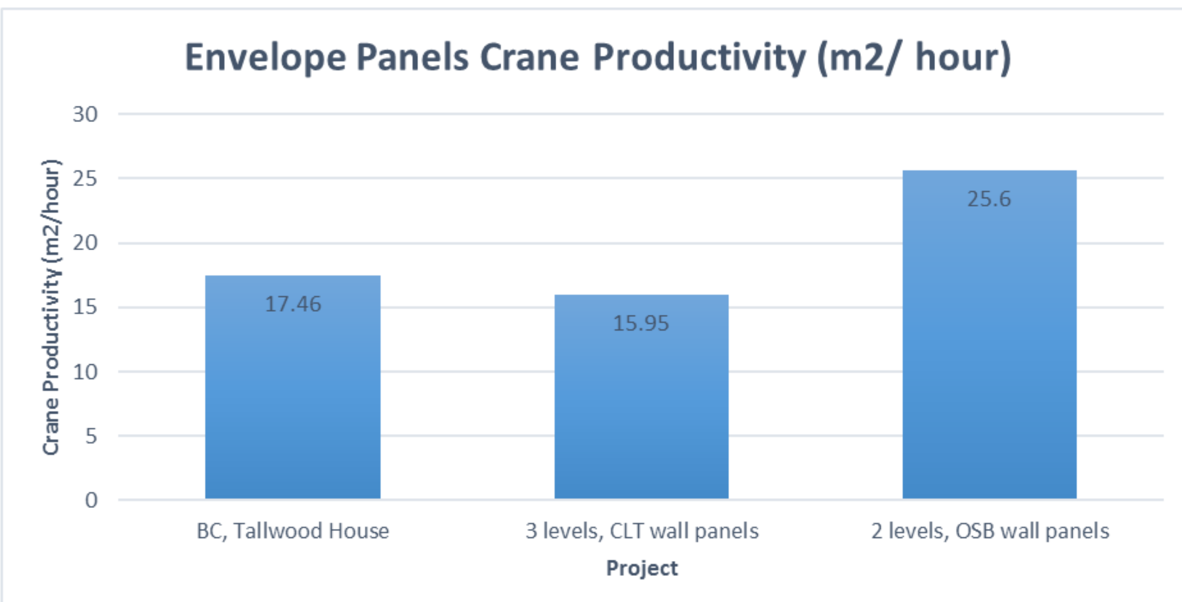


Figure 26: Comparison of TWH's productivity of installation of envelope panels to previous case studies

Table 14: Comparison to previous case studies (Forsythe and Sepasgozar 2016)

Name of Project	Type of Pre-Fabricated Part	Project Description	Output: Area (m2)	Output: Linear Length (m)	Input: Crane Cycles	Input: Net Crane Time (hours)	Productivity: Expressed in Area (m2/hr.)	Productivity: Expressed in Linear Meters (m/hr.)
BC, Tallwood House	CLT floor panels (16 levels)	404 beds. 18 levels. University Dormitory	11,553.14		464	63.70	181.38	
Project 5	CLT floor panels	3 levels. Residential	342.25		33	4.28	79.96	
Project 1	Floor/Roof Cassettes	18 apartments. 2 levels of floor cassette and a roof cassette level.	1,879.90		158	32.09	58.58	
Project 2	Floor/Roof Cassettes	12 townhouses. 2 levels, 2 buildings	970.77		72	8.93	108.71	
Project 3	Floor/Roof Cassettes	55 apartments. 3 levels, 5 buildings	829.00		60	8.79	94.31	
Project 4	Floor/Roof Cassettes	2 townhouses, 2 levels	137.60		10	1.94	70.93	
BC, Tallwood House	Envelope-Steel Stud Systems (18 levels)	404 beds. 18 levels. University Dormitory	6,235.15	2,244.47	378	128.52	48.52	17.46
Project 5	CLT wall panels	3 levels. Residential	241.60	144.98	52	9.09	26.58	15.95
Project 2	wall panels-OSB& Fiber Cement	12 townhouses. 2 levels, 2 buildings	1,188.97	456.65	116	17.84	66.65	25.60
Project 5	beams	3 levels. Residential		24.46	20	2.20		11.12

6.3 Lessons Learned

Prefabrication, combined with the use of a virtual design and construction (VDC) model, a building information model (BIM), early collaboration and planning with contractors and consultants and a full-scale mock-up offered a fast and productive site installation. Since inception, the project team has put in place some key measures that has ensured its success to date. The design and pre-construction stages informed many of the decisions that were subsequently made during the construction phase. Lessons learned from the construction phase are the following (adapted from (E. Poirier, A. Fallahi and M. Kasbar, et al. 2017)):

1. **Extensive pre-planning translates to direct benefits in the field:**

   Many of the trades involved during the preliminary design stages did not have a contract at the time of the workshop. Regardless, their presence provided valuable feedback that dictated the direction of the design, which later translated to better understanding of the project and better execution on-site. The idea with including the trades from the very early project onset was to ensure nothing is assumed about the constructability and everything in the budget estimations and schedule development were realistic.

   The extra design and preconstruction time has proved to be valuable due to the saved construction time. "From a project developer's perspective, the running cost is of construction is very high (approximately $5,000/ day or $150,000/ month [and can be] $10,000/day in a higher project). The profit made by renting out 404 beds is approximately $0.5M/ month. We spent [6] months longer in the design stages (14 months as opposed to a typical 8 month) to save 3 months of the construction time … [resulting in] a huge benefit"(Olund, 2016).

2. **Continuous and consistent communications amongst project team ensures tighter project control:**

   Weekly trade meetings, involving trades, the VDC integrator, the construction manager and designers, helped the project team determined a very detailed breakdown of work and sequencing of construction activities on site down to an hourly cycle to ensure the construction process is safe, efficient and that the schedule is aggressive, but obtainable. The presence of the site safety office both in all the trade meetings and while work was being commenced additionally ensured everybody was adhering to the procedures developed ahead of work.

3. **Pre-fabrication was key to achieve project targets:**

   Cost and schedule targets, albeit aggressive, were achieved in large part due to the ease of assembly of pre-fabricated building components, as highlighted by the project manager repeatedly throughout the project. Part of the pre-planning exercise was to ensure that targeted building components could be pre-fabricated and then work towards detailing each element as necessary. The level of automation of the pre-fabrication process largely dictated the level of detail required by the suppliers. For instance, much more coordination work went into the CLT panels (placing each plumbing route or electrical conduit) than into the envelope panels, which were very repetitious. Of course, the typology of the building lent itself well to this type of exercise. More time would have been required had the floor plans been different on every level.

The creation of standardized packages for the plumbing, based on Bills of Materials (BOMs) provided by the VDC integrators, was beneficial but could have been developed further. While the level to which the plumbing subcontractor used, the prepared packages are to be determined when the work is fully finished, it is a fact that the mechanical room was fully prefabricated off site and assembled on site which shaved 2-3 months of on-site work.

When asked if more of the building could have been pre-fabricated, the project team mentioned that further exploration is needed. Items such as framing for demising walls, bathroom units and electrical cabinets could all have been pre-fabricated off site. This would however have increased crane usage and made management of hook time more onerous. In this case, emphasis was put on structure and envelope.

4. **Full-scale mock-up provided positive feedback on constructability:**

   The construction team tested multiple proposed connections to investigate their constructability. Mass timber and envelope cladding installer providing feedback on to the construction management team and design consultants. This improved the constructability of the design, enhancing the construction process on-site.

5. **Repetition supported a rapid learning curve:**

   As demonstrated in Chapter 5, productivity rapidly adjusted after the installation of level 3. The timber erectors learned how to use the crane better rather than do everything manually as they are used to in stick frame constructions which are generally working in much less heights and weights. They started slow but made the schedule, in fact they could have gone faster if other weather and fire measures and interior work would have caught up. The structure was complete in less than 10 weeks. This constitutes half the planned schedule.

6. **Use of Virtual Design and Construction (VDC) means and methods, including BIM, improved communication between trades and management team:**

   VDC integrators were involved early in the project (E. Poirier, A. Fallahi and M. Moudgil, et al. 2016) and carried throughout the project. Typically, VDC integration is either absent in a project or tasks are divided up between the designers to hand in as part of their package submissions. The VDC integrators role was to support the coordination of building elements during design and then interface with the trades to further develop and detail several of the building's key components, including the CLT panels and the plumbing. To ensure that the VDC integrators could fulfill their role, they were hired directly by the owner to act as facilitators throughout the project.

   The research team has seen the superintendent explain a potential problem in a trades meeting and a VDC civil engineer model it on-site in real time. This improves the visualization of potential conflicts, allowing better communications, hence more efficient problem solving.

7. **Obtaining buy-in from trades to increase ownership of the project:**

   Open and clear communication throughout the bidding and hiring process of the trades were key in ensuring the trades have a clear idea of their scope and responsibilities. The construction management team instilled a collaborative spirit from the beginning. Thus, cost and schedule estimates were reliable, as discussed in Sections 5.2.3 and 5.2.4.

8. **Maintaining the structure on the critical path is key:**

   Similar to traditional construction, it is important to maintain structural elements on the critical path of the construction schedule. Drywall encapsulation had the potential to take over the critical path due to its labor and time consuming process relative to installation of pre-fabricated elements. The team overcame this problem by encapsulating only one layer of drywall to provide the fire safety needed during construction. This allows the structure to move forward. Later in the schedule, drywall installers finished the remaining two layers in all floors required for fire safety upon completion. This improved the productivity of structural installation by avoiding unnecessary stoppages. Moreover, it allowed the trades to maintain the same skilled labor for the full project.

9. **Increasing rate of production to 1 level per day:**

   Increasing the rate of production for the mass timber structure to 1 level per day was proven possible, as seen in section 5.1.2. However, successor activities, such as: acoustical concrete topping, drywall encapsulation and envelope cladding, could not keep the pace due to sharing one crane on-site.

Chapter 7: Conclusions

The findings of this research cover the construction performance of UBC's Brock Common's Tallwood House (TWH). Background on the building project and the research context were first presented. The project was well planned, coordinated and executed. Prefabrication, combined with the use of a virtual design and construction (VDC) model, a building information model (BIM), early collaboration and planning with contractors and consultants and a mock-up offered a fast and productive site installation. As part of the Tall Wood Initiative steered by Natural Resources Canada (NRCan), the Canadian Wood Council (CWC), Forestry Innovation Investment (FII), the National Research Council (NRC), the Binational Softwood Lumber Council (BSLC), and FPInnovations, the project demonstrates that mass timber can be an economical choice and can compete with traditional materials such as steel and concrete.

The UBC TWH, as one of three demonstration projects in Canada, highlights how these various barriers to high-rise mass timber construction can be overcome while demonstrating that wood is a viable option for most construction applications. For instance, it has demonstrated that mass timber construction is economically viable. It also serves to highlight the sustainable characteristics of wood as a renewable and carbon sequestering material to promote its use in the industry. This initiative is part of a clear willingness on the part of multiple governmental and non-governmental agencies to encourage the use of wood in construction in Canada. The lessons learned both in the construction process are presented in research and can be adapted to other contexts to expand the use of mass timber in the Canadian construction industry.

Fortunately, the research team was allowed considerable access to the project team during the construction phase because a researcher was hired a summer intern during the timber installation process. Most of the analysis was done on hook time because it is the best way to compare the numbers of different levels. Total durations were studied; it was suggested to involve more analysis on total durations. Moreover, preliminary schedules were considered reliable due to no extra complications arising on site, as explained in Section 2.1. This resulted in reduction of the schedule to half the planned periods for the construction of the superstructure. While this result is favorable in the construction industry, researchers question the reliability of the plan. The research team settled this by studying the planned percent complete to compare the weekly work plans to construction schedules. All research findings are discussed in Chapter 5 and summarized in a cumulative table in Appendix D.

Future work can further improve the understanding of construction performance of timber. Comparative studies of productivity of steel, concrete and mass timber at the activity level can be developed by the quantitative outcomes of this research. Furthermore, exhaustive studies of this typology of subsequent tall timber buildings can be performed using the combination of metrics provided in this thesis. Planned future research includes covering the post-construction phase through: commissioning, project hand-off, monitoring the structural performance, moisture content of the mass timber structure as well as an in-depth comparative life cycle environmental and cost analysis of this building with a similar concrete building.

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Appendix

Appendix A Full Construction Schedule

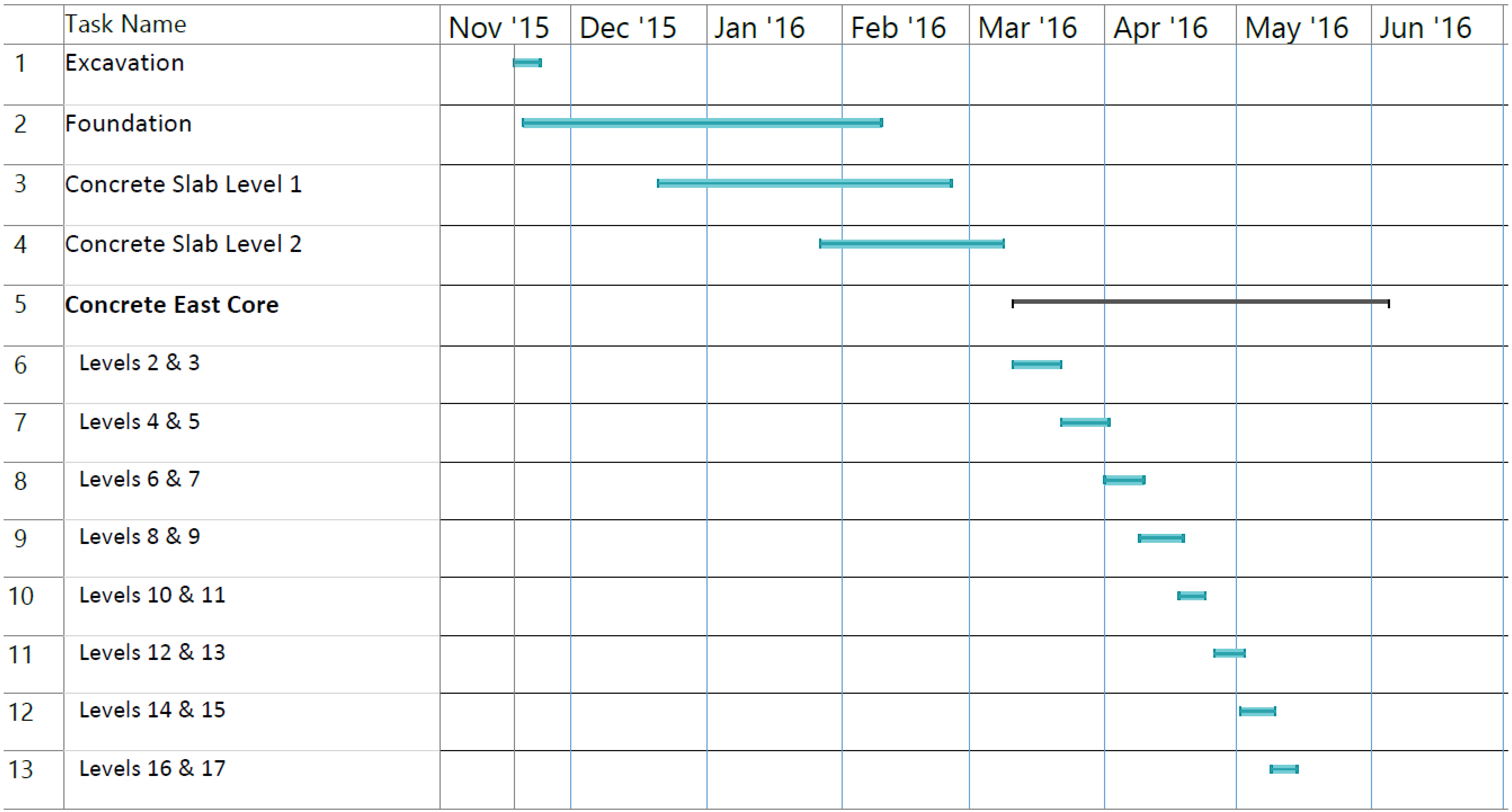


Figure 27: Complete construction schedule

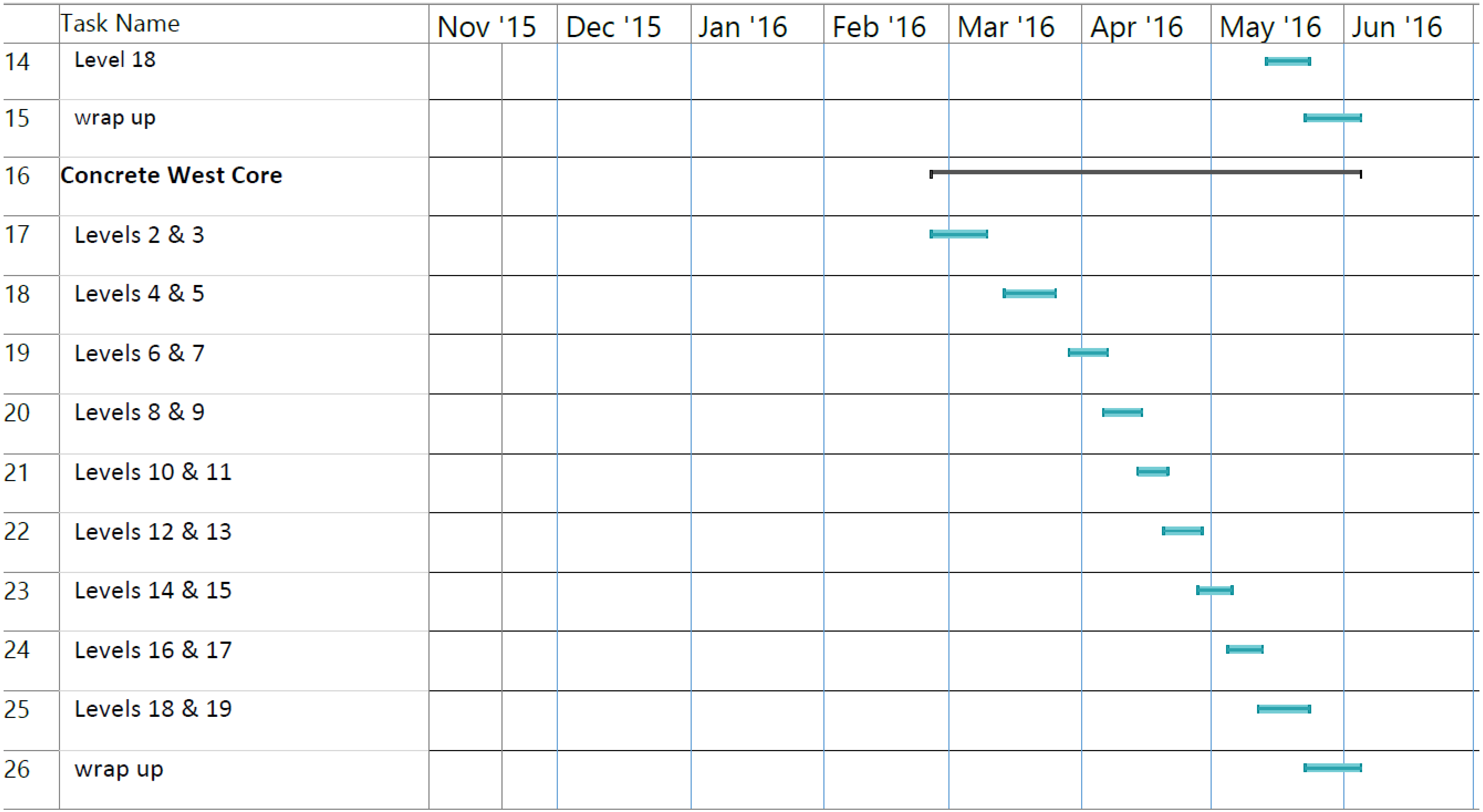


Figure 27 (Cont.) Complete construction schedule

Figure 27 (Cont.) Complete construction schedule

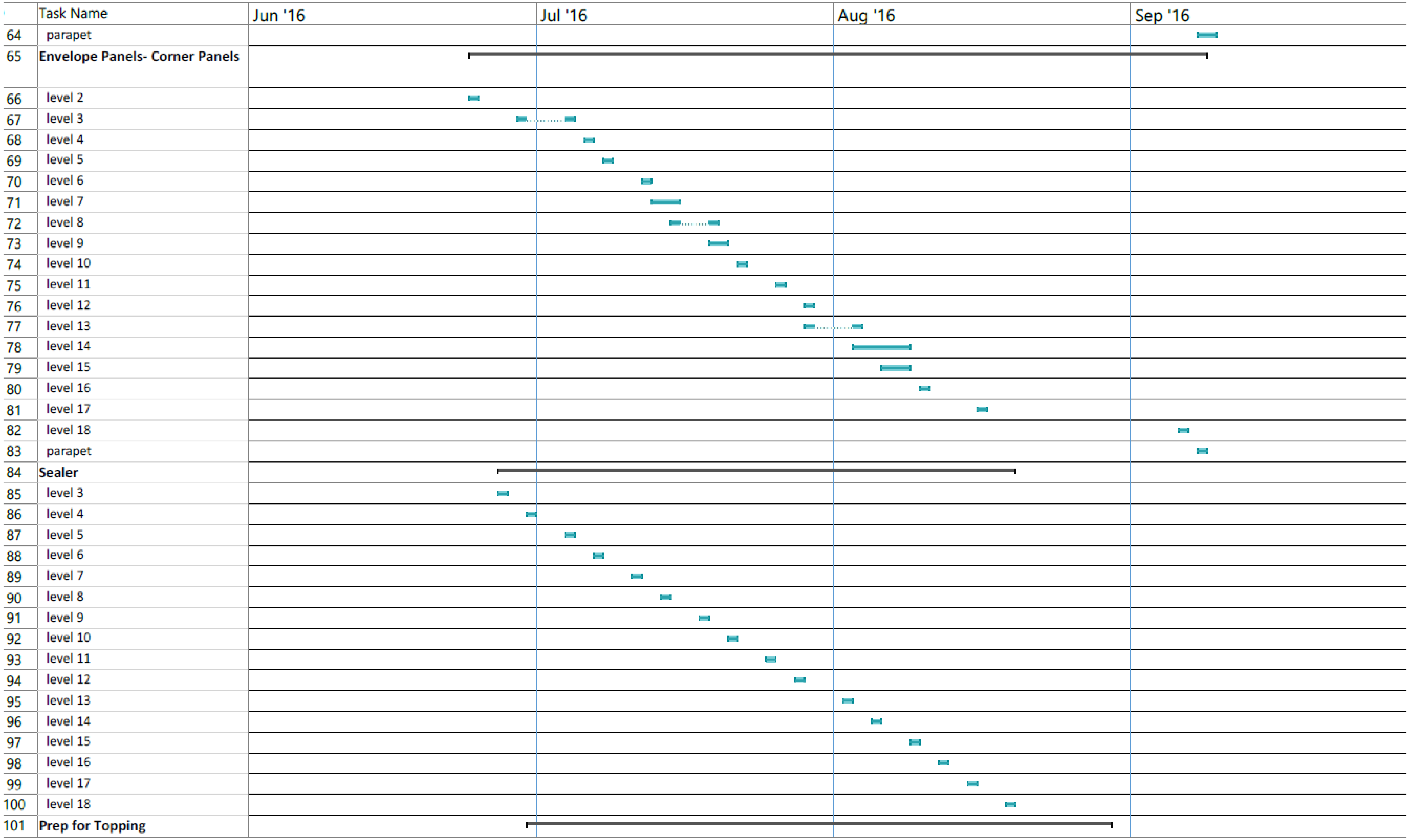


Figure 27 (Cont.) Complete construction schedule

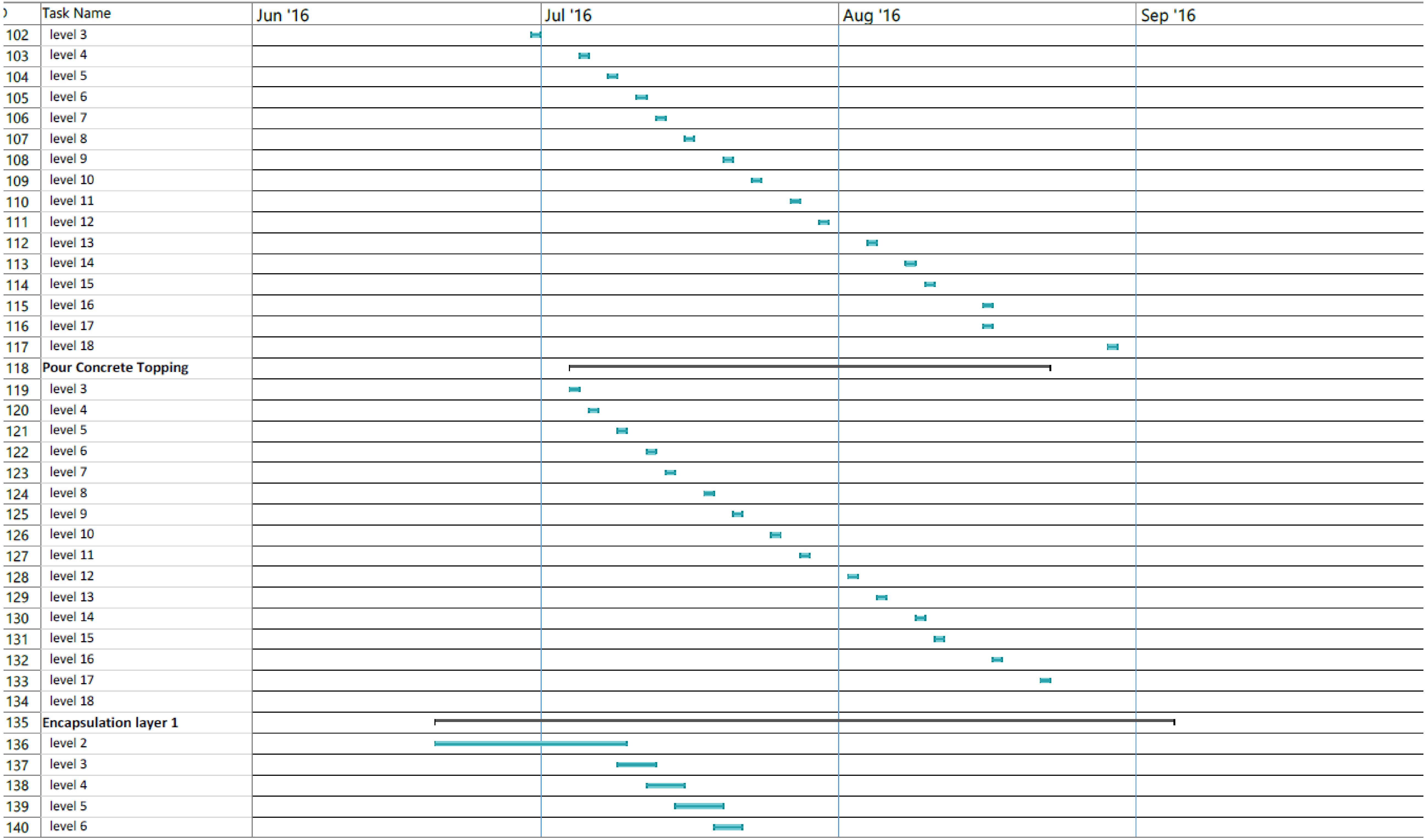


Figure 27 (Cont.) Complete construction schedule

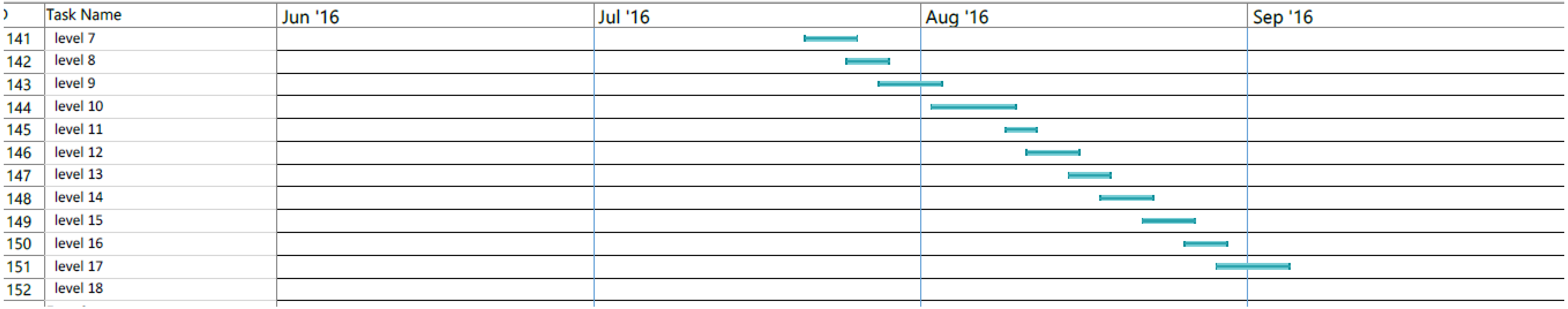


Figure 27 (Cont.) Complete construction schedule

Figure 27 (Cont.) Complete construction schedule

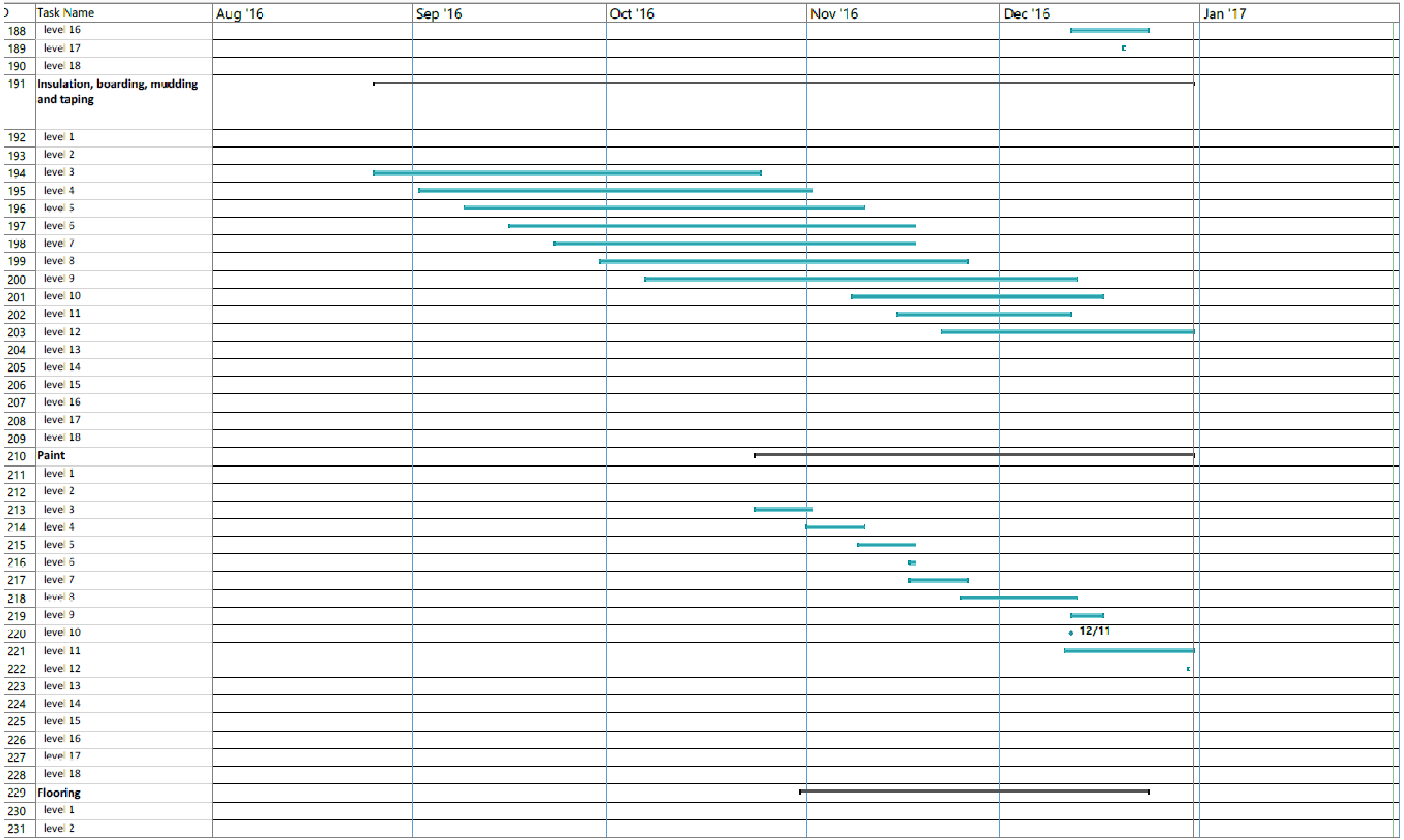


Figure 27 (Cont.) Complete construction schedule

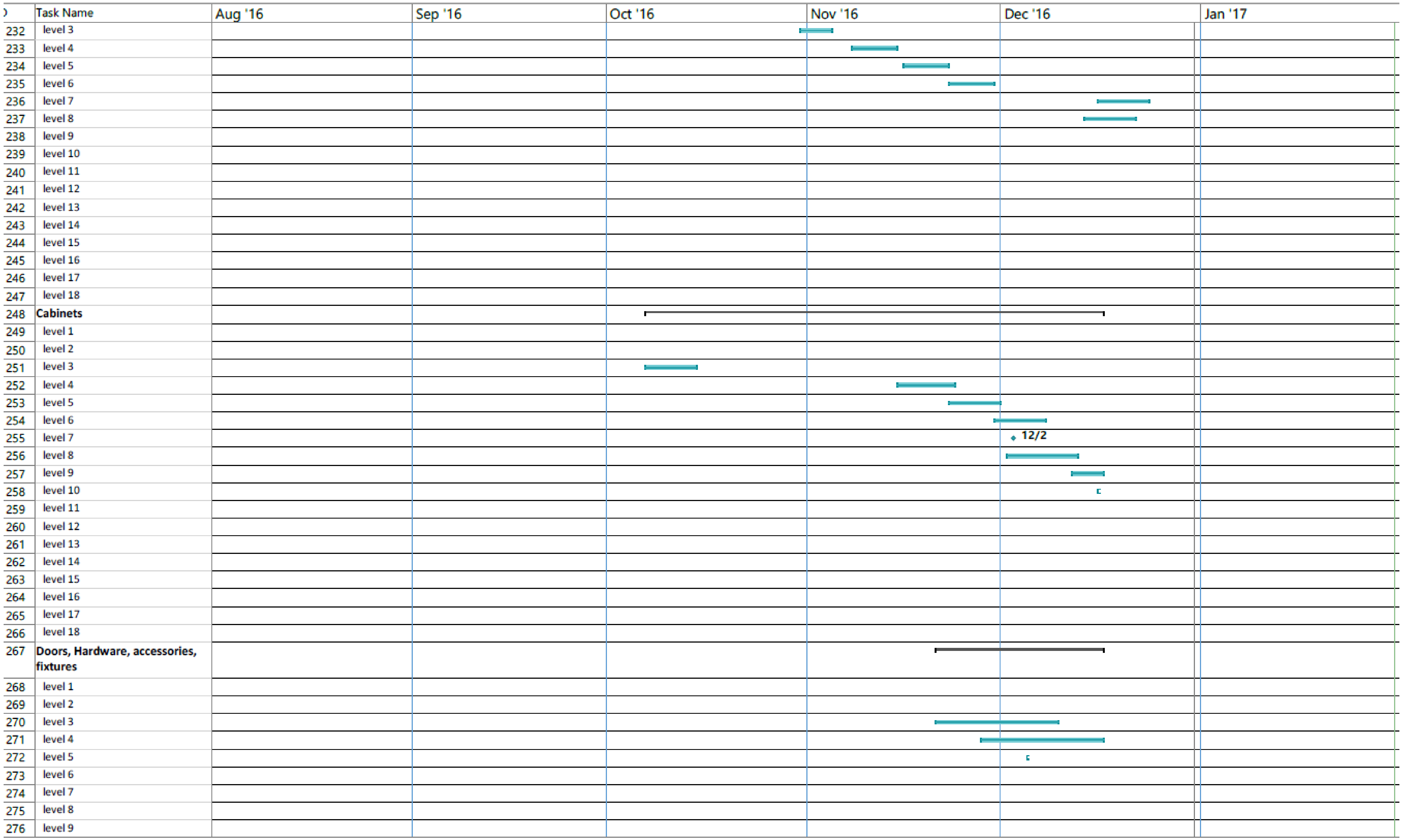


Figure 27 (Cont.) Complete construction schedule

D	Task Name	Aug '16	Sep '16	Oct '16	Nov '16	Dec '16	Jan '17
277	level 10						
278	level 11						
279	level 12						
280	level 13						
281	level 14						
282	level 15						
283	level 16						
284	level 17						
285	level 18						
286	**Final Paint**						
287	level 1						
288	level 2						
289	level 3						
290	level 4						
291	level 5						
292	level 6						
293	level 7						
294	level 8						
295	level 9						
296	level 10						
297	level 11						
298	level 12						
299	level 13						
300	level 14						
301	level 15						
302	level 16						
303	level 17						
304	level 18						

Figure 27 (Cont.) Complete construction schedule

Appendix B Variability of Productivity Value Tables

B.1 CLT Floor Panels

Table 15: Productivity rates for mass timber structure

Level	Date	Gross Hook Time (hrs.)	Stoppage (hrs.)	Misc. Rigging (hrs.)	Crane Op. Time (hrs.)	Rework (hrs.)	Net Hook Duration (hrs.)	Net Crane Productivity (m2/crn-hr)	Crew Size	Net Crew Productivity (m2/ lab-hr.)	Weather	
3	10-Jun & 13-Jun	13.11	2.19	2.99	0.48	0.11	7.34	98	11	8.9	rain	14°C
4	15-Jun & 16-Jun	11.99	2.36	4.71	0.41	0.00	4.51	160	11	14.6	overcast	12°C
5	20-Jun	5.52	0.57	0.78	0.13	0.00	4.04	179	10	17.9	cloudy	16°C
6	22-Jun & 23-Jun	6.38	0.68	0.65	0.24	0.00	4.82	150	10	15.0	rain	13°C
7	27-Jun	4.50	0.74	0.49	0.00	0.00	3.26	221	11	20.1	sunny	19°C
8	4-Jul	6.61	1.12	2.00	0.00	0.00	3.48	207	10	20.7	overcast	17°C
9	7-Jul	5.02	0.00	0.50	0.19	0.00	4.32	167	10	16.7	rain	16°C
10	11-Jul	8.47	3.15	0.70	0.37	0.00	4.26	170	11	15.4	cloudy	15°C
11	14-Jul	5.63	1.09	1.20	0.00	0.00	3.34	216	8	27.1	sunny	18°C
12	18-Jul	5.22	0.97	1.05	0.00	0.00	3.21	225	9	25.0	sunny	20°C
13	21-Jul	5.28	1.30	0.47	0.00	0.00	3.52	205	8	25.7	sunny	20°C
14	25-Jul	4.65	0.53	1.04	0.00	0.00	3.09	234	8	29.2	sunny	20°C
15	28-Jul	4.90	0.57	0.97	0.00	0.00	3.37	214	9	23.8	sunny	20°C
16	2-Aug	6.18	0.40	1.20	0.00	0.13	4.45	162	9	18.0	rain	15°C
17	5-Aug	5.72	0.10	2.04	0.00	0.00	3.58	202	8	25.2	sunny	17°C
18	9-Aug	5.90	0.69	1.97	0.13	0.00	3.12	231	9	25.7	rain	16°C

B.2 Envelope Panels

Table 16: Productivity rates for envelope cladding system

Level	date	Gross Hook Time	net hook duration (hours)	crew size	Crane Productivity (m2/ hr.)	Crew Productivity (m2/hr.)	weather (Description, Wind min, Wind max (m/s))		
2	21-Jun 22-Jun& 24-Jun	12:39:48	12.7	4	27.35	6.84	Cloud	2.7	7.2
3	24-Jun 29-Jun& 4-Jul	8:12:45	8.2	4	42.18	10.54	Cloud	1.8	3.6
4	29-Jun 5-Jul& 6-Jul	8:32:23	8.5	4	40.56	10.14	Sunny	2.2	3.6
5	30-Jun& 8-Jul	8:02:46	6.9	6	50.35	8.39	Cloud	3.6	4.1
6	5-Jul& 12-Jul	7:30:06	6.5	5	53.17	10.63	Light Rain	2.2	4
7	8-Jul 13-Jul& 15-Jul	8:14:41	7.1	6	48.79	8.13	Cloud	2.7	3.5
8	12-Jul 15-Jul& 19-Jul	7:04:06	7.1	5	49.01	9.80	Light Rain	1.8	5.4
9	15-Jul 19-Jul& 20-Jul	8:48:30	7.5	5	46.05	9.21	Cloud	2.2	5.8

Table 16(Cont.): Productivity rates for envelope cladding system

Level	date	Gross Hook Time	net hook duration (hours)	crew size	Crane Productivity (m2/ hr.)	Crew Productivity (m2/hr.)	weather (Description, Wind min, Wind max (m/s))		
10	19-Jul& 20-Jul	7:14:50	5.4	5	64.02	12.80	Cloud	4.5	6.4
11	22-Jul& 26-Jul	7:24:10	5.7	5	61.22	12.24	Sunny	2.7	4
12	26-Jul& 29-Jul	11:32:00	11.5	5	30.03	6.01	Sunny	5.4	7.6
13	29-Jul& 3-Aug	7:12:46	5.9	5	59.11	11.82	Sunny	6.8	9.4
14	3-Aug& 6-Aug	6:38:56	6.6	5	52.10	10.42	Sunny	2.2	7.2
15	6-Aug& 8-Aug	5:29:08	4.4	5	77.97	15.59	Cloud	5	7.2
16	10-Aug	6:36:40	4.8	5	72.55	14.51	Sunny	2.7	4
17	16-Aug	6:36:00	5.1	5	67.93	13.59	Cloud	0	6
18	6-Sep	9:11:58	7.2	4	48.44	12.11	Sunny	2.7	4
19 Para-pet	8-Sept& 9-Sept	7:39:04	7.4	4	46.56	11.64	Cloud	1.9	7.6

Appendix C PPC Values and Validation

Table 17: Lookaheads and construction Schedules for CLT installation

level	week 1 9 Jun- 15 Jun	week 2 16 Jun- 22 Jun	week 3 23 Jun- 29 Jun	week 4 30 Jun- 6 Jul	week 5 7 Jul- 13 Jul	week 6 14 Jul- 20 Jul	week 7 21 Jul- 27 Jul	week 8 28 Jul- 3 Aug	week 9 4 Aug- 10 Aug	Construction Schedule	
										Day #1	Day #2
3	13-Jun									10-Jun	13-Jun
4	15-Jun	16-Jun								15-Jun	16-Jun
5		18-Jun								20-Jun	
6		22-Jun	23-Jun							22-Jun	23-Jun
7			27-Jun							27-Jun	
8				4-Jul						4-Jul	
9					7-Jul					7-Jul	
10					11-Jul					11-Jul	
11						14-Jul				14-Jul	
12						18-Jul				18-Jul	
13							21-Jul			21-Jul	
14							25-Jul			25-Jul	
15								28-Jul		28-Jul	
16								2-Aug		2-Aug	
17									5-Aug	5-Aug	
18									9-Aug	9-Aug	

Table 18: Lookaheads and construction schedules for envelope cladding system

	week 1		week 2		week 3		week 4		week 5		week 6		week 7		week 8		week 9		week 10	
Level	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**
2			20-Jun	21-Jun																
3					24-Jun	25-Jun														
4					28-Jun	29-Jun														
5							30-Jun	30-Jun												
6							5-Jul	5-Jul												
7									8-Jul	8-Jul										
8									12-Jul	12-Jul										
9											15-Jul	15-Jul								
10											19-Jul	20-Jul								
11													22-Jul	22-Jul						
12													26-Jul	26-Jul						
13															29-Jul	29-Jul				
14															3-Aug	3-Aug				
15																	6-Aug	6-Aug		
16																	10-Aug	10-Aug		
17																			16-Aug	16-Aug
18																				
19 parapet																				

Table 18 (Cont.): Lookaheads and construction schedules for envelope cladding system

Level	week 11		week 12		week 13		week 14		Construction Schedule	
	Start Date	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**
2									21-Jun	22-Jun
3									24-Jun	24-Jun
4									29-Jun	29-Jun
5									30-Jun	30-Jun
6									5-Jul	5-Jul
7									8-Jul	8-Jul
8									12-Jul	12-Jul
9									15-Jul	15-Jul
10									19-Jul	19-Jul
11									22-Jul	22-Jul
12									26-Jul	26-Jul
13									29-Jul	29-Jul
14									3-Aug	3-Aug
15									6-Aug	8-Aug
16									10-Aug	10-Aug
17									16-Aug	16-Aug
18	23-Aug	23-Aug			6-Sep	6-Sep			6-Sep	6-Sep
19 parapet							9-Sep	10-Sep	8-Sep	9-Sep

Table 19: Lookaheads and construction schedules for encapsulation

Level	week 1		week 2		week 3		week 4		week 5		week 6		week 7		week 8		week 9		week 10	
	Start Date	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**
2			20-Jun	22-Jun		27-Jun			x	9-Jul										
3					27-Jun	29-Jun			9-Jul	12-Jul										
4									12-Jul	x	x	14-Jul								
5											15-Jul	18-Jul								
6											19-Jul	x	x	21-Jul						
7													21-Jul	23-Jul						
8													25-Jul	27-Jul	x	28-Jul				
9															28-Jul	30-Jul				
10															2-Aug	x	x	9-Aug		
11																	9-Aug	10-Aug		11-Aug
12																			11-Aug	13-Aug
13																			15-Aug	17-Aug
14																				
15																				
16																				
17																				

Table 19 (Cont.): Lookaheads and construction schedules for encapsulation

	week 11		week 12		week 13		Construction Schedule	
Level	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**	**Start Date**	**Finish Date**
2							20-Jun	9-Jul
3							9-Jul	12-Jul
4							12-Jul	15-Jul
5							15-Jul	19-Jul
6							19-Jul	21-Jul
7							21-Jul	25-Jul
8							25-Jul	28-Jul
9							28-Jul	2-Aug
10							2-Aug	9-Aug
11							9-Aug	11-Aug
12							11-Aug	15-Aug
13		18-Aug					15-Aug	18-Aug
14	18-Aug	20-Aug					18-Aug	22-Aug
15	22-Aug	24-Aug	x	26-Aug			22-Aug	26-Aug
16			26-Aug	27-Aug			26-Aug	29-Aug
17			29-Aug	31-Aug	x	4-Sep	29-Aug	4-Sep

Figure 28 to 31: Validation for construction progress on Jun-13, Jun-10, Jun-27 and Jul-4, respectively

Figure 32 to 35: Validation for construction progress on Jul-11, jul-18, Jul-22 and Aug-1

Figure 36: Validation for construction progress on Aug-10

Appendix D Cumulative Summary of Metrics

This table summarizes the obtained results from the analysis of the case study (Table 20).

Table 20: Research summary

Section 5.1: Marco-level Study

5.1.1 Macro-level Productivity

Building Element	Productivity (Working Days/ Level)
Excavation	4
Concrete Foundation	59
Concrete Slabs (L1 and L2)	28.5
East Concrete Core (L2 to L18)	6.7 days per 2 Levels
West Concrete Core (L2 to L19)	
Mass Timber Structure (L2 to L18)	2.4
Structural Steel Roof	16
Envelope Panels (L2 to L19 Parapet)	2.5
On-site Water Sealer (L3 to L18)	1
Prep. work for Concrete (L3 to L18)	1
Concrete Floor Topping (L3 to L18)	1

5.1.2 Crane Days

Building Element	Total Crane Days
CLT Panels (L3 to L18)	19
Glulam Columns (L2 to L18)	17
Envelope Panels (L2 to L19 Parapet)	21

5.1.3 Labor Efforts

Building Element	Breakdown of Labor
Mass Timber	3.0%
Envelope Cladding	3.3%
Drywall	20.6%
Concrete	15.8%
MEP	26.4%
Civil Work	2.7%
GC Management+ Labor	16.4%
Other Structural Trades	5.4%
Other Finishing Trades	6.0%

Table 20 (Cont.): Research summary

Section 5.2: Micro-level Study

Mass Timber Building Element

Sections 5.2.1 to 5.2.3

Average Hook Time for CLT Panels	3.98 hours/ level			
Level	**Net Hook Duration (hrs.)**	**Net Crane Productivity (m2/crn-hr)**	**Net Crew Productivity (m2/ labour-hr.)**	**Schedule Variance (days)**
3	7.34	98	8.9	-7
4	4.51	160	14.6	-4
5	4.04	179	17.9	5
6	4.82	150	15	8
7	3.26	221	20.1	9
8	3.48	207	20.7	14
9	4.32	167	16.7	20
10	4.26	170	15.4	26
11	3.34	216	27.1	30
12	3.21	225	25	35
13	3.52	205	25.7	42
14	3.09	234	29.2	47
15	3.37	214	23.8	50
16	4.45	162	18	55
17	3.58	202	25.2	62
18	3.12	231	25.7	68

Table 20 (Cont.): Research summary

Section 5.2: Micro-level Study

Mass Timber Building Element

5.2.4 Earned Value Analysis

Term	Acronym + Formula	Value	Unit
Budget Cost at Completion	BAC	3,500,000.00	$
		218,750.00	$/ floor
Construction Cost at Completion		3,400,000.00	$
		212,500.00	$/ floor
Schedule Variance	SV= BCWP - BCWS	-437,500.00	$
		1,750,000.00	
Cost Variance	CV= BCWP - ACWP	100,000.00	$
Percentage Schedule Variance	(SV/ BCWS) %	-100	%
		100	%
Percentage Cost Variance	(CV/ BCWP) %	2.86	%
Schedule Performance Index	SPI = BCWP/ BCWS		
Cost Performance Index	CPI = BCWP/ ACWP		

5.2.5 Percentage Planned Work Completed (PPC)

Lookahead Period	PPC
1	75%
2	100%
3	100%
4	100%
5	100%

Table 20 (Cont.): Research summary

Section 5.2: Micro-level Study
Envelope Cladding Element
Sections 5.2.1 to 5.2.3

Average Hook Time for Envelope Panels	7.1 hours/ level			
Level	**Net Hook Duration (hrs.)**	**Net Crane Productivity (m2/crn-hr)**	**Net Crew Productivity (m2/ labour-hr.)**	**Schedule Variance (days)**
2	12.7	27.35	6.84	-9
3	8.2	42.18	10.54	-13
4	8.5	40.56	10.14	-6
5	6.9	50.35	8.39	2
6	6.5	53.17	10.63	6
7	7.1	48.79	8.13	11
8	7.1	49.01	9.8	15
9	7.5	46.05	9.21	25
10	5.4	64.02	12.8	31
11	5.7	61.22	12.24	35
12	11.5	30.03	6.01	41
13	5.9	59.11	11.82	46
14	6.6	52.1	10.42	51
15	4.4	77.97	15.59	56
16	4.8	72.55	14.51	62
17	5.1	67.93	13.59	67
18	7.2	48.44	12.11	55
19 Parapet	7.4	46.56	11.64	58

Table 20 (Cont.): Research summary

Section 5.2: Micro-level Study

Envelope Cladding Element

5.2.4 Earned Value Analysis

Term	Acronym + Formula	Value	Unit
Budget Cost at Completion	BAC	4,100,000.00	$
		227,777.78	$/ floor
Construction Cost at Completion		8,900,000.00	$
		494,444.44	$/ floor
Schedule Variance	SV= BCWP - BCWS	-455,555.56	$
		1,822,222.22	
Cost Variance	CV= BCWP - ACWP	-4,800,000.00	$
Percentage Schedule Variance	(SV/ BCWS) %	-100	%
		114.29	%
Percentage Cost Variance	(CV/ BCWP) %	-117.07	%
Schedule Performance Index	SPI = BCWP/ BCWS		
Cost Performance Index	CPI = BCWP/ ACWP		

5.2.5 Percentage Planned Work Completed (PPC)

Lookahead Period	PPC
1	100%
2	100%
3	100%
4	100%
5	100%

Section 5.2: Micro-level Study

Drywall Encapsulation

5.2.5 Percentage Planned Work Completed (PPC)

Lookahead Period	PPC
1	0%
3	100%
4	80%
5	100%

Appendix E Structural Plan

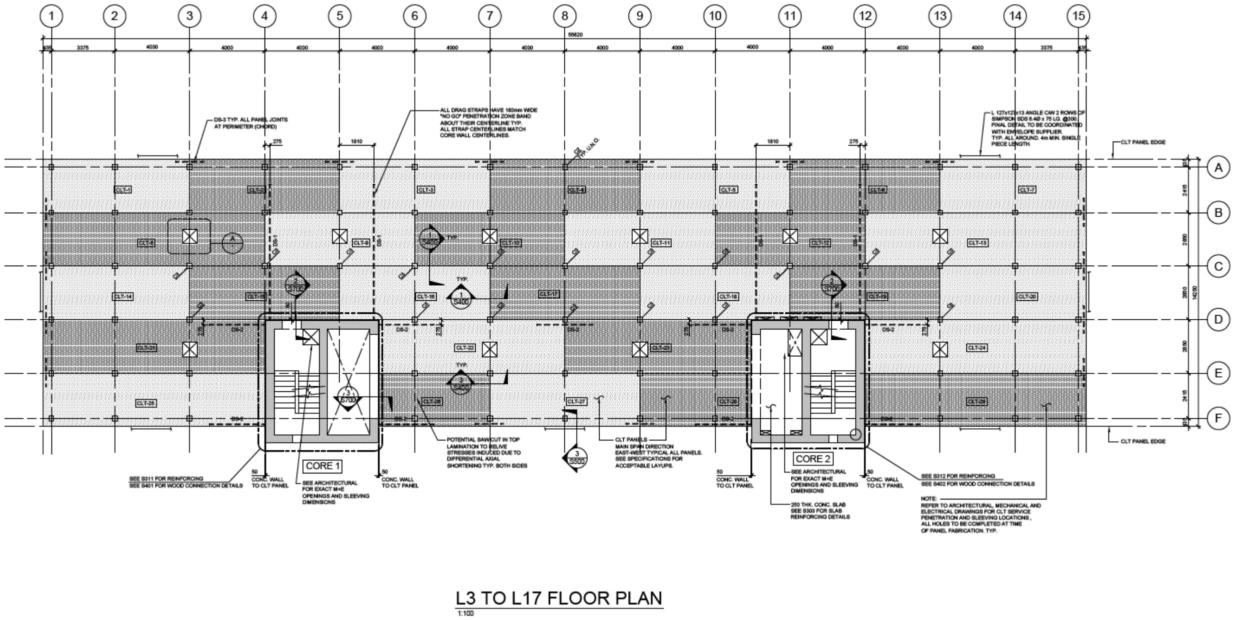


Figure 37- Structural plan of typical floors

Appendix F Installation Methods

F.1 L2 Columns

This step is done by construction manager:

1. Offset gridline and elevations at level 2 (transfer slab)
    a. Vertical elevation on concrete walls in red (93.000 m geodetic) using a red chalk line
    b. Horizontal gridlines are of 1, 15, 8, and D

This step is done by concrete contractor:

2. Create line intersections of all 78 column locations in black chalk line
3. Drill into concrete for anchors
    a. see picture: https://goo.gl/photos/ZnxjfsecR7dAVQdL7
    b. https://goo.gl/photos/RmmHoFWYfHRgD1sZ8
4. Install steel anchor using epoxy RE 150
    a. It takes a few hours to harden and works even if it is raining and/ or in wet concrete
5. Temporary install of pedestal on top of lumber
    a. Left in this condition until the next day
    b. see short video: https://goo.gl/photos/SCvcBaN6SbGtxnmJA

This step is done by construction manager:

6. remove pedestal temporarily
7. Install leveling nuts to receive column pedestals
8. Install pedestal and secure with nuts

This step is done by concrete contractor:

9. Check elevation of pedestal

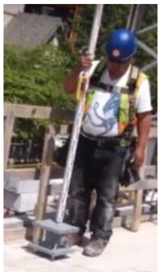


Figure 38: Pedestal elevation check

a. Side note- Pedestals can now be used for fall protection

<u>This step is done by construction manager:</u>

10. Grout pedestals through the center hole
    a. Video: https://goo.gl/photos/aAtg5o3tLsynrFDd9

<u>This step is done by timber installer:</u>

11. Rig 10 bundles of columns to active slab into these locations:

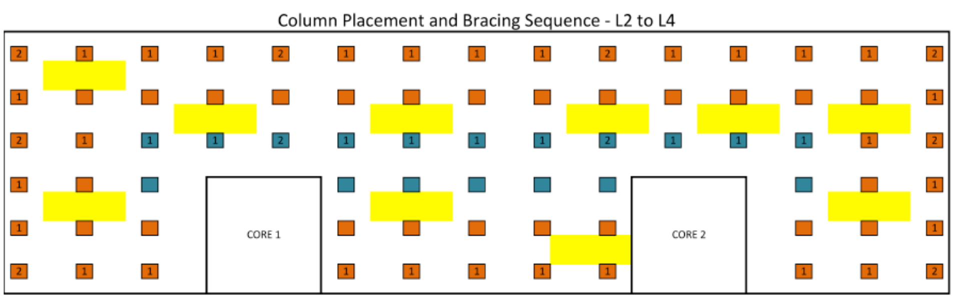


Figure 29: Mass timer construction layout © Seagate Structures

    a. Bundles are rigged in pairs for efficiency- see picture: https://goo.gl/photos/hhG3HLnsUaNygcvU7

12. Install columns using the crane.
    a. Safety requirement: installers must be tied off when working on perimeter columns. They can use a non-perimeter column pedestal as an anchor point.
13. Install diagonal braces and spreaders
    a. The numbers in previous picture refer to number of bracers needed for each column

b.

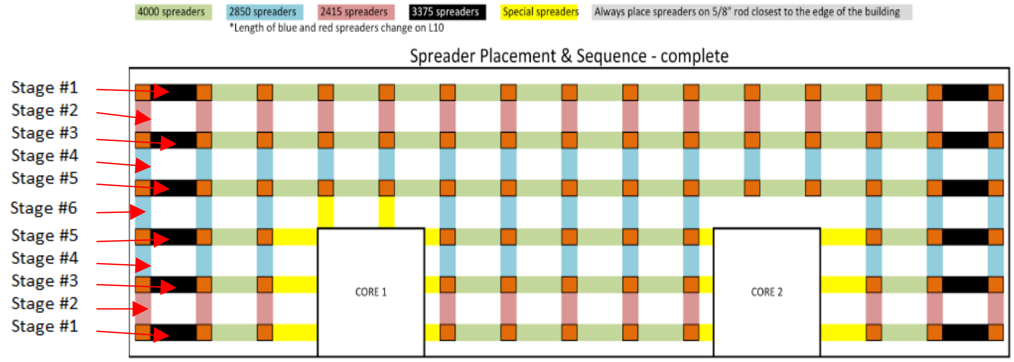


Figure 39: Steps for installation of spreaders

c. Source: Seagate QC records

d. Spreaders are color coded by length.

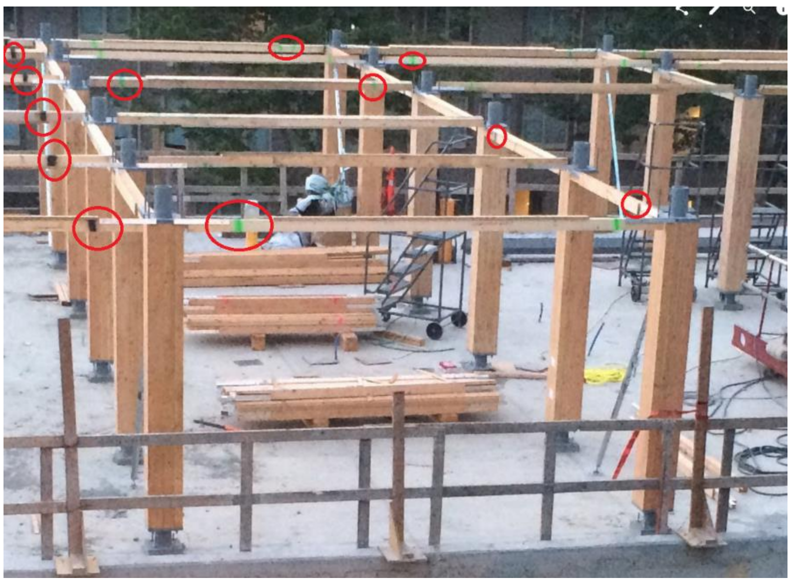
e. 

Figure 40: Spreaders

14. Plumb and line columns using offset gridlines and a vertical line laser.

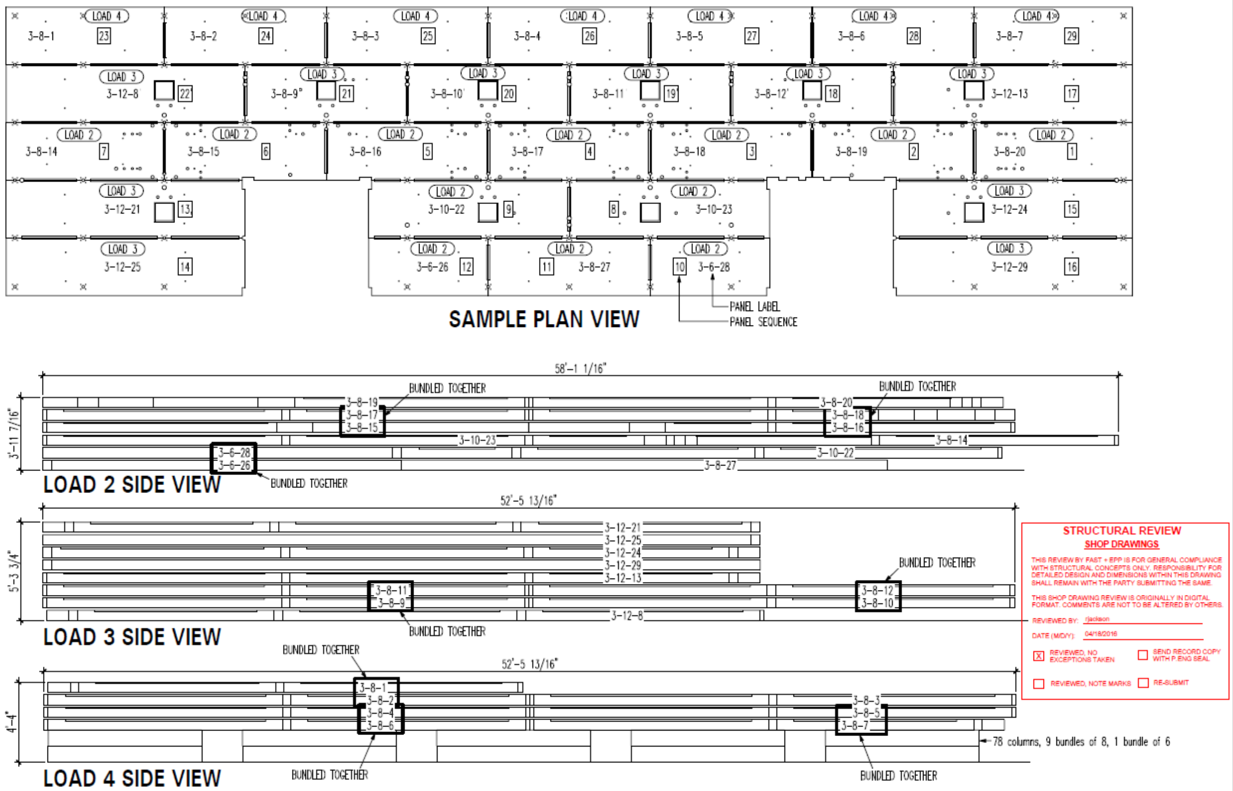
F.2 Typical Columns

The following steps are performed by the timber installer:

1. Shoot benchmark elevation and offset gridlines for A, F, 1, 8 and 15.
    a. Seagate hired a surveyor for this task.
    b. The surveyor first came for level 2 and then every second level (all even-numbered levels).
    c. Seagate used a laser level and a vertical line laser to perform this task for the odd-numbered levels.
2. If required, install steel shims as per structural engineer's specifications
    a. This inspection is performed by Urban One (myself + surveyor)
    b. Fast + Epp follows-up with the shimming plans
    c. Seagate installs the shims
3. Rig 10 bundles of columns to active slab into these locations:
    a. Bundles are rigged in pairs: https://goo.gl/photos/hhG3HLnsUaNygcvU7
4. install columns
    a. perimeter columns require crane + fall arrest for safety
        i. columns are rigged into location in pairs
        ii. Safety requirement: installers must be tied off when working on perimeter columns. They can use a non-perimeter column pedestal as an anchor point.
    b. non-perimeter columns are tilted into place either by labor or dolly
5. Install diagonal braces and spreaders
    a. The numbers in previous picture refer to number of bracers needed for each column
6. plumb and line glulam columns using offset gridlines, vertical line laser and line laser
7. install bolt and cotter pin to column connector B.

F.3 Cross-Laminated Timber Panels

1. receive packing list and CLT panels in 3 trucks.



a.

Figure 41: Shop drawings © Fast + Epp

   b. Note that the sequence of installation of panels 19 and 20 was switched. Seagate installed CLT #19 then CLT #20.

2. Install Bergen plates lifting devices to panels at 4 locations specified by Strurcturlam, as seen in previous figure.
   a. Bergen plates are screwed in with 4 6" total threaded assy screws
   b. Seagate has 12 (3 sets of 4) Bergen plates to install a total of 29 panels. They rotate through them as further below in this section.

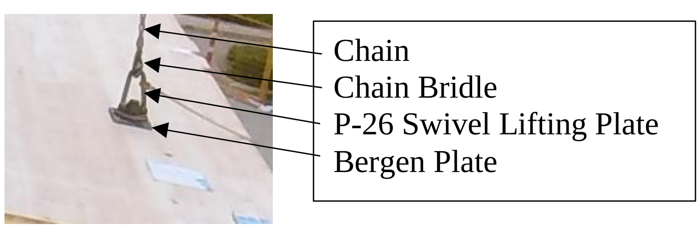


Figure 30: Anchorage system

3. Identify and mark the lower side

    a. Explanation: the lower side is the first touch side. For example: panel number 18 will be installed after 19, as shown in the figure below. Active floor rigger will be standing on panel #18 and expecting the panel from east side. Active floor riggers need the first touch to be the east side of the panel. Hence, ground riggers will hook the east side with the longer chains.

Figure 43: Fit CLT into location

4. If required, install D-ring fall arrest anchor.
    a. It was required in panels 8 to 14 and 20 to 24 because they are one-panel-in from the perimeter.

1. Installing of First Panel (CLT #19)

5. Hook the first CLT panel to crane using 4 P-26 swivel connectors. This is a 1¼" steel bolt connection. Attach two tag-lines to the swivel plates.
6. Receive the first panel.
    a. 1 signaler + 2 workers aligning columns on roller ladders at the first touch location in the lower level
    b. 2 workers inside concrete core 2.
7. Fit the CLT panel's 25mm holes into the 16mm threaded rods.
8. Unbolt the 4 swivel plates. The crane can now start its return trip.
    a. Clarification: the crane is now returning to the truck with the chain bridle and the swivel plates attached. One set of Bergen plates is still on the active deck. Ground

riggers have 2 more sets of Bergen plates. They can start preparing the next CLT panel for rigging.

9. Align the CLT panel into place using a laser pointer and column bracers.
10. Screw the CLT panel to concrete L angle using 2 rows of 6mm wide x 89 mm long SDS screws at 250 mm spacing, as seen in the figure below.

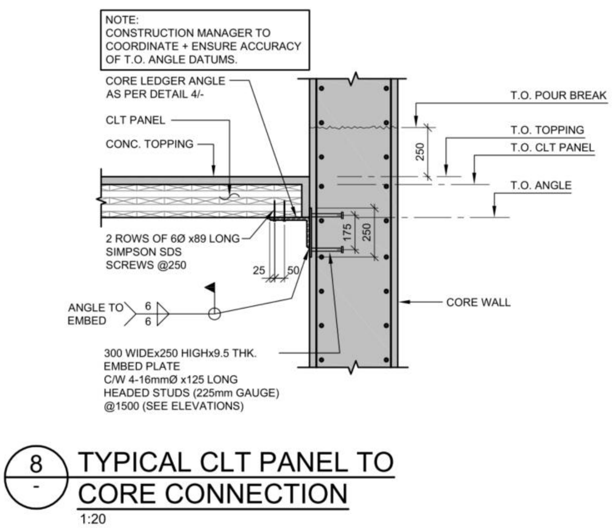


Figure 44- Source: IFC Structural Drawings

11. Unscrew Bergen plates from CLT #19 while waiting for CLT #20 to be arrive to location.

2. Continue to Install the First Strip

12. Install CLT #20 the same way
    a. Lateral stability of CLT #20 is not a concern at this point. Seagate will address it after installing CLT #24.
13. Attach Bergen plates from CLT #19 to crane to be transported to ground rigger during the crane's return trip.
14. Install CLT #18 the same way
    a. Align it by 3 workers in the level below
    b. Use hooks puller to pull it in place, as seen in the picture.

Figure 45: Hooks puller

   c. Screw CLT to concrete L angle
   d. Keep hooks puller between panels 19 and 18.
15. Install panel #17
   a. Align by 3 workers in level below
   b. Use hooks puller to pull it in place
16. Install panel #16
   a. Align by 3 workers in level below
   b. Remove hook puller from between panels 19 and 18 and use it between panels 17 and 16.
      i. Explanation: we do not need to laterally support panels 19 and 18 because they are screwed to concrete core 2.
   c. Screw to L angle on concrete core 1.
17. Install panel 15
   a. Align by 3 workers in level below
   b. Remove hook puller from between panels 18 and 17 and use it between panels 16 and 15, to pull panel #15 in place
   c. Screw CLT to concrete L angle
18. Install panel #14.
   a. Align by 3 workers in level below
   b. Remove hook puller from between panels 17 and 16 and use it between panels 15 and 14, to pull panel #14 in place

3. Continue to install panels around concrete cores

19. Install panel #23
   a. Align by 3 workers in level below

b. Remove hook puller from between panels 16 and 15 and use it between panels 18 and 23 or 17 and 23, to pull panel #23 in place, depending on which gap is wider.

20. Install splines between CLT #s 18 and 23 and between 17 and 23.
    a. Add only screws PSW 8mm diameter x 120 long at the corners. We will address the remaining fasteners later.
    b. Explanation: notice that we are only installing splines in the north and south direction; to address lateral stability in this direction.
    c. Lateral stability in the east-west direction was temporarily addressed by screwing panels 19, 18, 16 and 15 to concrete cores.
21. Install panel #22 the same way.
22. Install splines between panels 17 and 22 and between 16 and 22.
    a. Add only screws PSW 8mm diameter x 120 long at the corners
23. Continue to install CLT panels 28, 27, 26, 21, 25, 24 and 29, in this order, the same way. Add splines in the North-South direction after every panel.

4. Transport materials and equipment from lower level to active level using the crane.

5. Continue to install remaining panels

24. Continue to install the remaining panels (CLT panels 1 to 13), using the sequence highlighted in the figure above. Adding splines in North-South direction after every panel.

6. Wrap up

25. Install steel washers and nuts on column connector B.
26. Install the remaining splines.
    a. Splines in East- West direction
    b. Nails all splines using Rothoblaas anker nails at 100 mm spacing (64 mm for levels 17 and 18).
27. Install temporary guard rails
28. Install drag struts
    a. Fix to core brackets
    b. Screw into CLT panels using SDS screws

<u>This step is done by the construction manager:</u>

29. Install a waterproof, non-breathable peel-and-stick tape on splines.

Tolerance: a maximum of 2 mm gap between panels (source: Specs 06.15.23).

F.4 Perimeter L-angles

1. Rig perimeter L-angles to active level. L-angles are rigged 2 bundles at a time for efficiency.
2. If required, remove guardrails and use fall restraint
3. Move L-angle into position using pallet jacks
4. Secure L-angle in "close to" positions with a minimum of 4 SDS screws per piece
5. Reinstall guardrails
6. After coordination with curtainwall contractor, fasten the balance of the screws.

Envelope panels can only be installed after all screws are fastened.

F.5 Envelope panels

1. Rig envelope panel to location using a W 8x31 lifting I-beam.
   a. Connect I-beam to the crane by one point using a ¾" steel plate and 3/8" steel stiffeners. Connected I-beam to an envelope panel by 2 points. See drawing of lifting beam, submitted by Centura: https://drive.google.com/file/d/0ByYtmFXaO5SmOEZzZkVBWTdDVGs/view?usp=sharing
   b. In the long panels (8770 mm), a spreader bar, spanning 1400 mm, is connected between two lifting pints. The envelope panels would still be connected by two chains.
   c. Shop drawings of an envelope panel (submitted by Centura), showing the lifting points and spreader bar.

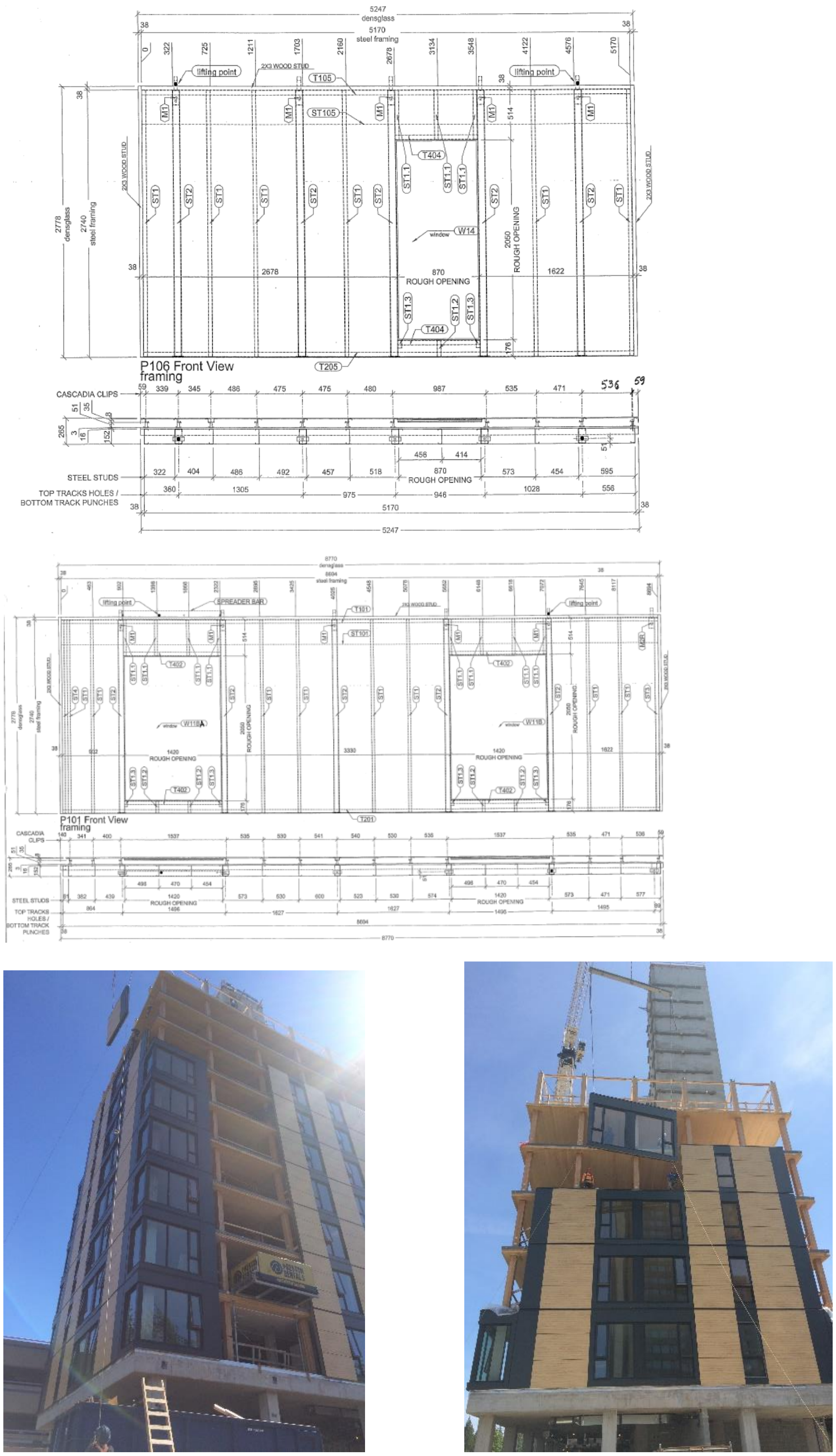


Figure 46: Installation of envelope panels

2. Two workers, on the lower slab, fit the panel's female connection into the lower panel's male connection.

a. the lifting point of the lower level panel acts also as the male connection.

b. In level 2 transfer slab, male connectors were installed into the concrete curb. This is the first level of envelope panel cladding.

3. Two workers, on the upper slab, half-fasten the panel to 2 points to the perimeter L angles.

   a. The holes in the L-angles are 40 mm wide. The holes in the envelope panels are 15 mm wide. The bolt used is 15 mm wide. As a result, there is some tolerance available within the L-angle hole, but the bolt has to be 100% square to the envelope panel.

   b. Gums, shims and micro-shims are used to facilitate the bolting process

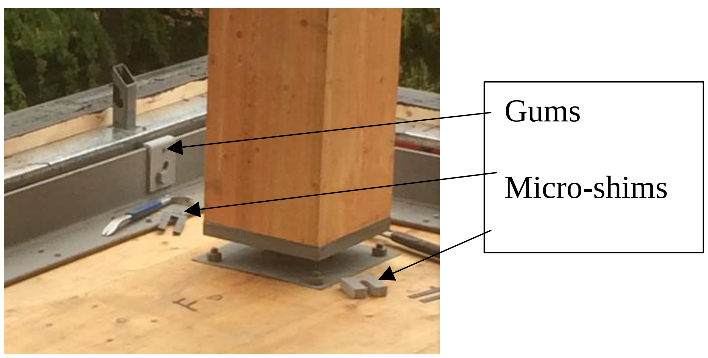


Figure 47: Envelope panels' installation pieces

4. Check the correct elevation using a laser level, a laser detector on a 2-foot level on the upper slab.

5. Workers in the lower slab should shim the panel up as per instructions form the workers in the upper slab.

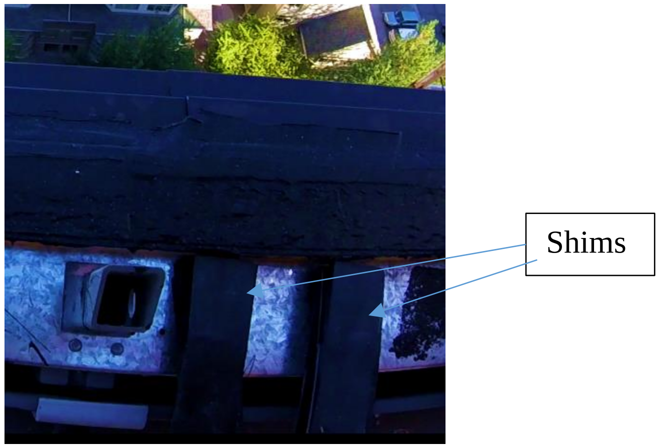


Figure 48: Envelope panels vertical shims

6. Check the elevation again, on the upper slab.
7. Fully fasten the envelope panel to L-angle by two bolts.
8. Unhook panel from crane.
9. Install the rest of the panels the same way.
10. Fully tighten the remaining bolts in all panels.