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Productivity in Multi-storey Mass Timber Construction

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Productivity in Multi-storey Mass Timber Construction

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1. Introduction

The aim of this project was to quantitatively measure the onsite installation productivity of Cross Laminated Timber in multi-storey building projects. Specifically, the work aims to improve an evidence-based understanding of expectations concerning:

- The speed and productivity of CLT installation.
- Assumptions when planning CLT processes onsite.
- Benchmarks to facilitate comparisons between CLT and other forms of construction.
- Guidance about process improvement on-site.

Multi-storey CLT buildings are relatively new to Australia and so an in-depth case study of a specific building project was the chosen method of undertaking the research. Time-lapse photography was used to gather site assembly information and the resulting footage was converted into quantitative data including the number of worker hours and crane hours used in installing the wall and floor panel areas involved. Statistical analysis was used to derive productivity rates (m^2/hour), floor cycle times and other related findings, concerning the installation of CLT.

2. Background and Rationale

Productivity is important to anyone who is responsible for planning, supervising, estimating and procuring construction work. Prefabrication, in its general terms, is seen as a way forward in improving the productivity and efficiency of construction onsite. This is also applicable to CLT construction which is widely regarded as panelized prefabrication. Unfortunately, progress in making this a common reality in Australia has been slow particularly because of a lack of understanding and knowledge about the potential advantages it offers. The reasons for undertaking prefabricated construction are many but those of specific relevance to this study, include:

- Reduced construction time
- Simplified construction processes
- Higher quality, better control and greater consistency through mechanized factory production
- Reduced costs when resources are scarce and/or construction in remote areas
- Improved working conditions and reduced on-site risks
- Fewer trade packages and interfaces to manage and coordinate on-site.
- Reduced waste on and off site.
- The incorporation of sustainable solutions.

Blismas (2007)

Despite these potential advantages, quantitative evidence to support the above advantages is still relatively scarce. The main examples include an earlier report by Forsythe, Brisland & Sepasgozar (2016) which mainly focused on the installation productivity of framed panels (e.g. floor cassettes and stud wall frames) but also included a relatively small CLT house case study. A Masters' thesis also exists, studying the 18 storey Brock Commons student housing project, in Vancouver (Kasbar 2017). This building involved hybrid construction involving CLT floor plates, Glue Laminated Timber (GLT) columns, steel stud partition infill walls, concrete core and composite façade elements.

Consequently, there is relatively little data about what to expect under Australian conditions and where a more holistic CLT (mass timber) solution, has been used. In addressing this, the advantage of this study is that it not only includes both CLT wall and floor panels in the Australian context, it also focuses upon cellular style apartment building construction (where individual rooms are like cells that are joined horizontally and vertically to create an overall structural frame) which is appropriate given the now burgeoning extent of apartment construction in major Australian cities. Designers, contractors, quantity surveyors and cost engineers need to know information about CLT productivity to choose the best methods on offer. Unfortunately, the current lack of knowledge acts as an impediment for CLT concerning its cost competitiveness when pitted against traditional site-based construction (especially insitu-concrete construction).

3. Principles of Construction Productivity Measurement

Productivity concerns the conversion process of input resources to output quantities (Thomas et al. 1990) and is commonly formulated as follows:

Productivity = Outputs/inputs

= installed quantity/actual hours worked

= m^2*/hours*

The greater the number from the calculation, the higher the productivity. The inputs in the above formula are the main site resources including labour, materials, plant and equipment. Even so, prefabrication technologies tend to change the traditional mix of these inputs because onsite works take place in a different way. It becomes less about bulk man-power and crafting components on site, and more about greater use of plant and equipment (mainly cranage) to assemble larger scale assemblies onsite. Subsequently, a smaller and more focused team of workers is used on the jobsite (refer to Table 2 for crew size and composition). This allows for a more manufactured approach to construction that can take greater advantage of offsite digital technologies and offsite production methods which aims to reduce on-site costs.

In operationally enacting the above formula, there are a number of *key issues involved in measuring productivity*. Within this context there is the need to:

- Carefully define the boundaries of the work being measured.
- Identify a production unit which can be visually measured (Adrian & Boyer 1976). In this study the focus is mainly on input crane hours and output square meterage of installed wall and floor areas.
- Identify a leading resource as required by the production method (Adrian & Boyer 1976). In this study, the lead resource involves crane usage to lift assemblies into place. Labour is typically in a supportive role whereby crew sizes are balanced to enable optimal crane speed.
- Identify a production cycle relating to the time between consecutive occurrences of the production unit (Adrian & Boyer 1976). In this study the focus is on the number of crane cycles in installing panels on site.
- Recognise that the work being studied is likely composed of one or several operations; each operation being performed by a specific trade, typically defined in jurisdictional

or subcontract terms (Buchholz et al. 1996). For this research, the focus is only upon the trade workers directly involved in installing CLT panels and therefore excludes site management and activities associated with shared site infrastructure, such as scaffolding and safety measures.

- Recognise that sick leave, vacations and holidays potentially impact on productivity but are very difficult to estimate and are largely random in occurrence. For this research, these factors have been omitted from the study.

In adding to the above, sampling plays an important role in terms of how much data needs to be collected in order to provide indicative or representative results such that productivity measurements can be generalised across the entire project. Measurement revolves around quantification of hours worked and options for this include work sampling and group timing (Liou & Borcherding (1986); Thomas & Daily (1983); Thomas & Mathews (1986); Yi & Chan (2013)). In this study, the *work sampling* approach, as detailed by Thomas & Daily (1983), was used. In addition, large samples were attained in the study, thus making it possible to make generalisations from these samples about the overall productivity achieved on the project. Greater detail on this issue is provided under the *Research Method* section of the report.

Further, as suggested by Yi and Chan (2013), efforts have been made to focus on work days that are unaffected by significant rework, bad weather or lengthy disruptions. It is not so much that these variables do not exist in the real world but they tend to occur as irregular events whereby practitioners must normally make an allowance for such events rather than try predict them in advance. By doing this, it is more possible to measure work in a way that is reliable, repeatable and predictable, hence making it possible to compare and use by others.

In linking these points to earlier discussion, crane usage is seen as the lead resource in assembling panels onsite and also allows establishment of a database of standard productivity expectations. Measuring productivity in terms of crane cycles also has the advantage of being a relatively homogenous task which means it occurs in a predictable way. For instance, whilst a degree of variance occurs in all work activities, homogenous processes have variance that occurs within the context of a relatively well-known work process and within relative limits or what is normal. Accordingly, the above principles have been applied in this study.

4. Cross Laminated Timber (CLT)

CLT represents an innovative approach to construction prefabrication that comes out of Europe and can be applied to buildings as small as individual houses, and as large as multi-storey apartment buildings. As alluded to previously, the largest example at the time of writing this publication is the 18 storey Brock Commons building in Vancouver (Kasbar 2017).

The solid thickness and diaphragm action obtained by CLT panels (refer Figure 1) provides good structural performance as well as a degree of thermal and fire insulation – thus reducing, or at least simplifying, the remaining work involved in the overall construction system. A *file-to-factory-to-site* approach is commonly adopted by CLT manufactures including transition of the 3D architectural model used on the project (e.g. Revit, Archicad) into a detailed panelisation file (e.g. Cadwork) which can be used to drive Computer Numeric Cutting machines (e.g. Hundegger machinery) for automated cutting of panels. For example, openings can be accurately cut from the panels, as can “chases” for building services. The detailed design information can also be sent to site to help sort panels and clarify where they go during onsite installation procedures.

Of additional note, CLT is dimensionally stable and lightweight relative to concrete construction and this provides for lighter weight cranage options on-site, which carries advantages concerning crane selection requirements.

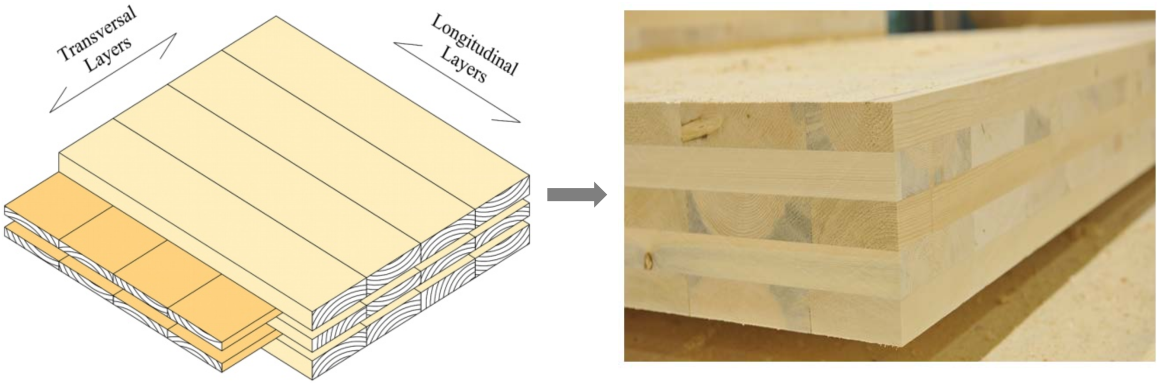

Figure 1: Cross Laminated Timber: Concept Layout (left) and Final Product (right), (Adopted from Fragiacomo et al. (2013))

5. Case Study Research Method

As mentioned previously, quantitative data on installation productivity was gathered using a "time and motion" approach (Groover 2007). The time-lapse footage also allowed detailed observational data as well. This was applied to a specific case study project located in Sydney's western suburbs involving CLT multistorey construction (7.5 floor levels) and sitting on top of 2 concrete basement levels and 2.5 mezzanine levels - 12 levels in total. It involved a complex and non-rectilinear architectural form including a mix of predominantly 1-3 bedroom retirement apartments. It is a large CLT project (especially in terms of CLT volume) given the medium to large floor plate area of 1280m^2 and the 7.5 timber floor levels involved.

Data was captured by two cameras:

- The side-mounted camera - mounted on a nearby shopping centre roof
- The top-mounted camera – mounted on the mast of the site tower crane.

The cameras were positioned to obtain an overview of the site including a frame/by-frame capture rate at 5 seconds (side-mounted) and 30 seconds (top-mounted) intervals – thus allowing a high level of detailed data. In total, 1075 individual crane cycles were captured and analysed for CLT panels. Details of the data capture for each floor level is shown in Table 1.

Table 1: Overview of data capture crane cycle data

Floor level	Total floor area (m^2)	Total wall area (m^2)	Cameras' captured floor area (m^2)	Cameras' captured wall area (m^2)
4	- Note 1	76	-	28
5	506	178	217.6	148
6	1271	181	864.3	153
7	1263	182	1162	154
8	1287	182	1068.2	159
9	1289	184	1057	156
10	1285	181	1092.1	147
11	1289	189	1108	155
12	1288	- Note 2	1120	-
Total	9478	1353	7689	1100

Notes:

1. *Level 1-4 involved concrete floor construction as part of the basement and podium levels, but with CLT walls atop half of the Level 4 area.*
2. *CLT Roof level was excluded from the study to prevent confusing the calculation of floor cycle times.*

The time-lapse photography includes time/date stamping of each frame, thus allowing quantification of the work onsite. By viewing the footage in slow motion, frame by frame, and recording time and date stamping on each frame, it was possible to convert the footage into time data relating to input resources involved in the installation process such as crane time and labour time. Output data about the wall and floor areas installed was also recorded from the footage and by cross-referencing this with the design documentation, site observations and working drawings. Other information such as feedback from the site management and workers, were also used to assist in understanding and supporting the above data sources.

Both quantitative input data and output data were recorded into a spreadsheet format and from this, statistical analysis was undertaken using SPSS software. As stated previously, this enabled measurement of installation productivity.

As mentioned, crane cycle time was the main unit of interest as labour tasks were ultimately tailored around the crane cycle. Core emphasis was placed on seeing it as a highly repetitive and predictable processes, as only such data can be generalised for use in predicting and comparing productivity rates with other projects. Efforts were therefore made to separate random events and irregular incidents from more standardised procedures.

In analysing the above, it was useful to separately consider:

- The *overall timber tower construction period -* which covered the period from commencement until completion of the timber tower floor levels. This also included a small amount of structural steel work to support the CLT balconies and in addition, bad weather and stoppages. It did not however include the CLT roof level, so as not to confuse calculation of repetitive floor cycles;
- A subset of the above concerns specific *timber installation days,* which excludes the project wide issues mentioned above (i.e. days when timber specific work did not take place).

Importantly, *timber installation days* were used for productivity calculations. On this basis, the captured data reflects a sample of 81% of the CLT panel floor area and 82% of CLT wall panel area. A micro study was also undertaken of timber beam installation (2 floor levels in the timber tower floor levels) which was purely for the purpose of looking at beam installation in detail. A similar sample was taken for the external steel framework used to support CLT balconies, but this was mainly to determine if it impacted significantly on overall floor cycle times or not. Excluded from the study was CLT stair installation (unsighted by the time-lapse camera) and the CLT roof level construction (omitted so as not confuse the calculation of floor cycle times).

Labour time was also measured where important in both facilitating crane processes and contributing to setout, installation and structural completion activities.

The sample is in general terms thought to provide a strong and representative sample of the timber construction on the project[1]. Specific subheadings (below) break the analysis down into appropriate headings.

[1] Loss of time-lapse captures occurred occasionally due to: high winds, occasional obstructions to the cameras, redundant camera locations due to building growth, and changing batteries. These factors prevented a 100% capture rate.

6. Complex Shapes Impact on the Productivity Achievable

A key initial point to make before discussing the findings from the study, is simply that the findings relate to a complex building shape including non-rectilinear floor and wall layouts.

Figure 2: Architectural impression of the building (CLT only relevant to tower levels)

This is externally evident in the architectural impression of the building, shown in Figure 2, which gives some indication of the projections and curved appearance of the building form. Figure 3 and Figure 4 show more detail including:

- the many different offset angles and segmentations in the floor plate shape;
- the complex wall setout, which again includes offset angles;
- the complex floor panel layout where different panel zones yet again intersect at non-rectilinear angles.

The key issue here is simply that it is commonly known that the more complex the shape of the building and panels being installed, the slower the productivity attained relative to the likes of a rectilinear building with an optimised panel layout (see for instance the economies achieved in the carefully planned office building layout described by (Forsythe 2015)).

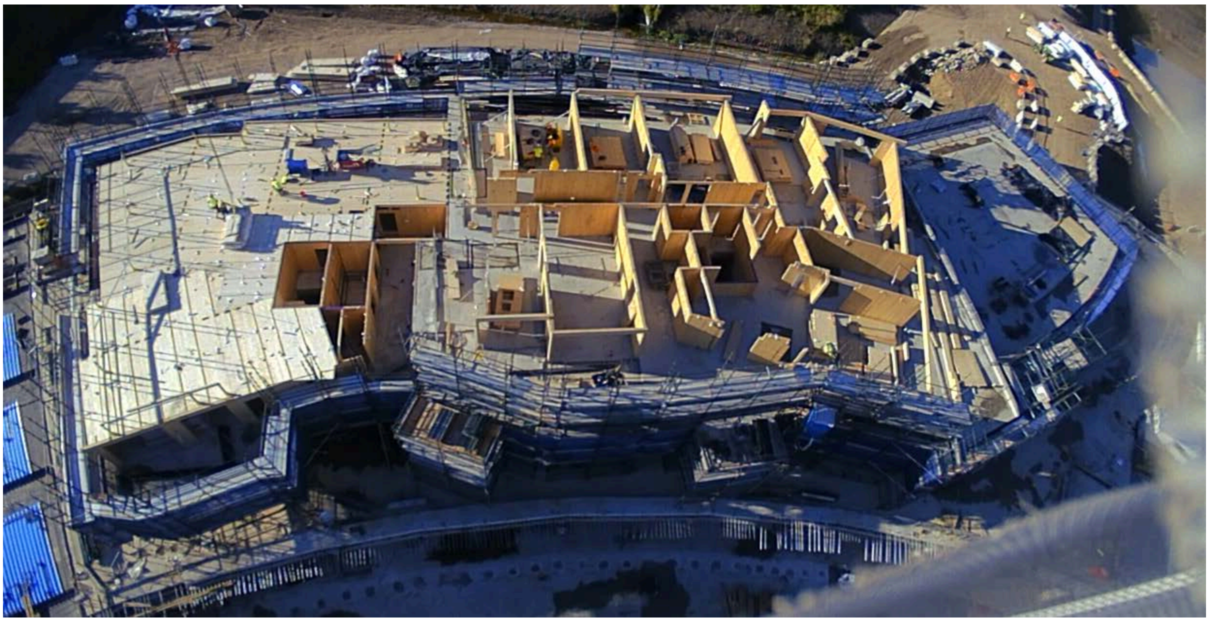

Figure 3: Overview of floor and wall installation on split Levels 4 and 5

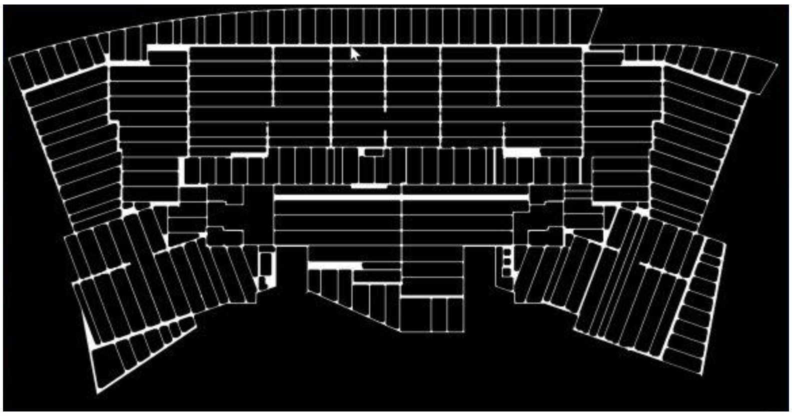

Figure 4: Floor and wall layout of a typical floor plate

7. Findings

An overview of key descriptive data is shown in Table 2 which of note indicates an overall *timber tower construction period* of 17.2 weeks (86 days) spanning from the beginning of the CLT tower until completion of the top floor level (excluding the CLT roof level construction). As mentioned, this includes not only timber installation time but also related activities such as installation of the steel structure supporting CLT balconies and stoppages from rain and wind affected days. Within this period, time focusing purely on *timber installation days* equates to a lesser 74 days. Subsequently, the overall *timber tower construction period* averages out to approximately 11.5 days per floor level and the *timber installation days* equates to approximately 10.0 days per floor level.

Within these cycle times it is notable that floor and wall panels (analysed separately below) took place with a degree of concurrency onsite. For example, wall placement on certain floor levels was still being undertaken at one end of the building, whilst floor placement on the next floor above, had already commenced at the other end of the building. This is relevant in terms of equating how individual floor and wall installation cycle times (discussed later), fit into overall floor cycle times.

Table 2: Overall data

Number of timber levels	7.5[1,2]
Typical floor plate area	1280m^2
Start date	10 May 2017
Finish date of top floor (excluding roof)	8 September 2017
Overall timber tower construction work period	17.2 weeks, 86 days[2,3]
Timber installation work days	74 days[2,4]
Approximate CLT panels per floor (including wall and floor panels)	295
Fixed tower crane	Jib: 75m (at full reach) Height (from ground to boom): 57m approx. Maximum lifting capacity: 16 tons Capacity at full reach: 2.9 tons
Mobile crane	Folding jib: 40m (at full working radii) Height (from ground to boom): 60m approx. (with the telescopic jib) Maximum lifting capacity: 42 tons Capacity at full reach: 3.1 tons
Timber related work crew	Total crew of 12[5] including: - 1 tower crane operator (all floor levels)

	- 1 mobile crane operator (half of floor levels) - 2 dogmen - 2 carpenters: setting out and/or organising - 3 carpenters: installing, landing panels, assisting tower crane - 3 (occasionally 4) carpenters: structural completion (nailing/fixing/bolting)
Sample size of floor panel installation	81% of CLT floor area
Sample size of wall panel installation	82% of CLT wall area

Notes:

1- *The half floor relates to level 4 which incorporates placement of CLT walls panels (only) to approximately half of the concrete floor plate area;*
2- *The CLT roof used on the building has been excluded from the "number of timber levels" and "work day" calculations so as not to confuse calculation of repetitive floor cycles.*
3- *"Overall timber tower construction period" is based on a 5 day work week; no significant cranage took place on weekends and only a skeleton labour crew worked on Saturdays. The 5 day working week includes rain days, winded days etc.*
4- *"Timber installation" work days includes all days when timber construction work was undertaken and assumes an 8 hour work day; it excludes scheduled breaks, rain days, winded days, days when the crane did not operate.*
5- *Within the overall crew, the carpentry team worked in a cohesive way where workers moved from one role to another according to need and as circumstance changed during installation; specific roles within the carpentry team therefore reflect typical rather than exact worker numbers.*

In general, the floor cycle times above suggest a reasonably good result given the medium to large floor plate area (1280m^2) and complex building shape. If comparing this with the likes of concrete construction, then certain caveats are necessary. For instance, the above floor cycles include both external and internal (CLT) wall installation as part of each floor cycle, whilst the concrete equivalent would normally delay these activities to later in the process. As widely practiced by the industry, external walls (facade) would normally trail significantly behind the floor level under construction or may not even begin until the tower is structurally complete; internal walls would normally be delayed until internal fit-out processes. In addition, work that typically follows the main floor cycle - such as Mechanical, Electrical and Plumbing trades (MEP) - is also delayed with concrete construction because back propping is required for 3 to 4 floor levels below the floor under construction. These issues effectively mean that the concrete construction floor cycle time effectively requires extra time elsewhere in the overall construction program relative to the CLT timber study undertaken here. In any event, greater details about specific aspects of timber floor construction are provided under dedicated headings that follow.

7.1. A Focus on Floor Panel Installation per Floor Level

The following discussion focuses on the duration of time for installing floor panels on a per floor basis and therefore represents a subset of the previously discussed, *timber installation days*. As mentioned previously, the floor panel installation sometimes overlapped with wall panel installation on the floor above/below.

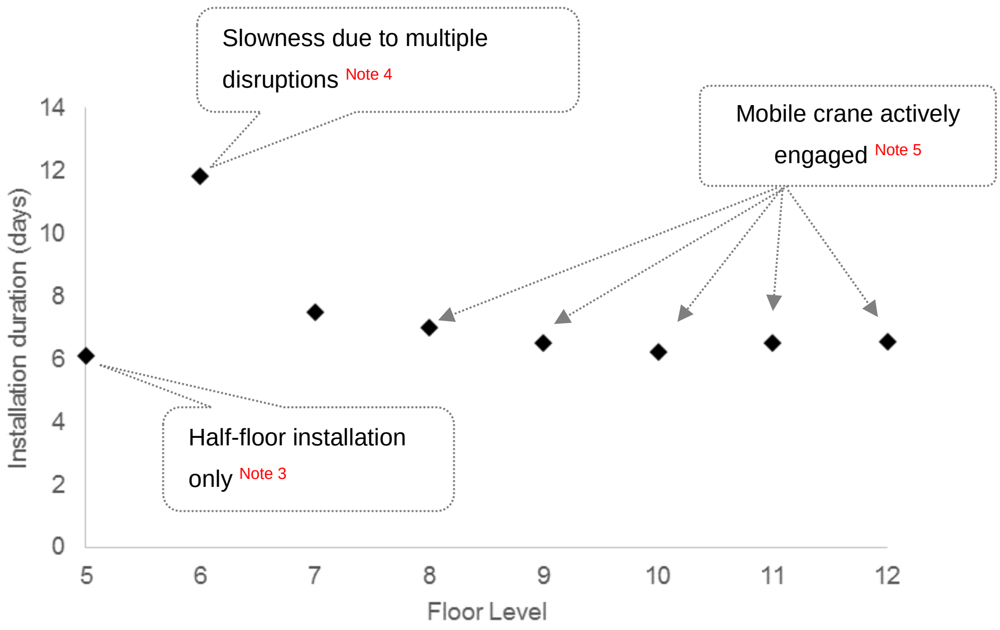

Figure 5: Installation duration of floor panels per floor level[1]

Notes:

1- *Installation duration per floor is based on the start time of the first floor panel placed on a given floor, until the last floor panel placed (minus situations where the crane was used for non-timber activities or where the crane was not operating at all onsite i.e. rain days, winded days)*
2- *Floor levels shown in the figure are counted from the lowest basement level (as level 1).*
3- *Floor 5 is a composite of timber floor panels and concrete slab construction (approximately half of the floor area); the duration shown is calculated for timber floor panels only.*
4- *Floor 6 floor panel installation was frequently disrupted due to crane usage for concrete pours, servicing reinforcing bar fixers, moving waste bins etc. The calculated duration excludes such disruptions, though the overall installation duration of this floor was significantly affected by virtue of the fragmented process and loss of rhythm caused by the deployment of the crane to non-timber activities.*
5- *Floors 8 -12 made full time usage of a mobile crane to assist timber installation which increased floor cycle speed (previously, it was only used on an occasional basis). The mobile crane was*

typically used to carry floor packs from the staging area to the live deck. Individual panels within the packs were later distributed to the insitu location using lifts by the tower crane.

Drawing on data presented in Figure 5, it can be seen that levels 7-12 represent a relatively stable and fast installation cycle concerning the processes used. Within these levels, levels 8-12 had the benefit of a dedicated mobile crane to work in conjunction with the fixed tower crane (this mobile crane had only been used sporadically on lower levels). It served to maintain installation speed as the building reached upper levels. For instance, it simplified work flow for the tower crane which had been experiencing sighting difficulties in loading panels efficiently from the unseen on-ground staging area, as the building increased in height. This effectively meant that two approaches to cranage were used on the project:

- a “single movement” lifting process (mainly on lower levels) where panels were moved directly from the on-ground staging area to the insitu location, using only the tower crane.
- a “double movement” lifting process where the mobile crane facilitated lifting of packs of panels from the staging area up to the live deck, then the tower crane distributed individual panels from a given pack into the final insitu panel location.

The two methods are analysed in more detail later in this report.

Figure 5 also shows that level 5 appears to be of a similar time period to these upper floor levels, but in productivity terms this is not really the case as it only relates to installation of half a timber floor level. This half level can be seen if carefully looking at Figure 3 where the timber construction abuts the adjoining concrete floor construction (near the centre line of the building). Level 5 was, therefore, less productive (less installation given the time taken) than levels 7-12 and observation from the video footage suggest multiple reasons for this including: it was the first timber floor section placed and thus suffered more process start-up time; the crew had yet to establish a standard process; the smaller area reduced the economy of scale compared to full floor installations; there was extra set-out work and abutment work at the interface between the timber and concrete floor areas; the floor installation occurred concurrent to wall installation work on level 5 (as seen on the right side of Figure 3) which caused a degree of divided work resourcing; being the first timber level it had yet to benefit from the learning effect potentially present on upper floor levels.

Level 6 also showed lower productivity than levels 7-12 (refer Figure 5) but viewing of the video footage showed that this was because the crane was regularly deployed to other non-timber activities (mainly concreting, rebar and related activities). Whilst the specific time involved in these other activities was subtracted from the timber installation time included in the charted data in Figure 5, it was found from observing the time lapse footage that each deployment acted to prevent the crane from getting back to a consistent and repetitious crane cycle when installing CLT panels, hence resulting in a less productive timber installation process relative to the upper floor levels. Put simply, the cycle lost its rhythm and needed time to re-balance and regain this rhythm.

7.2. A Focus on Wall Panel Installation per Floor Level

The following discussion focuses on the duration of time for installing wall panels on a per floor level basis and therefore represents another subset of the previously discussed, *timber installation days*. Again, as mentioned previously, the wall panel installation sometimes overlapped with floor panel installation on the floor above/below.

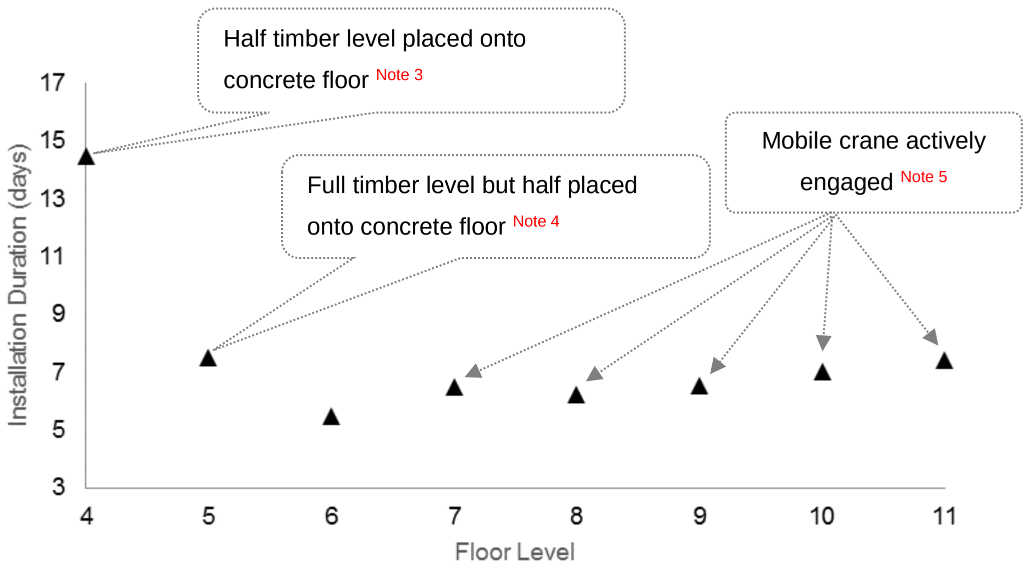

Figure 6: Installation duration of wall panels per floor level Note 1

Notes:

1- *Installation duration per wall is based on start time of the first wall panel placed on a given floor, until the last wall panel placed (minus situations where the crane was used for non-timber activities or where not operating).*
2- *Floor levels shown in the figure are counted from the lowest basement level (as Level 1).*
3- *Floor level 4 involved installation of half a floor area placed onto concrete slab construction.*
4- *Floor level 5, involved approximately half of the timber walls being placed onto a concrete slab.*
5- *Floor levels 7-11 made full time usage of a mobile crane to speed up wall installation speed (previously, it had only been used on an occasional basis); this included carry packs of mainly small and medium sized walls from the staging area to the live deck. Individual panels in the packs were later distributed to the in-situ location using lifts by the tower crane.*

Drawing on data presented in Figure 6, it can be seen that similar to the floor panel installation, wall panels on levels 6-11 represented a relatively stable and fast installation process. Again, the first wall level (level 4) was somewhat lower in productivity given that it was slower and only involved wall panel installation relating to half a floor level. Reduced speed can at least be partially explained by similar reason to those mentioned for the first level of floor panels i.e. more process start-up time; yet to establish a standard process; smaller area with lower economies of scale; concurrent floor and wall construction; yet to benefit from a learning effect. However, of specific importance to this floor is the fact that wall panels were being placed onto concrete slabs and this was slower than equivalent timber wall to timber floor placement. This was due to the greater difficulty in fixing to concrete and in addition, greater tolerance variance in the slab flatness which resulted in more time spent creating a level wall panel (e.g. levelling, shims, grouting procedures etc.). Level 5 was much faster, due perhaps to a learning effect, where half the timber walls were on concrete and half on timber floor panels.

7.3. Overview of Installation Time per Floor Level and Associated Productivity Rates

In bringing the previous discussion into a common framework, data presented in Table reflects the average floor and wall panel installation times of 7.17 and 6.25 days respectively (these averages are taken from individual floor level data presented previously in Figure 5 and Figure 6). These times reflect freestanding activities but as mentioned, in reality, a degree of overlap existed between these activities ultimately resulting in a reduced overall cycle times. To show this, the time with overlap taken into account is shown in brackets in Table 3 and this can be cross checked against previously presented data in Table 2.

Table 3: Average timber installation time per floor level

	Average Timber Installation time per floor level (days)
Floor panels	7.17 (6.3)
Wall panels	6.25 (5.5)
Overall (floor + wall)	11.38 (10.0)

Notes:

1. *These figures are based on timber installation days and therefore exclude winded days, rain days and days where the crane was not operational.*

These times can be broken down further into a number of productivity rates for walls and floors, as shown in Table 4. For instance for floors, the most common (mode) rate in the tower was 78.5 m^2/hour whilst the worst floor was 60.5 m^2/hour and the best 89m^2/hour. As mentioned previously, the floor layout for this project was complex and this is known to impact on productivity. It is therefore noteworthy that only approximately 25% of the floor area involved rectilinear areas and simple setout, so it was interesting to partition-off productivity rates in these areas – especially where laying large panels – as this yielded a much higher productivity rate of 141 m^2/hour.

Table 4: Installation productivity based on crane hours (inclusive of mobile and tower crane usage)

Productivity rate (m^2/h)	Lowest[2]	Mode (most likely)[1]	Highest[2]
Floor	60.5	78.5	89
Wall	44	56	66.5
Total	**57.5**	**74.5**	**85**

Notes:

1- *“Mode” calculations refer to the most common value in a data set i.e. productivity rates for each and every wall (or floor) panel measured in the study; sample details are reported earlier in this section of the report;*
2- *“Lowest” singles out data from the poorest performing floor level (level 5 floors and level 4 walls); and “Highest” singles out the best performing level (Level 9 floors, level 6 walls).*
3- *The “Total” productivity rate have been derived using a weighted average of wall and floor productivity rates. The weights assigned to wall and floor are 0.1775 and 0.8225, respectively. These weights are calculated based on total areas of wall and floor.*

The most common (mode) rate for all CLT walls in the tower was 56.0 m^2/hour whilst the worst floor was 44.0 m^2/hour and the best 66.5m^2/hour. Of note, it shows that when comparing mode values in the table, floor productivity is significantly higher (40%) than wall productivity. To some extent, this is not surprising given that floor panels have gravity working advantageously when landing panels and manipulating them into place, whilst walls have a number of more complex issues including:

- Must be placed vertically including the application of temporary holding braces to stabilise the panels.
- Closing the joints between adjoining panel (e.g. using a turfer tool) takes extra time
- The need to spend time “plumbing” the wall to ensure it is perfectly vertical
- Applying sufficient fixing brackets to allow the work to proceed to the next panel.

It is also notable that walls still only occupied a relatively small panel area on the project compared to floor panels. Based on the sample of floor panels (81%) and wall panels (82%), the ratio of area was still 82% floor panel area and only 18% wall panel area.

One final issue, was the concurrent installation of the steel balcony support structures which were typically being placed on the floor immediately below the live floor, hence requiring split resources and competitive crane usage (as per earlier discussion). To better understand the impact of this, the steel work was measured for 4 floor levels and was found to average 2.1 days per floor level albeit that this largely overlapped with concurrent wall installation activities. Whilst this was obviously a necessary structural aspect of the building, it should also be taken into account when assessing the productivity of wall panel installation.

Adding further to the discussion about wall panel productivity, is the complementary issue of beam installation over openings. On this project, beams were used to span between panels to limit the need to cut openings within wall panels. A good example is the large glass wall/door balcony units shown across the front façade in Figure 7.

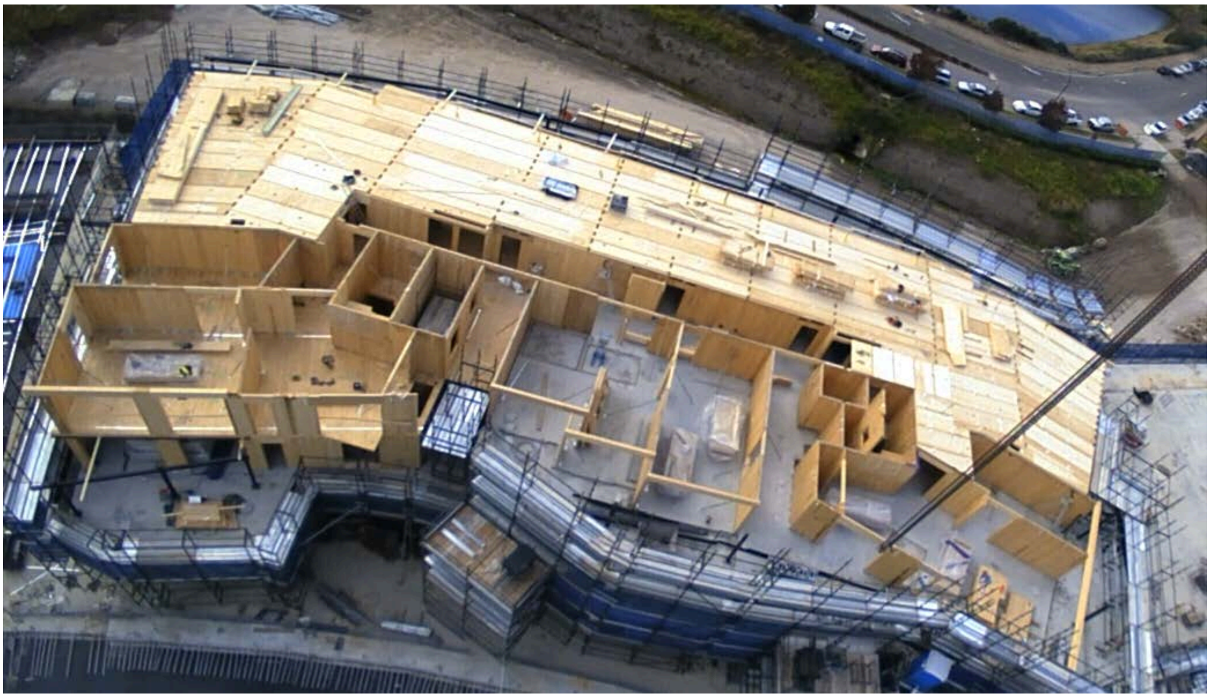

Figure 7: Beams across openings in the apartment layout (Note: significant usage of beams also occurred in the balcony construction albeit not shown in this picture)

The time dedicated to beam placement is incorporated in the previously reported wall panel installation durations for each floor level, but even so, Table 5 presents the beam only productivity rates for a limited number of floor levels, which aims to provide greater detail for strategic design and decision making.   In general, the Table 5 data shows that short beams

– as may occur over internal doors - provide almost half the installation productivity (25m/hour) compared to long beams (48m/hour). Put simply, crane cycles take a relatively similar length of time irrespective of carrying short or long beams. Arguably, the key issue here concerns re-detailing beam-to-panel connections to facilitate faster placement and reduce slow seating of the beam between panels which requires too much accuracy and crane operator vigilance. For instance, if beams ends were not cut at 90 degrees but instead with a more open splay cut, and the same was done to the receiving panel, then the beam could potentially be seated more easily, with less chance of jamming during placement.

Table 5: Beam installation productivity

Beam Type	Productivity (m/hour)	Approximate linear length (meters/per floor)	Sample
Long Beam (≥ 6 meters)	48	100	2 floors
Short Beam	25	75	2 floors

7.4. Investigating Crane Cycle Times

Crane cycle times are important because they represent the main factor influencing the speed and productivity of panel installation. As mentioned previously, two approaches were taken to lifting panels from the staging area to insitu:

- Single movement lifts – single tower crane cycle direct from the staging area to the insitu panel location
- Double movement lifts – involving part one where packs of panels (wall or floor packs) are lifted from the staging area to the deck under construction using a mobile crane; and part two that lifts each individual panel from the landed pack, to its insitu location using the tower crane.

Table 6: Example of crane cycle data capture and pack/panel sizes in each lift (i.e. 5th floor)

Crane cycle times		Duration	Pack Size	Panel size
Start time	Finish time			
7:36:09 AM	7:42:09 AM	0:06:00	Large	Medium
8:06:39 AM	8:14:09 AM	0:07:30	Large	Large
8:14:09 AM	8:20:09 AM	0:06:00	Large	Large
8:51:39 AM	9:00:09 AM	0:08:30	Large	Large
9:00:09 AM	9:05:39 AM	0:05:30	Medium	Large
9:11:09 AM	9:16:09 AM	0:05:00	Small	Large

Table 6 shows the method of logging crane cycle times for the 1075 cycles measured in the study. It also shows the panel and pack sizes lifted in a given crane cycle and this is useful base information, in comparing and evaluating single movement and double movement crane cycles. Reading from Table 7 it can be seen large panels equate to a mean size of 12.39m^2, medium 7.6m^2 and small 2.8m^2. Reading from Table 7 it can also be seen that double movement lifts involved packs with large panels which averaged 2.89 panels per pack, medium panels that averaged 3.25 panels per pack, and small panels that averaged 3.95 panels per pack. This base information is particularly useful latter in the ongoing analysis.

Table 7: Parameters for panel size

Floor Panel Category	Panel size			Mean No. of panels per pack (where lifted as packs)
	Minimum Area (m^2)	Mean area (m^2)	Maximum Area (m^2)	
Large	10.59	12.39	14.19	2.89
Medium	5.31	7.6	9.88	3.25
Small	0.76	2.82	4.88	3.95

Note: Panel size categorisation was based on medium being a proportion of large (0.5×Min size $_{Large\ panel}$ <Medium size< 0.7×Max size $_{Large\ panel}$) and small being a proportion of large (Small size< 0.5×Min size $_{Large\ panel}$)

Figure 8 shows that the most common cycle time (mode) for a single lift was 7.5 minutes and the vast majority of such lifts were for large panels (i.e. 12.39 m^2). Obviously, comparison of this needs to be made in terms of time efficiency relative to double movement lifts which is discussed in further detail below.

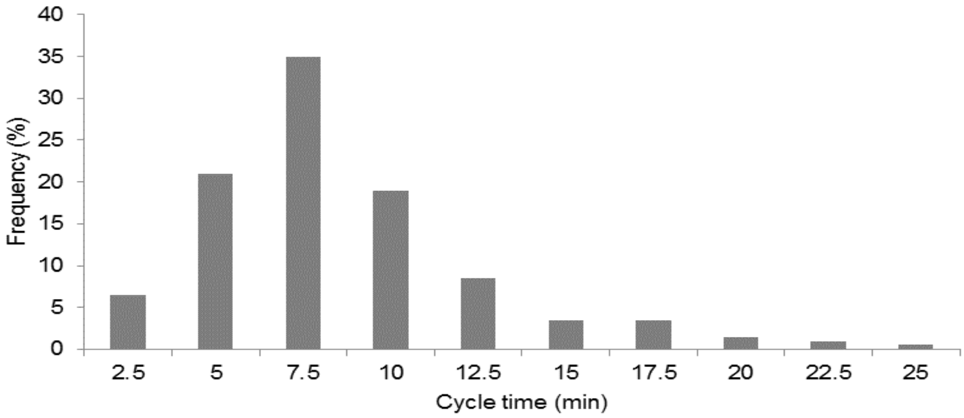

Figure 8: Frequency of crane cycle times for single movement lifts when handling large panels (i.e. n=277 of which the vast majority were for large panels)

In considering the same analysis but using a double movement, a key issue is that the first stage involves lifting packs of panels and then the second stage reverts back to a single lift process as analysed in Figures 9 to 11. Therefore for the first stage, Figure 9 shows that large packs having an average panel area of 35m^2 (±5m^2) mainly involved 5 minute cycle times. In Figure 10, the cycle time was much the same for medium size packs, having an average area of 25m^2 (±5m^2). In Figure 11, this dropped only slightly to 4.5 minutes for small packs, having an average surface area of only 15m^2 (±5m^2). What can be said from this modal data is that where possible, it is best to lift large packs because it affords 2.3 times the lifted area compared to small packs but only takes 11% longer – hence a very minor time penalty.

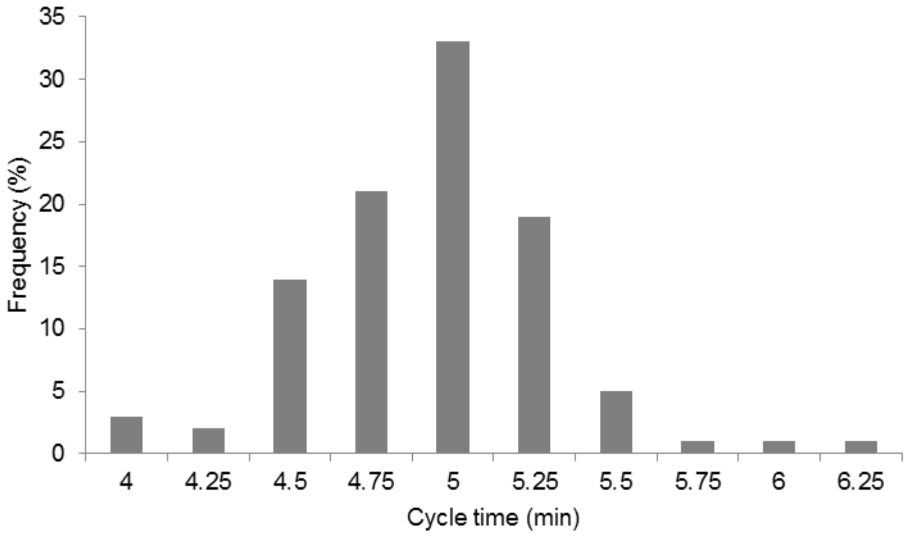

Figure 9: Frequency of crane cycle times for the first part of double movement lifts - Large packs (n=32; average surface area of the lifted packs= 35m^2±5)

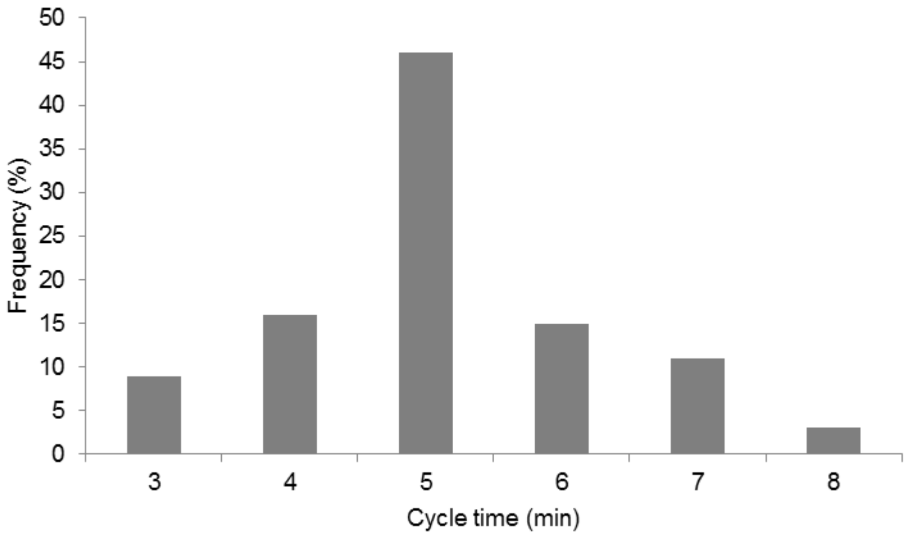

Figure 10: Frequency of crane cycle times for the first part of double movement lifts - Medium packs (n=46; Average surface area of the lifted packs= 25m^2±5)

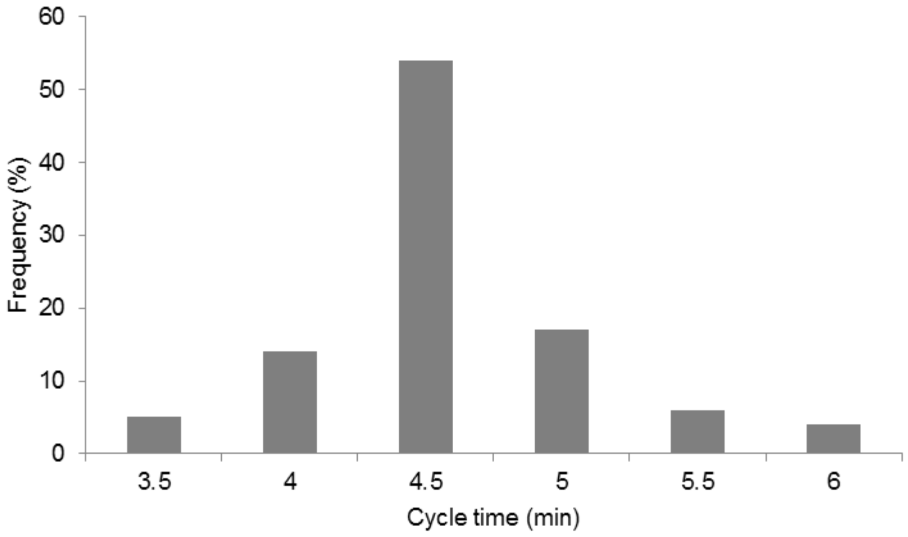

Figure 11: Frequency of crane cycle times for the first part of double movement lifts- Small packs (n=99; Average surface area of the lifted packs= 14m^2±4)

Moving now to the second part of the double movement which reverts back to lifting a single panel from pack to insitu, data is presented in Figures 12 to 14. It can be seen from Figure 12 that for large panels having an average area of 12.4m^2 (±1.8m^2), the most common crane cycle was 6 minutes. Medium sized panels (refer Figure 13) having an average area of 7.6m^2 (±2.3m^2), was less at 4.5 minutes. This time was the same for small panels (refer Figure 14) having an average area of 2.8m^2 (±2.1m^2). Again, this indicates a similar trend to pack lifts insofar as large panels take a little longer but place a much larger panel area insitu. For instance, average large panels are 4.4 times larger than average small panels but take only 33% longer to place.

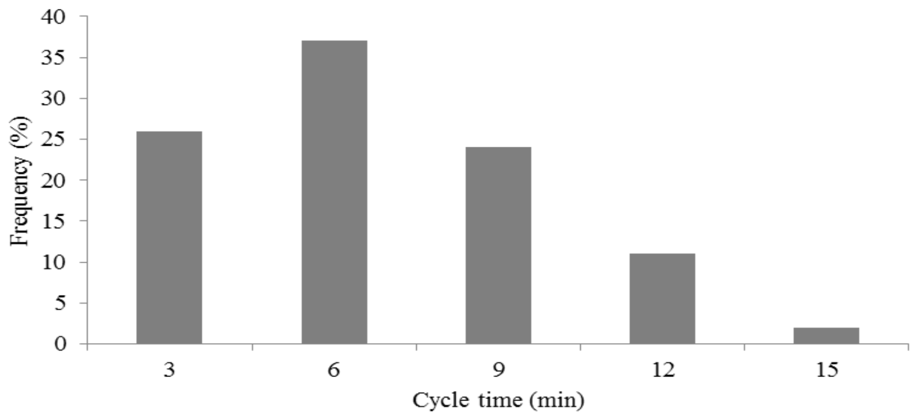

Figure 12: Frequency of crane cycle times for the second part of double movement lifts- Large floor and wall panels (n=75).

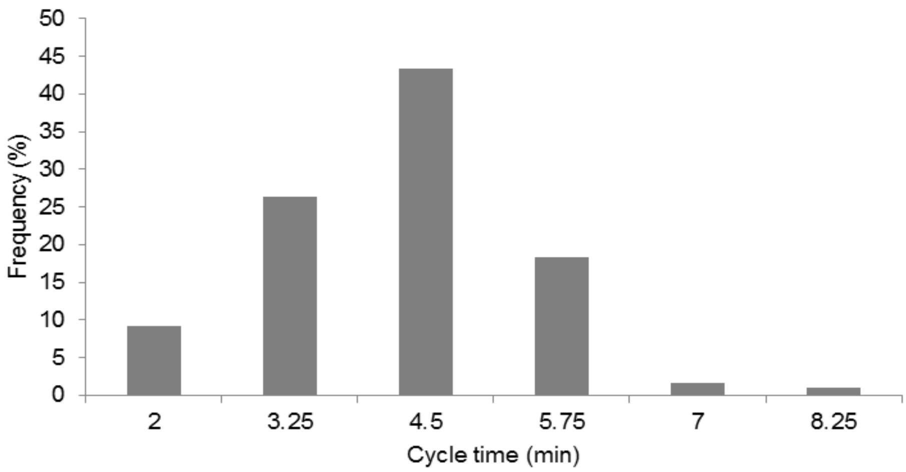

Figure 13: Frequency of crane cycle times for the second part of double movement lifts- Medium floor and wall panels (n=136).

It is also worthwhile considering which is the best lifting strategy – a single or double movement strategy - and in what situation each is best applied? For instance, whilst double movements in theory involve a degree of double handling, there are other practical factors to consider on construction sites such as the need for inventory storage space and lack of free site area. The ability to manipulate storage space by using the live deck could potentially assist this issue and if so, provides certain practical advantages.

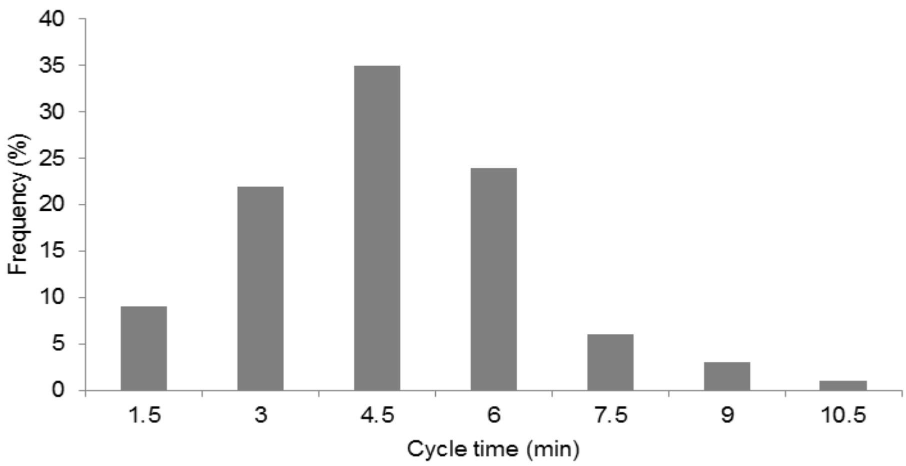

Figure 14: Frequency of crane cycle times for the second part of double movement lifts - Small floor and wall panels (n=410)

To some extent this can be modelled using the data discussed above. For instance, if assuming a double movement lift for large packs (35m^2) which commonly involves a 5 minute crane cycle for the first stage (as taken from Figure 9), and assuming the second part could involve large panels (12.39m^2) with commonly take a 6 minute crane cycle (refer Figure 12) which would apply to approximately 3 panels in the packs, hence 18 minutes, this would equate to a total of 23 minutes to get all 35m^2 of panels from the staging area to the insitu location. Therefore, 35m^2 divided by 23 minutes equates to 1.52m^2/minute. If this is compared to single panel lifts of large panels, the most common cycle time is 7.5 minutes (refer Figure 8) and so 12.39m^2 divided by 7.5 minutes equates to placement of 1.65m^2/minute. This suggests that single lifts may be marginally faster but an alternative perspective is that the difference in real terms may vary according to circumstance and so the margin is not large enough to be confident that one method is better than the other – especially if one method suits other site-specific criteria better than the other i.e. if one method better deals with inventory or the preferred laying method. More study is required to assess this with greater confidence.

7.4.1. The Reliability and Rhythm of crane cycles

It is apparent from earlier discussion that creating a reliable and rhythmic crane cycle is pivotal to achieving high productivity. For those interested in improving in this area, statistical methods typically applied in manufacturing provide improved understanding. Figures 15 to 17 show the extent to which different samples of crane cycles correspond to a statistically uniform distribution. This includes details on the standard deviation which shows how far the overall set of crane cycles, vary from the mean value. The *coefficient of variation* is also provided which is a measure of relative variability that can be used to compare different sets of crane cycles performed. It is the *ratio of the standard deviation to the mean (average)* and can be expressed as *a percentage*, making it easy to compare different sets of crane cycles. These measures provide indicators of crane cycle reliability and rhythm.

Figure 15 plots crane cycle times for a sample of 32 consecutive single panel lifts on level 7 with an average (mean) cycle time of approximately 8.5 minutes and where most (22 out of 32 cycles) of the data falls within one standard deviation (2 minutes) which equates to a low coefficient of variance from the mean of 23%. This indicates that the cycles were relatively well controlled, where most were only oscillating as much as one standard deviation (i.e. 2 minutes) from the average cycle time (i.e. 8.5 minutes) which led to high panel installation efficiency.

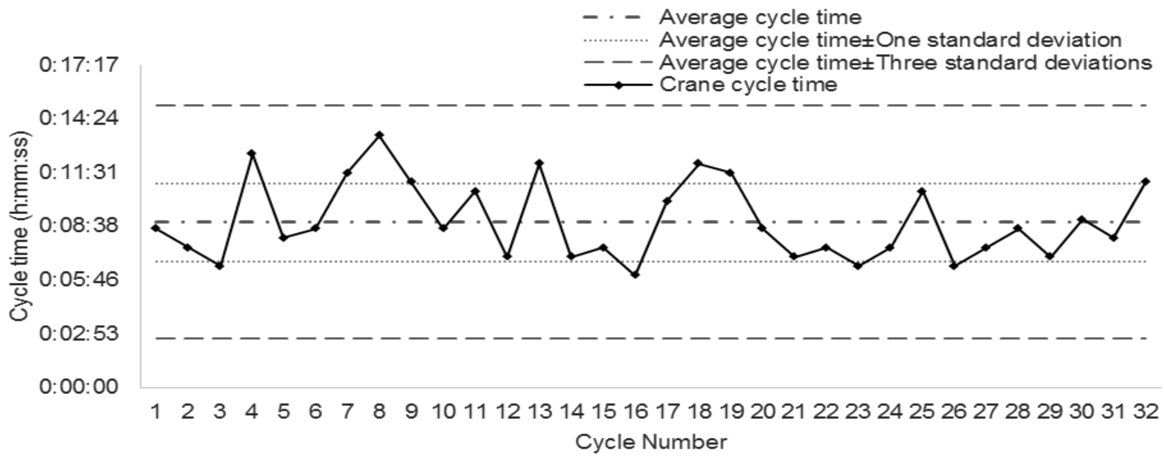

Figure 15: Crane cycle times for single movement crane cycles (n=32 samples)

The crane cycle times for first part of a double movement cycle on the same level (level 7), are shown in Figure 16. This involved lifting 26 packs of panels from the staging area to the deck. In this case, the average lifting cycle time for packs was 5.1 minutes with a 1.4 minute standard deviation which again equates to a low 27% coefficient of variance. As may be expected, this lift was relatively simple because packs are placed on the floor deck in virtually any interim location, and unlike panels, do not need to be manipulated into final position. To some extent this consolidated by the fact that 21 out of 26 lifted packs were laid within one standard deviation above or below the mean crane cycle time.

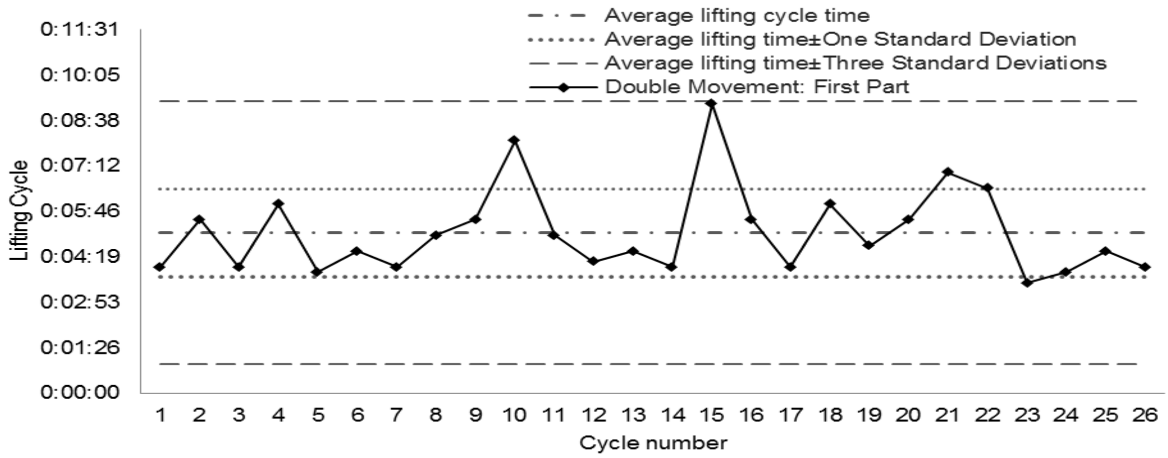

Figure 16: Crane cycle time for the first part of double movements (n=26 samples)

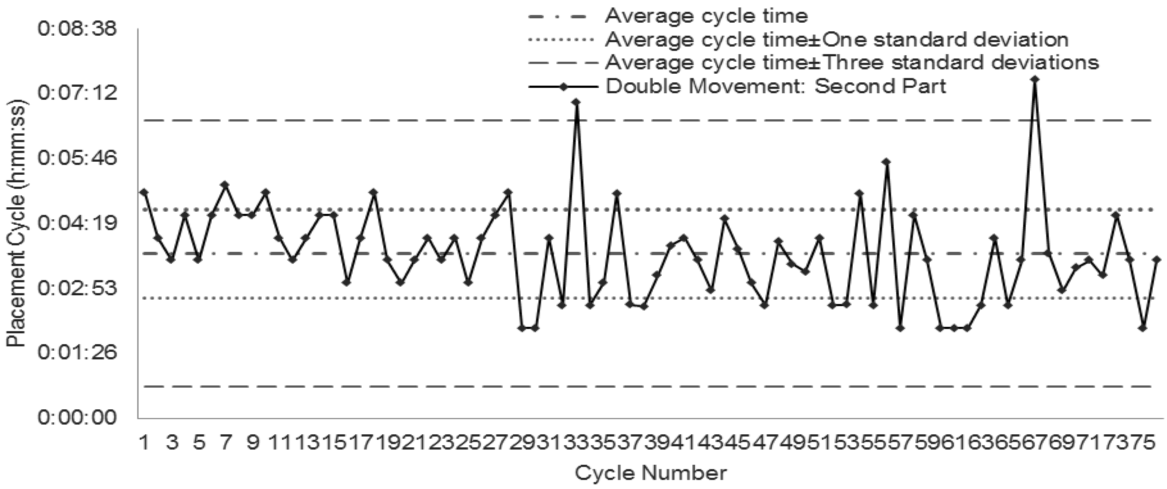

Figure 17: Crane cycle time for the second part of double movements (n=75 samples)

Stage two of the double crane movements is shown in Figure 17 including 75 crane cycle times for distributing panels from on-the-deck packs to their final in-situ locations on level 7. On average, this second movement was 3.65 minutes per cycle with a standard deviation of 1.1 minutes which equates to a coefficient of variance of 30%. Moreover, there were still two outliers (removed from the above calculations) which took 7 minutes and 7.5 minutes respectively to pick up small panels from the pack and place them in-situ. One belonged to an irregularly shaped panel and the other was the last panel placed in a section of the floor area. If these were included in the above calculations then of note, the coefficient of variation would have been significantly higher and would the presence of too many outliers suggests a cycle that does not conform to a reliable rhythm.

8. Conclusions

This study used photogrammetry methods to measure installation productivity of CLT panels in a medium-rise timber building. Analysis of the captured data indicated that an average floor cycle of 10 *timber installation days* per floor, was achieved for a large and complex shaped floor plate area of 1280m^2. Of note, the floors and walls layout of the case project had a complex and non-rectilinear architectural form which is known to significantly impact on productivity – this should be taken into account when making comparison with other construction methods.

The study proved different installation speed for floor panels and wall panels. For the CLT floors, the most common (mode) rate in the tower was 78.5 m^2/hour where the worst performing floor level was 60.5 m^2/hour and the best 89m^2/hour. It is noteworthy that approximately 25% of the floor area involved rectilinear areas and so it was interesting to partition-off productivity rates in these areas – especially where laying large panels – as this yielded a much higher productivity rate of 141 m^2/hour. The most common (mode) rate for all CLT walls in the tower was 56.0 m^2/hour where the worst performing floor level was 44.0m^2/hour and the best 66.5m^2/hour.

Of note, the above findings show that floor productivity is significantly higher (40%) than wall productivity, when comparing mode values. To some extent this is not surprising given that floor panels have gravity working advantageously when landing panels and manipulating them into place, whilst walls must be placed vertically including the application of temporary holding braces to stabilise the panels. Closing the joint between adjoining panels is also harder. There is also the need to spend time “plumbing” the wall to ensure it is perfectly vertical and then applying sufficient fixing brackets to allow the work to proceed to the next panel.

Crane cycle times are important because they represent the main factor influencing the speed and installation productivity. The case project used a fixed tower crane and a mobile crane. The cranes operation involved two lifting strategies namely single movements or double movements: the single movement strategy (lifting directly from the staging area to the insitu location) and; the double movement (where panel packs are lifted onto the live floor deck and then a second lift places individual panels insitu). The former allows good productivity when installing large panels. The double movement strategy is very marginally less productive but this method may also work better in managing pack inventory and buffer times because packs can be lifted to the live deck, thus freeing up limited site space. Using the mode cycle, productivity rate of the single movement strategy was approximately 1.65m^2/minute. Under the double movement strategy and using large panels, the productivity rate was1.52m^2/minute.

The presented data also serves to demonstrate the importance of creating a reliable and rhythmic crane cycle when installing panels. The coefficient of variance was introduced as a tangible metric for recognizing a well-controlled installation process. Achievement of this should be given priority in day-to-day site operations.

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