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Measuring Installation Productivity on Panelised and Long Span Timber Construction

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Level 11, 10-16 Queen Street
Melbourne VIC 3000, Australia
T +61 (0)3 9927 3200 E info@fwpa.com.au
W www.fwpa.com.au

Forest & Wood Products Australia

Measuring Installation Productivity on Panelised and Long Span Timber Construction

Prepared for

Forest & Wood Products Australia

By

Professor Perry Forsythe, Richard Brisland and Dr. Samad Sepasgozar
University of Technology Sydney

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Researcher/s:
Professor Perry Forsythe, Richard Brisland and Dr. Samad Sepasgozar
Faculty of Design Architecture and Building,
University of Technology Sydney

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Forest & Wood Products Australia Limited
Level 11, 10-16 Queen St, Melbourne, Victoria, 3000
T +61 3 9927 3200 F +61 3 9927 3288
E info@fwpa.com.au
W www.fwpa.com.au

Executive Summary

Panelised prefabricated timber construction offers a fast and productive site installation process. Cranage provides the lead resource as it dictates the speed of installation – optimising crane time is central to optimising productivity.

This study used time lapse photography on 5 active case study construction sites to measure installation productivity. Net crane time was used as the basis for measuring productivity, being the time dedicated purely to crane cycles involved directly in installing prefabricated timber panels (521 cycles were measured relating to the installation of 5,592m^2 of panels). Other contributors to Gross crane time and general down time must be added to these productivity figures to estimate overall program time. For instance, Gross crane time can include issues that are only peripherally related to the timber installation aspect of the project such as unexpected stoppages, miscellaneous handling of other materials, and crane operation attributes (setup time, take down time, and scheduled breaks). Down time is where the crane is sits unused. Such criteria often go beyond the pure needs of prefabricated timber installation and relate to project-wide scheduling issues. In general, the findings indicate the following guidelines:

- Larger panels take slightly longer to place than smaller panels but this minor extra time is more than offset by the increased area installed per hour.
- On the 2 and 3 level buildings studied, no statistically significant difference existed in terms of the time for crane cycles for each separate floor level. This situation may change on taller buildings especially where wind will likely slow upper floors.
- The greater the synchronisation between the crane and installation crew, the better the overall productivity. Here, the crane crew is often supplied as a fixed part of the overall crane package and so the installation crew is the main labour variable of interest because it can be more readily up-scaled or down-scaled according to perceived need. Only small crews were required on the sites studied: the crew for pre-clad wall panels project ranged from 2-3 workers, crews for cassette projects ranged from 3-4 workers, and the crew for the CLT project still only involved a relatively small 5 workers. This may not need to change much for larger projects.
- Variances in productivity within each panel type (refer Table 1) is a function of the size of the project, the appropriateness and inherent efficiency of the chosen prefabrication system, delivery logistics, and the prevailing on-site work environment (including work flow, wind, site access, rain, and safety requirements). The efficiency and appropriateness of crane selection is particularly important.

- Care in pre-construction and offsite production planning are important including early pre-fabricator involvement, panelising the architectural design with a view to creating economies of scale, designing-in structural efficiency, providing accurate dimensional tolerances and installation friendly delivery logistics.

- Floor panel installation productivity tends to be somewhat faster than the general panel average. Contributing factors include less exposure to wind and greater assistance by gravity when placing floor panels compared to wall panels. Wall panels are also slower due to the greater time and accuracy required in aligning and positioning walls, dealing with floor flatness tolerances and greater need for temporary bracing and cramping (especially CLT wall panels).

Average crane productivity rates for panels (including overall plus individual panel types) are provided in Table i. Of note, pre-clad walls and CLT rates are based on relatively small samples (a single case study each). The CLT project was also a large house and tight site, and so it is felt that productivity rates would likely be better where applied to larger, repetitive projects. Consequently, the stated figures must be taken in terms of the context of the projects studied. Verification from ongoing research will provide greater confidence in generalising findings to other projects.

Table i: installation productivity rates

Panel type	**Average Installation productivity (based on net crane hours)**	
	Typical rate (crane hours/m2)	**Outliers removed (crane hours/m2)**
All panels (include below)	67.4m^2/crane hour	79.8m^2/crane hour
Floor/roof cassettes only	83.1m^2/crane hour	100.1m^2/crane hour
Pre-clad wall frame panels*	66.65m^2/crane hour	77.47m^2/crane hours
CLT floor panels*	80.03m^2/crane hour	84.88m^2/crane hour
CLT wall panels**	26.59m^2/crane hour	32.85m^2/crane hour

"*" Denotes small sample and for CLT wall panels denotes odd shaped walls in sample

Ongoing research work aims to focus more on holistic productivity issues surrounding the delivery of entire structure/envelope solutions which and the interface with other trades, which goes beyond the installation of individual panel assemblies (as analysed in this study).

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1. Introduction

The key aim of this project was to quantitatively measure the site installation productivity of prefabricated panelised and long span timber construction. The method focused on undertaking case studies of active projects using time lapse photography – thus allowing a contemporary approach to *time-and-motion* studies (Groover 2007) and the application of statistical methods of data analysis. The focus was specifically on cranage and labour resource usage and from this, productivity rates (m^2/hour) concerning installation were derived. From this, the study explores and demonstrates what is achievable concerning the installation productivity of prefabricated timber assemblies from a construction process perspective, including the following objectives:

- To help develop an evidence-based understanding about prefabricated timber in terms of installation productivity.
- To provide information that will assist construction managers and other stakeholders about preferred processes, design details and underlying assumptions concerning prefabricated timber productivity.
- To help improve confidence in providing project management benchmarks for the productivity performance of prefabricated timber construction.
- To provide guidance concerning areas where there is potential for process improvement.

2. Background and Rationale

It is well known that construction projects have many different stakeholders brought together under temporary arrangements, with complex supply chains and specified project outcomes, hence reducing the ability to control the productivity environment in the same way as manufacturing settings (Blismas 2007). Productivity is important to anyone who is responsible for supervising, estimating, accounting and paying for the resourcing of trades work on construction projects. Over the years there has been constant pressure to improve productivity performance as driven by the likes of total quality management (Easton & Jarrell 1998), construction process reengineering (Love & Li 1998) and continuing efforts at utilising lean production principles in the construction industry (Jørgensen & Emmitt 2008). Prefabrication serves as a physical manifestation that encapsulates a number of these themes and is of central relevance in this study. Unfortunately, progress in making it become a common reality in Australia has been slow.

Part of the issue is the need to compare and prove the efficiency and economic benefits of prefabricated construction over traditional methods. Having information that helps confidently predict productivity levels when using prefabricated assemblies is clearly a step in the right direction. It allows greater accuracy and objectivity in making comparisons and less conjecture. It allows all of those involved in the construction supply chain greater confidence in predictably improving performance.

Despite this need, the design, contracting, quantity surveying and cost engineering professions appear to have relatively little information at hand when making such comparisons. Confident predictions are hard to make and so extra cost is allowed to protect against risks and uncertainty when compared to better-known methods. Of note, there is little known about new installation methods of prefabricated timber construction and this acts as an impediment concerning its cost competitiveness when pitted against traditional construction.

Given the above, a measured approach to productivity should serve to allow improved comparison between timber and traditional construction including an improved ability to calculate associated cost savings.

3. Reporting Structure

This report covers the following:

- Literature based principles around construction productivity measurement.
- Key prefabricated timber assemblies (upon which this study is based).
- Details concerning the research methodology.
- Quantitative data analysis (i.e. measured site productivity).
- Qualitative data analysis (i.e. interview data from supply chain participants and linked. site observations that help provide greater insight to the quantitative findings).
- Discussion, conclusions and recommendations.

4. Principles Surrounding Construction Productivity Measurement

Studies focusing on on-site productivity are still said to be relatively scarce in the academic literature and not much attention has been paid to construction productivity metrics (Yi & Chan 2013). Productivity ostensibly concerns the conversion process of input resources to output quantities (Thomas et al. 1990). The main resources include labour, materials and plant but these are impacted by the likes of project management expertise, labour skills, work practices, work environment, information technologies and certain climatic conditions.

Prefabrication technologies change the way that labour, materials and plant resources are deployed on-site. For instance, greater value adding to materials takes place off site; plant such as cranage plays a stronger role on-site; site labour plays less of a lead role and more of a support role in supporting cranage operations.

Early work on construction productivity has mainly focused on labour productivity. The United Nations (1965) began by identifying two major factors that affect site labour productivity:

- Organisational continuity – which ostensibly concerns the definition of the work that needs to be done and;
- Executional continuity – being the work environment and how well the job is organised and managed. This category especially applies to the main area of focus in this study.

Adrian and Boyle (1976) were instructive in setting out the main issues involved in measuring productivity at an on-site, activity specific, level of detail. For instance, they assert that for a given construction activity there is:

- The need to identify a production unit which can be visually measured. A unit that is too broad may be of limited use in explaining how to improve productivity; units that are too small (such as the time it takes to lay a single brick) may exclude too many aspects of the overall work process to be informative (Adrian & Boyer 1976). In this study the focus is on the square meterage of installed wall and floor areas, and the lineal meterage of installed beams.
- A production cycle relating to the time between consecutive occurrences of the production unit. In this study the focus is on the cycle time in lifting and fixing timber

assemblies into place. This also includes concurrent labour plus any preparatory or trailing activities required to complete the installation process.

- A leading resource as required by the production method. In this study, the lead resource involves crane usage to lift assemblies into place, as facilitated by on-site workers.

Principles of work sampling in construction productivity studies involve the work being broken down into a series of stages, where each stage is composed of one or several operations; each operation is performed by a specific trade, typically defined in jurisdictional or subcontract terms (Buchholz et al. 1996). The focus in this study has purely been on the cranage and installation crews (for prefabricated assemblies and as relevant to defined work areas). This effectively means that there is an inbuilt exclusion of unwanted intervening variables such as sick leave, vacations and holidays. 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 project wide “noise” or irregular events, they disrupt the overall project work environment, rather than relating to a specific work activity. Such issues prevent a reliable and predictable process from being measured in a way that can be compared and used elsewhere. Along a similar vein, Ellis et al (2006) cite the concurrent need to establish a database of standard and relatively homogenous tasks within targeted trade activities, and whilst these tasks typically cause a degree of variance, they also occur within the context of a relatively well-known work process. Accordingly, the above principles have been applied in this study.

It is also apparent from the literature that there are macro, micro and case specific levels of studying productivity (Edkins & Winch 1999). The main differences between these options include the sources of data, the level of data aggregation, the boundaries defining production processes, and the completeness with which productivity processes are described (Chau & Walker 1988). For instance, given the stated aims and exploratory nature of this research, there is a distinct need for detailed case study data in order to define, measure, and sufficiently understand productivity issues relating to daily on-site processes, and to develop a framework for measuring productivity in a way that can be used by the industry at large.

4.1 Productivity Concepts

As alluded to previously, there is a natural tendency in productivity studies to focus on the lead resource for a given process and this often involves a single factor approach to productivity as distinct from a total (or multi) factor approach (Rakhra 1991). For instance, in past studies there has been an obvious focus on labour usage as distinct from the cranage focus which is more central to this study. Even so, conceptual guidance can still be gained from labour productivity studies in terms of the underpinning principles of measuring input hours compared to output products (Hanna et al. 2008; Sonmez & Rowings 1998; Thomas & Yiakoumis 1987). At its core, productivity has been expressed by authors such as Thomas and Matthews as: *Productivity = actual hours worked/installed quantity* (Thomas & Mathews 1986). Whilst there is no debate about the main variables involved, it is clear from first-hand experience, that in the Australian context, it is more common to express the productivity ratio in an inverse way to the above, whereby: *Productivity = installed quantity/actual hours worked.* Of note, it is thought to be simpler to mentally process in so far as, the greater the number from the calculation, the higher the productivity. This contrasts with Thomas and Matthews approach where the lower the number from the calculation, the higher the productivity.

In addition to the above, Thomas & Zavrski (1999) identified the need to determine the baseline productivity for a given unit which represents "the best and most consistent productivity for a particular project or database (of productivity measures)" (p. 5). They also introduce the concept of a standard item of work and this is used to create expected work outputs for standard work and "conversion factors" for work that is non-standard but needs to be compared to standard work.

Thomas and Zavrski (1999) also conceptualised project wide performance. This not only considers the above focus on individual work activities but other differences brought about by things like design, management and the weather. With this in mind they proposed 6 parameters (p. 14) for the performance of individual projects including:

- Variability in daily productivity i.e. where there is high variability in daily labour productivity.
- Baseline productivity and work content i.e. the best productivity is when there are few disruptions; as work complexity increases, the baseline productivity decreases.
- Cumulative productivity i.e. the overall effort required to install work.
- Number of abnormal days i.e. such days may reduce productivity by as much as half relative to baseline productivity.

- Total work days.
- Total work hours.

It is considered that there is potential for the current study to utilise a number of the basic tenets put forward by Thomas and Zavrski's (1999) methodology – to suit the specific aims of the project – but with a view to a simplified approach that can be readily undertaken on-site and utilised by industry practitioners.

5. Prefabricated Construction to Improve Productivity

Given the previous discussion, it is worth considering some of the underlying reasons and issues that motivate the use of prefabricated construction. The basic intent is captured in Figure 1 by showing the differing degrees of moving the work offsite to industrialised manufacturing processes, and subsequently reducing on-site processes.

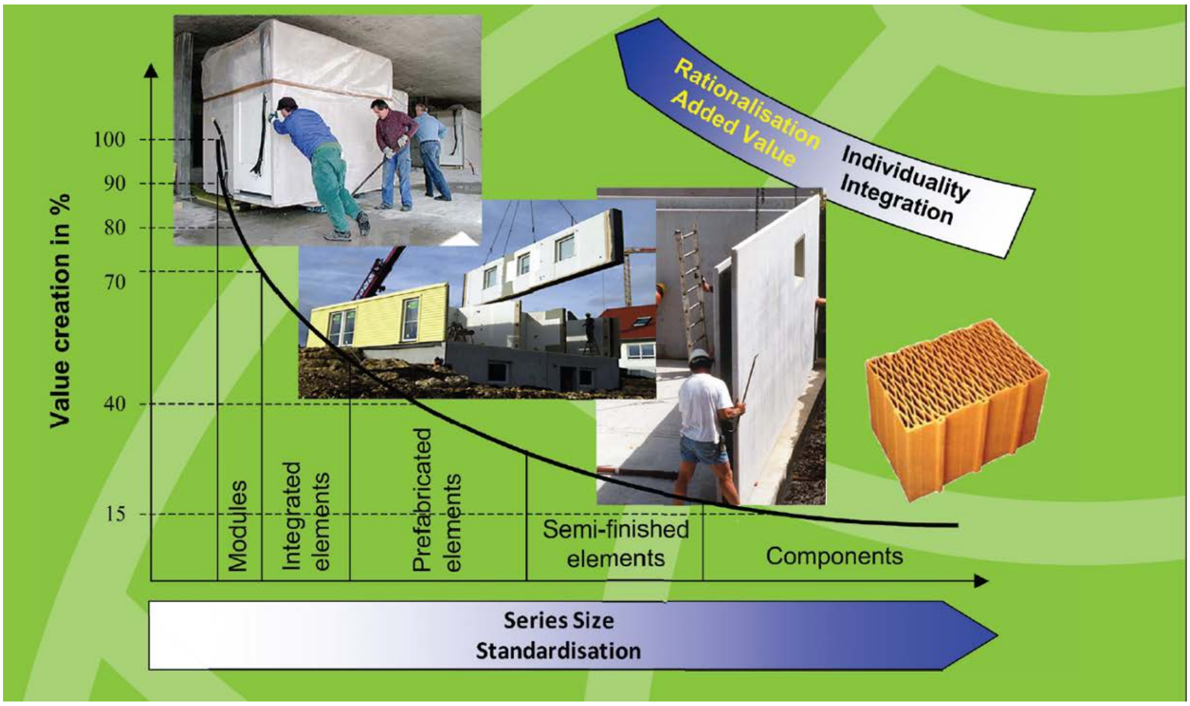

Figure 1: Cover page excerpt from “New perspective in industrialisation in construction”, (CIB 2010).

Reading from the graph in Figure 1, it can be said that most timber prefabrication approaches currently utilised in Australia currently involve components (e.g. engineered beams) and a degree of semi-finished elements (e.g. lightweight trusses and wall frames). More advanced prefabricated elements – such as the relatively new but growing market of floor cassettes, roof cassettes, pre-clad wall frames and Cross Laminated Timber (CLT) panels cut-to-size – are still in their infancy in the Australian market, but represent the primary prefabricated elements of interest in this study. Each is dealt with briefly below.

5.1 Cross Laminated Timber (CLT)

The CLT concept comes out of Europe and can be applied to buildings as small as individual houses, and at the time of writing, up to 10 story apartment buildings, see for example Lend Lease (2016).

The focus is on a holistic superstructure solution including floor, wall and roof panels (refer to Figure 2 and 3). The thickness and diaphragm action obtained by CLT panels provides reasonably good structural performance as well as varying degrees of inherent thermal and fire insulation – thus reducing the need for dedicated trades or separate systems in these areas. A *file-to-factory-to-site* approach is commonly adopted by CLT manufactures including the use of 3D digital models (i.e. BIMs) that can be input directly into Computer Numeric Cutting (CNC) manufacturing technology capable of automatically and accurately cutting wall, floor and roof panels in the factory. Window and door openings can be accurately cut from the panels as can “chases” for building services. Digitally assisted technology can also be utilised to assist site delivery and installation logistics. CLT is dimensionally stable and lightweight relative to concrete construction. The latter provides for lighter weight cranage options on-site.

Figure 2: Cross Laminated Timber wall temporarily panels braced during construction.

Figure 3: Panels being manoeuvred into position.

5.2 Cassettes and Pre-Clad Wall Frames

Cassettes and pre-clad wall frames are relatively new to Australia but are essentially a simple extension of existing frame and truss prefabrication methods. Cassettes typically consist of multiple floor sheets (plywood/OSB/particleboard) fixed to underlying joist framework of either parallel cord floor trusses or engineered timber joists. The cassettes can also be applied to certain flat roof or low pitched skillion roof situations. The cassettes are structurally designed using commonly available timber design and manufacturing software (which in practice provides a *file-to-factory-to-site* approach). The resulting modular assemblies are then craned into position on-site, as shown in (Figure 4).

Figure 4: Floor cassettes during installation.

5.3 Pre-Clad Wall Frames

Similar to the above, some frame and truss manufacturers have extended from open stud wall frame manufacture (conventional lightweight timber wall framing) to pre-clad (or pre-sheathed) walls which may also include the offsite installation of window and door units. This aims to provide a weather resistant structure very quickly for the builder.

Figure 5: Walls panels with openings cut using CNC technology.

5.4 Engineered Beam Assemblies

Whilst the mass production of certain engineered timber beams (e.g. LVL, Glulam) is relatively common in Australia, an arising advancement that takes it beyond commodity level production is the addition of various slot-in or drop-in style metal plate connectors for post and beam construction, thus providing a more concise kit of parts that can be rapidly assembled on-site with little or no further cutting and processing on-site.

5.5 Issues Concerning Prefabrication

Quantitative studies into the productivity of the above technologies appear to be currently non-existent in Australia. None could be found that actually measure productivity in any level of genuine detail. At best, a pilot study was undertaken by Blismas (2007) who observed 7 case study projects using various methods of construction. The project found that there are numerous drivers and benefits of prefabrication with an edited list of relevance to this study, including:

- Reduced construction time.
- Simplified construction processes.
- Higher quality, better control and more consistency.
- Reduced costs when resources are scarce, or 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.

However, prefabrication also raises challenges that need to be overcome. An edited list of barriers thought to be of potential relevance to this project include:

- Lengthened lead times.
- Difficulties in implementation due to the high level of fragmentation in the industry.
- High set-up costs to manufacture.
- Loss of control on-site by deploying processes to the offsite supply chain.
- A lack of skills in design/manufacturer/supplier concerning prefabrication.
- Difficulties in inventory control.
- Constraints due to site conditions.
- Interface problems on-site due to low tolerances.

Issues of this nature are considered as a matter of course, in this ongoing study.

6. Research Methods

As mentioned in the introduction, a modern take on "time and motion" study was used as the main basis for meeting the needs of the project in obtaining productivity data (Groover 2007). This approach was applied to a number of case study projects (5 projects in total). The selection of the case study projects was somewhat guided by contractors who were prepared to participate in the study and the availability of suitable prefabrication projects. Ultimately, the case study projects shown in Table 1 were drawn from cities along the eastern seaboard of Australia, spanning from Melbourne to Brisbane. Time lapse photography was utilised to capture work processes on all the sites studied. The main interest was in upper storeys where crane handling was involved. Quantitative measurement was undertaken on crane cycle times and site labour used to load and install prefabricated assemblies. In total, 521 crane cycles were recorded and measured. As stated previously, the aim was to derive a unit rate for the installation productivity of prefabricated timber assemblies (e.g. the amount of floor, wall, or beam installed per hour).

Table 1: Case study sample details.

Project No.	**Building type**	**No. of dwellings**	**Floors levels above ground**	**Prefabricated assemblies measured**	**No. of Crane cycles and related floor levels**	**Crane type**
1	Apartment building	18	3	Floor and roof cassettes	158 (2 upper floors and roof level)	Mobile crane (130 tonne, 45m reach, 1.2 tonne capacity).
2	Townhouses (complex of 2 rows)	12	2	Floor cassettes; pre-clad framed walls	72 (upper floor level) 116 (ground and upper floor walls)	Delivery truck with remote control crane (20m reach; 1 tonne capacity)
3	Apartment buildings (3 buildings)	55	3	Floor cassettes	60 (upper floor levels)	Remote controlled, fixed hammerhead crane, (40 metre reach, 1 tonne capacity.
4	Townhouses	2	2	Floor	10 (upper	Mobile crane (20 tonne, all terrain, 15m reach,

Project No.	Building type	No. of dwellings	Floors levels above ground	Prefabricated assemblies measured	No. of Crane cycles and related floor levels	Crane type
	(single building)			cassettes	floor level)	1.5 tonne capacity)
5	Large dwelling (steep site, difficult access)	1	2	CLT wall and floor panels, engineered beams	33 floors (upper floor levels) 52 walls (ground and upper floor wall levels) 20 beams (roof level)	Mobile crane (40 tonne, 20m reach, 2 tonne capacity)
Total		**88**			**521**	

Additional notes:

1. There was very little difference in floor-to-floor height of the above projects ranging from 3000mm – 3300mm.
2. Crane capacity should be taken as capacity at full reach.

6.1 Units of Measure, Data Gathering Scope, and Time Lapse Photography

As mentioned, crane cycle time (measured in hours) was the main unit of interest as it represented the lead resource used in installation processes – other tasks were ultimately tailored around the crane cycle as it represented the most expensive single resource involved. Even so, labour was still important in both facilitating crane processes and contributing to installation activities. Labour was therefore measured for:

- The crane crew (measured in man hours) including the crane operator and dogman.
- The installation team (measured in man hours) including carpenters and/or riggers – they prepared the work area, unloaded the panels at the workface and fixed them in place.

Of note, project management staff were not included in the productivity calculations as they were considered to provide managerial infrastructure across the entire project, and were therefore not specific to the work package being focused upon. In addition, any other labour resources that were not directly involved in handling the materials and using tools or equipment to install them, were excluded from the productivity measurement. Consequently, things like safety management and scaffold erection were excluded from the study as these activities were again thought to provide general infrastructure to the entire project and were not specific to the targeted work package involved.

Intimately connected to the previous step was the need to carefully define the boundaries of the work package being measured. As is already apparent, core emphasis was placed on 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, irregular incidents and activities that were not directly or fully related to the installation processes.

Time lapse photography was used to capture the main work processes on-site including a time/date stamp for each frame taken. The camera was positioned to obtain an overview of the site and a 20-30 second frame capture rate was predominantly used in measuring crane cycle times and installation processes – thus allowing a high level of detailed data.

On each project, the above was supplemented by architectural drawings, delivery schedules, shop drawings, installation schedules and panel layouts relating to the prefabricated assemblies. This allowed areas and lineal meterages to be determined. When coupled with crane cycle times, this allowed productivity to be determined per panel, per day and per floor. Other information such as feedback from the site foreman and prefabrication plant, were also used to assist in understanding and supporting the above data sources. In some cases, data was also captured by on-site observation and measurement.

6.2 Methods of Quantitative Analysis

After capture, the time lapse photography was converted into a video format which made quantitative data analysis simpler to undertake. The video was viewed in slow motion by a researcher who recorded data into a spreadsheet.

In analysing crane cycle time it was useful to separately consider “net crane time” as distinct from “gross crane time”. The former represented time made up purely from multiple crane cycles devoted to installing prefabricated timber assemblies. Importantly, net crane time was used for productivity calculations gross crane time included net crane time plus indirectly or unrelated tasks such as:

- Unexpected stoppages – waiting, lengthy conversations, problems[1].
- Miscellaneous crane movements – movements not associated with prefabricated timber assemblies being studied (e.g. window units, brick pallets).
- Crane operational attributes – crane set-up time, change of crane position, takedown time, scheduled breaks.

Net crane time was measured in terms of the start and finish time of every crane cycle for a given study area and a given day. In some cases, it was not possible to measure the entire floor or wall area for the project however in such cases, large samples considered to be representative of the entire area were still obtained (e.g. samples greater than 50% of total area). The data was entered into a spreadsheet table – recreated as an example, in Table 2. The number of workers included in crane operation plus any additional installation processes (including preparatory and trailing tasks) were similarly recorded.

Gross crane time was measured to show the contextual input of the above-mentioned issues and was measured slightly differently for different crane types. For mobile cranes and delivery truck mounted cranes, it was taken from when the crane arrived on-site until it left after the installation. For fixed cranes, it was taken from when the crane was deployed on to the prefabricated timber installation activity, until finished.

[1] As an operational definition, unexpected stoppages included those stoppages longer than the mean crane cycle time for a given case study project.

Table 2: An example of cycle time measurement and data preparation.

No	Date	Day	Floor	Start time	Finish time	Cycle Time	Time converted to number (Number of hours)
2	9/11/2015	1	1	10:00:00	10:14:41	0:14:41	0.244

Charting of gross time versus net crane was undertaken to show the overall make-up of crane time on a project and to help separate installation productivity issues from broader based issues.

Line charts were used on each case study to systematically show the spread of data and identify outlier points. This included identification of a trimmed dataset within the overall dataset, to define the normally distributed portion of the sample and to separate it from outlier points.

Here, histograms were used as an initial means of visually checking whether or not the above trimmed dataset conformed to a normal distribution[2]. More rigorous testing was undertaken using the Shapiro-Wilk test and then verified using quantile-to quantile plots (Q-Q plots). For instance, the Shapiro-Wilk test rejects the hypothesis of normality when the Significance value (or p-value; shown as Sig.) is less than or equal to 0.05. In order to further check normality, the Q–Q plot compares the shapes of distributions, providing a graphical view of how properties such as location, scale, and skewness are similar or different in the two distributions. If the data are normally-distributed, the points should fall along a line through the first and third quartiles. As for histograms, whilst this method was used as part on the research process, plot findings are not detailed in the report to promote simplicity.

The normally distributed dataset was particularly useful in undertaking certain types of statistical analysis discussed further below. This dataset was also considered to more accurately represent repeatable and characteristic work processes which could be thought of in terms of benchmark productivity levels that could potentially be achieved if the causes

[2] To promote simplicity, these initial approaches are not shown in the report.

of slow outlying crane cycles could be avoided[3]. With regard to this, the time lapse footage enabled individual features and idiosyncrasies within outlier crane cycles to be observed and checked to make sure that they indeed contained features that were not characteristic of normal work processes. Details on this are reported individually for each case study.

From this approach, descriptive statistics for crane cycle times were generated in terms of minimum, maximum, median, mean and range values. This was undertaken for both the overall dataset and the trimmed (normally distributed) dataset, for each case study project.

In addition to the above, more advanced statistical analysis was undertaken using SPSS software. Primarily, *analysis of variance tests* (ANOVA) were undertaken using the trimmed (normally distributed) datasets to identify potential variables that impacted on the productivity process. For example, a one-way ANOVA was used to test if the key variable of crane cycle time differed according to the different panel sizes being lifted on a project. This test ostensibly compared the mean values between these sub-groups (e.g. different panel sizes) to determine if there was a statistical difference between them or not, by way of the F-statistic generated by the test. Similarly, t-tests were used where the number of data categories (e.g. number of panel sizes) were limited to only two sizes. The above tests were also supported by post hoc tests which were used as a means of checking that the results were correct and valid.

6.3 Methods of Qualitative Analysis and Site Observations

In parallel with the above, face-to-face interviews were undertaken with those directly involved in the supply chain and/or those directly involved in on-site installation processes. Of note, semi-structured interviews were undertaken with fabrication plant staff (involved in detailing, production and delivery scheduling); construction project managers; and leading hands from installation crews. Each was asked a battery of simple, semi-structured questions, as provided in Appendix A. These aimed to provide greater depth of understanding to the nuances of the overall process and to find out about any areas of potential improvement. To assist processing of the data, most interviews were recorded using an audio device. On some occasions, note-taking was necessary but in such

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[3] It was useful to draw upon methods for determining construction workmanship tolerances (originally used (1990)) where a normal frequency distribution is used to determine 'Characteristic Accuracy' that is likely to be achieved in common workmanship activities. Data falling outside the range of normal work practices are considered to be outliers which are not representative of characteristic accuracy. A similar approach has been applied in this study.

instances respondents were subsequently asked to sign off on the correctness of the information. Basic content analysis was undertaken to extract relevant themes.

Further to the above, observations were made from site visits and from regular telephone conversations with the above-mentioned personnel.

7. Quantitative Results

Results of timber productivity studies for the 5 case study projects – as previously described in Table 1 – are presented under separate headings below for cassettes, pre-clad stud wall frame panels, CLT floor/wall panels and a limited number of prefabricated beam scenarios. Under each situation crane cycle times, crane crew times, installation crew times and productivity calculations are provided.

As detailed in Section 6.2, the analysis separates “net crane time” from “gross crane time”. The former focuses specifically on time devoted to crane cycles installing the above-mentioned prefabricated timber assemblies and is used for productivity calculations. Other items are discussed where contextually relevant – mainly concerning crane operational attributes (such as crane set-up, change of crane position, takedown time, and various breaks) and how this varies for different crane types.

7.1 Productivity Analysis for Floor and Roof Cassettes

Floor and roof cassettes were used on 4 out of the 5 case study projects, as presented under separate headings that follow.

7.1.1 Case Study Project 1

This project involved 18 apartments within a single building. Measurements included two upper floor cassette levels and a roof cassette level. In order to obtain an overview of crane usage for the floor cassette installation, Figure 6 is helpful in separating gross crane time into its specific subgroups. As mentioned previously, of key relevance is the main subgroup of net crane time which represents 64% of gross crane time and is used for productivity calculations. It involved a total of 158 crane cycles concerning floor and roof cassettes (these crane cycles pertained to 80% of the installed cassette area).

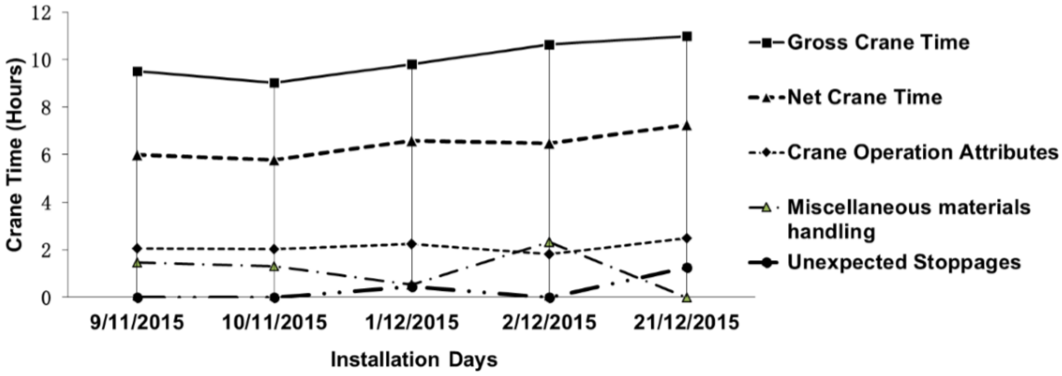

Figure 6: Project 1 gross crane time including breakdown of net crane time and lesser contributors to gross crane time.

As can be seen from Figure 6, other aspects of gross crane time were much lower such as: crane operation attributes (21%), miscellaneous materials handling (11%) and unexpected stoppages (3%).

Despite these occurring in and around the cassette installation process, they have varying degrees of implicated relevance to cassette productivity. Here, crane operation attributes, being the highest among these lesser items, deserves further discussion. As mentioned (refer to Table 1), a large 130 tonne mobile crane with 45m reach and 1.2 tonne capacity was used for lifting the cassettes. It was brought on-site for targeted daily use which had the effect of causing more time in daily setup and take down procedures – albeit that this choice carries other benefits insofar as not hiring the crane for longer than necessary. The other items mentioned above are of more distant relevance – refer to for details. For instance, *miscellaneous materials handling* deals with totally separate materials and occurs in a random rather than cyclic way as is apparent from the spike in usage on 2/12/15 relative to other days.

A line chart of the 158 crane cycles that contribute to net crane time, including the time for each cycle, is shown in Figure 7. Of note, the figure contains parallel red lines which delineate outlying data from a trimmed dataset within which was tested using the Shapiro-Wilk test to prove that it was normally distributed[4]. The figure also shows both the maximum outlier (36m:34s) and minimum outlier (2m:14s). It also shows the values that denote the

[4] Here, the Significance (Sig.) value of 0.550 (refer to Table 3) was greater than the chosen alpha level (0.05), therefore the null hypothesis that the data comes from a normally distributed population was accepted.

range of the trimmed dataset (6m:01s to 15m:00s). The trimmed dataset represents 113 cycles (72%) of the overall data set (i.e. outliers represent the remaining 28%). Reasons for the outliers were individually analysed using the time lapse video data and trends included:

- Slow cycles were mainly characterised by cassettes that needed to be nestled or jollied into confined spaces – this typically also involved a degree of waiting while workers made any on the spot preparations or adjustments to the area concerned.
- Fast cycles mainly arose from particularly small crane movements. This occurred where small panels had been stacked onto the floor deck. This happened because small cassettes were typically placed on top of the truck delivery so as not to create an unstable base for the delivery but were best installed later in the installation process.

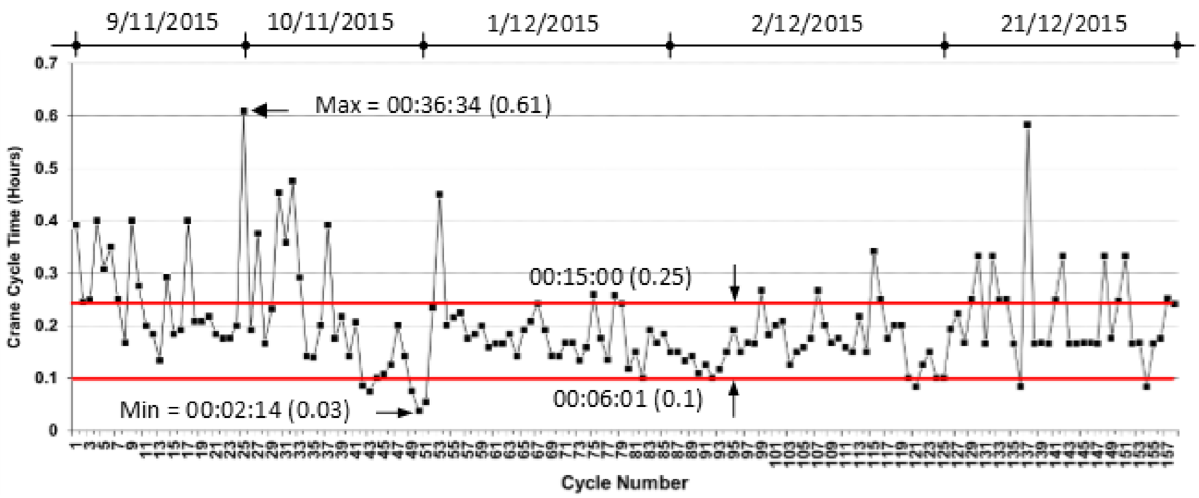

Figure 7: Project 1 line chart showing cassette crane cycle times i.e. cycles contributing to net crane time.

Using both the overall dataset and the trimmed dataset a variety of descriptive statistics are presented in Table 3. Some key points of interest include:

- For the overall dataset, the mean crane cycle time was 12 minutes and 10 seconds and the median cycle time was 10 minutes and 30 seconds.
- For the trimmed dataset the mean crane cycle time was 10 minutes and 29 seconds and the median cycle time was 10 minutes and 2 seconds.

Table 3: Project 1 descriptive statistics for crane cycle times (including overall and trimmed datasets).

Statistic	**Overall sample (total**	**Trimmed sample**

	number of measured cycles)	(after trimming outliers)
Sample size	158	113
Mean time (hours)	0.203 (12m:10s)	0.174 (10m:29s)
Median time (hours)	0.175 (10m:30s)	0.167 (10m:02s)
Range	0.572 (34m:19s)	0.150 (9m:00s)
Skewness	1.67	0.232
Value of Shapiro-Wilk Test	0.000 (alpha value 0.05)	0.055 (alpha value 0.05)

Note: Hours are expressed using both decimal number notation and time notation.

Measured productivity rates based on net crane time are presented in Table 4 for the overall crane cycle dataset. The Table also includes a breakdown of this productivity into individual components such as the trimmed dataset productivity and the outlier productivity.

For instance, reading from Table 4 time measured for the overall dataset was 32.1 hours and involved laying 1879m^2 of cassettes, thus resulting in an *overall* productivity rate of 58.57m^2/hour. The trimmed dataset shows less time at 19.8 hours, a lower measured area at 1371m^2, but ultimately a higher *trimmed* productivity rate of 69.38 m^2/hour. The outliers achieved a much lower productivity rate of only 41.27m^2/hour.

As described in section 6.2, the trimmed dataset represents a crane cycle process that is more idealised in so far as it tries to capture normal or characteristic work processes, and subsequently the removal of outliers. It represents a benchmark for productivity performance. In this context, the trimmed dataset achieved 18.5% higher productivity than the overall dataset and 68% higher productivity than for outlier crane cycles, thus indicating the importance of reducing outliers in order to increase installation productivity.

Table 4: Project 1 cassette installation productivity rates.

Data recording days	**Area installed**	**Crane productivity**		**Crane loading crew productivity e.g. driver/dogman**			**Installation crew productivity i.e. carpenters & riggers**		
	(m^2)	**Net crane time (hours)**	**Crane Productivity (m^2/crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**

Data recording days	Area installed	Crane productivity		Crane loading crew productivity e.g. driver/dogman			Installation crew productivity i.e. carpenters & riggers		
	(m^2)	**Net crane time (hours)**	**Crane Productivity (m^2/crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**
9/11/2015	341.00	5.99	56.86	2	11.99	28.43	4	26.00	13.12
10/11/2015	188.43	5.77	32.64	2	11.55	16.32	4	25.09	7.51
1/12/2015	456.73	6.58	69.41	2	13.16	34.71	4	28.32	16.13
2/12/2015	341.90	6.49	52.71	2	12.97	26.35	4	27.95	12.23
21/12/2015	551.84	7.26	76.04	2	14.51	38.02	4	31.03	17.79
Overall dataset calculations	**1879.90**	**32.09**	**58.57**		**64.19**	**29.29**		**138.38**	**13.59**
Trimmed dataset only	**1370.66**	**19.76**	**69.38**		**39.51**	**34.69**		**86.12**	**15.91**
Outlier dataset only	**509.24**	**12.34**	**41.27**		**24.97**	**20.40**		**49.93**	**10.20**

Notes:

1. Installation crew hours includes net crane time and where required, any time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

Labour productivity can also be read from the above-mentioned tables. With regard to this, emphasis is placed on the installation crew rather than the crane crew (which is normally provided as part of cranage package)5. Given this, installation crew productivity for the

[5] The crane crew is normally provided as part of the crane hire package or is costed as part of central crane costs (under "preliminaries"). When viewed as a project resource it is implicitly fixed to the crane resource.

overall dataset came in at 13.59m2/hour and for the trimmed dataset, 15.91m2/hour. This is obviously much lower than crane productivity (discussed above) because a single crane achieves much higher output than single worker. For instance, the installation crew (refer to Table 4) involved 4 workers and so the installed area is divided by their combined time contribution. Of note, it is considered unlikely (from site observations) that adding more workers would necessarily increase productivity at a directly proportionate rate. Subsequently, crane productivity (being the lead resource in the process) is thought to be the most appropriate measure to generalise and compare productivity outcomes, except where comparing crew sizes from different projects or where comparing prefabricated approaches with more traditional labour-intensive methods of construction.

Drawing further on the previously tabulated data, it was decided to test for differences in crane cycle time from one building level to the next (including first floor level, second floor level and roof level). The trimmed (normally distributed) dataset was subsequently used to undertake a one way ANOVA test. The results (refer to Table 5) show that there was no statistically significant difference – the Sig. value of 0.063, fell above the 0.05 alpha value, which means the null hypothesis that the crane cycles for each level are equal, must be accepted.

Further, it was decided to test for differences in crane cycle time potentially brought about by differences in cassette size. Consequently, an independent t-test was run on the data using a 95% confidence intervals (CI). Here, the cassette sample was divided into roughly equal groups by using a frequency distribution and the median cassettes size to create a logical basis to the process. Details relating to large and small cassettes are shown below and related sample details are shown in **Table 6**.

- Small size: Less than 12.39m2 (the average of small size cassettes: 6.73 m2)
- Large size: Greater than 12.39m2 (the average of large size cassettes: 17.43 m2)

The results of the T-test (refer Table ?) show that there was a statistically significant difference in the crane cycle time for the two different floor cassette sizes - the Sig. value of 0.045, falls lower the 0.05 alpha value which means the null hypothesis that the crane cycles for different floor cassette size are equal, cannot be accepted. It was found that crane cycle time for installing larger cassettes (mean 0.181 ± 0.029 hours) was statistically higher than crane cycles for installing small cassettes (mean 0.168 ± .037 hours)..

Table 5: Project 1 ANOVA test of crane cycle time for different building levels (refer to Appendix B for SPPS generated statistics table).

Building levels	**N**	**Mean**	**Sig.**
First floor level	30	0.180	
Second floor level	61	0.168	
Roof level	22	0.185	
Total	113	0.175	0.063

Table 6: Project 1 t-test of crane cycle time for different cassette sizes (refer to Appendix B for SPPS generated statistics table).

	N	**Mean**	**Sig.**
Small (<12.39m2)	56	0.168	
Large (>12.39m2)	57	0.181	
Total			0.045

7.1.2 Case Study Project 2

This project involved 12 townhouses over two storeys and across two separate buildings. As for Project 1, an overview of crane usage for the cassette installation is provided in Figure 8 which focuses on gross crane time and its subset groups. Interpreting from Figure 8, the main subgroup of net crane time is again important because it represents 67.68% of gross crane time and is used for productivity measurement. Net crane time involved a total of 72 crane cycles relating to upper floor cassettes on both townhouse buildings (these crane cycles represent 100% of the installed cassette area). Other much lower and peripheral contributors to gross crane time, which can be seen in Figure 9, include crane operation attributes 16.11%, miscellaneous handling of other materials 13%, and unexpected stoppages 3.21%.

As mentioned under Project 1, these lesser items represent a mix of random, unexpected or site-specific crane selection issues. They have varying degrees of implicated relevance to cassette productivity so project managers should separately make allowance for these items on a project by project basis and as perceived to be appropriate. For instance, with regard to crane operation attributes (refer to Table 1) a delivery truck mounted crane was used for lifting the cassettes into place. It was located efficiently on-site in terms of being close to the building and being able to reach all lifting requirements from a single position. It was apparent that this piece of equipment was inherently efficient for the relatively small, low lift circumstances on this project – it was nimble in hooking up and moving cassettes and negated the need to separately coordinate crane and materials deliveries. It subsequently had relatively low impact on gross crane time (further details concerning these insights, relative to other crane selections issues, are dealt with more fully under section 8).

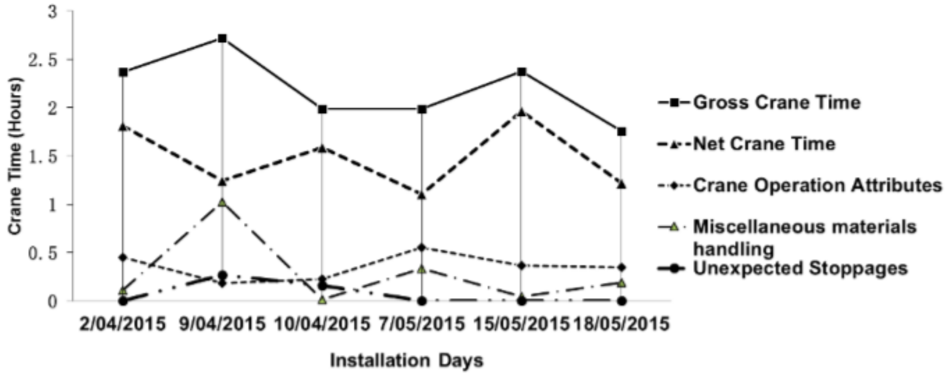

Figure 8: Project 2 gross crane time including breakdown of net crane time and lesser contributors to gross crane time.

In another instance (refer to Figure 8), it can be seen that *miscellaneous materials handling* had a similar amount of impact on gross time, but the majority of this revolved around day specific events on 9/4/15 (complicated by a truck arrival during a lunch break) hence demonstrating the random nature of this item. Subsequently and as mentioned above, items of this nature are separate to cassette installation productivity and must be allowed for according to project specific needs.

A line chart of the 72 crane cycles contributing to net crane time is shown in Figure 9. As for Project 1, the figure contains parallel red lines which delineate outlying data from the trimmed (normally distributed) dataset within. Again, the Shapiro-Wilk normality test was applied which confirmed that the trimmed dataset was in fact normally distributed[6].

The figure shows both the maximum outlier (21m:00s) and minimum outlier (2m:24s). It also shows the values that denote the range of the trimmed dataset (2m:24s to 12m:00s). The trimmed dataset represents 64 cycles (89%) of the overall data set (with relatively few outliers representing the remaining 11%). Reasons for the outliers were individually analysed using the time lapse video data and trends included:

- Delays whilst waiting for the installation crew to undertake other work activities during crane cycles.

[6] Refer to Table 13. Here, the Sig. value of 0.175 was greater than the chosen alpha level (0.05), therefore the null hypothesis that the data comes from a normally distributed population was accepted.

- Slow cycles which were mainly characterised by cassettes that needed to be nestled or jollied into confined spaces – this typically also involved a degree of waiting while workers made any on the spot preparations or adjustments to the area concerned.
- Fast cycles arose from small crane movements, especially where distributing small panels or where set out was accurate and infill panels fitted precisely.

Of note, the latter two reasons were broadly consistent with findings from Project 1.

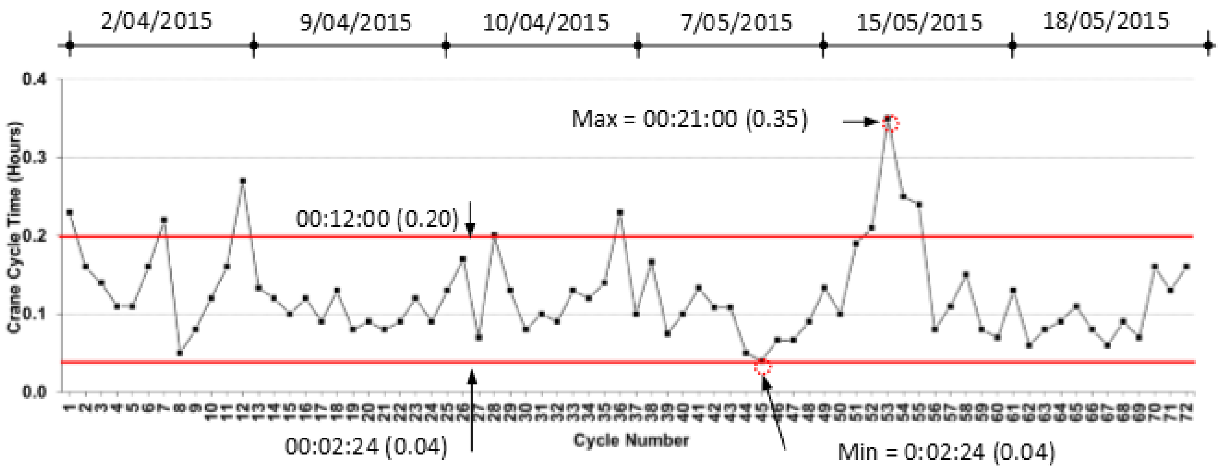

Figure 9: Project 2 line chart showing cassette crane cycle times i.e. cycles contributing to net crane time.

Using both the overall dataset and the trimmed dataset a variety of descriptive statistics are presented in Table 6. Some key points of interest include:

- For the overall dataset, the mean crane cycle time was 7 minutes and 26 seconds, and the median cycle time was 6 minutes and 36 seconds.
- For the trimmed dataset, the mean crane cycle time was 6 minutes and 28 seconds and the median cycle time was 6 minutes and 14 seconds.

Table 7: Project 2 descriptive statistics for cassette crane cycle times (including overall and trimmed datasets).

Statistic	Measured sample (a total number of the measured cycles)	Trimmed sample (i.e. after trimming outliers)
Sample size	72	64
Mean time (hours)	0.124 (7m:26s)	0.108 (6m:28s)
Median time (hours)	0.110 (6m:36s)	0.104 (6m:14)
Range	0.310 (18m:36s)	0.160 (9m:36s)
Skewness	1.459	0.432
Value of Shapiro-Wilk Test	Sig. value 0.000 (Alpha level 0.05)	Sig. value 0.175 (Alpha level 0.05)

Note: Hours are expressed using both decimal number notation and time notation.

Measured productivity rates based on net crane time are presented in Table 8 for the overall crane cycle dataset. The Table also includes a breakdown of this productivity into individual components such as the trimmed dataset productivity and the outlier productivity.

For instance, reading from Table 8, time measured for the overall dataset was 8.93 hours and involved laying 970.77m^2 of cassettes, thus resulting in an overall productivity rate of 108.69m^2/hour. For the same reasons as Project 1, the trimmed dataset shows less time at 6.93 hours, a lower measured area at 858.77m^2, but ultimately a higher trimmed productivity rate of 123.89m^2/hour. The outliers achieved a much lower productivity rate of only 56.00m^2/hour

As for case study Project 1, the trimmed dataset figures are mainly useful for benchmarking purposes but require greater attention to removing the impact of outliers. In this context, the trimmed dataset achieved 14% higher productivity than the overall dataset. It also achieved 121% higher productivity than for outliers – again indicating the importance of reducing outliers in order to optimise productivity.

Table 8: Project 2 cassette installation productivity rates.

Data recording days	**Area installed**	**Crane productivity**		**Crane loading crew productivity e.g. driver/dogman**			**Installation crew productivity i.e. carpenters & riggers**		
	(m^2)	**Net crane time (hours)**	**Crane Productivity (m^2/net crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**
2/04/2015	162.15	1.81	89.59	1	1.81	89.59	3	6.93	23.40
9/04/2015	159.04	1.24	127.91	1	1.24	127.91	3	5.23	30.41
10/04/2015	164.19	1.59	103.26	1	1.59	103.26	3	6.27	26.19
7/05/2015	162.16	1.11	146.75	1	1.11	146.75	3	4.82	33.68
15/05/2015	159.04	1.96	81.01	1	1.96	81.01	3	7.39	21.52
18/05/2015	164.19	1.22	134.58	1	1.22	134.58	2	3.44	47.73
Overall dataset calculations	**970.77**	**8.93**	**108.69**		**8.93**	**108.69**		**34.08**	**28.49**
Trimmed dataset only	**858.77**	**6.93**	**123.89**		**6.93**	**123.89**		**27.14**	**31.64**
Outliers dataset only	**112.00**	**2.00**	**56.00**		**2.00**	**56.00**		**6.17**	**18.17**

Notes:

1. Installation crew hours includes net crane time and where required, any time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

As per Project 1, it was decided to undertake a t-test for variables which may impact on productivity. In this case, it was both opportune and possible to test for differences in crane cycle time for different cassette sizes. The test was run using a 95% confidence intervals (CI) for the mean difference. The Cassette sizes (also refer to Table 9) were divided into two sizes by splitting the frequency distribution into approximately even portions as follows:

- Small size: Less than 14.33m^2 (mean=10.12m2)
- Large size: Greater than 14.33m^2 (mean = 15.98m2)

The results of the t-test (refer Table below) show that there was no statistically significant difference in the crane cycle time for the two different floor panel sizes – the Sig. value of 0.29, falls higher the 0.05 alpha value which means the null hypothesis that the crane cycles for different wall panel size are equal, must be accepted. With regard to this, the crane cycle time for installing larger cassettes (mean 0.112 ± 0.036 hours) was not significantly higher than crane cycles for installing small cassettes. If this same finding was found in a high proportion of other projects, it would suggest that where possible, building layouts should be converted to a cassette layout that optimises large panels, as small cassettes do not yield a proportionally faster crane cycle time.

Table 9: Project 2 t-test of crane cycle time for different cassette sizes (refer to Appendix B for SPPS generated statistics table).

	N	**Mean**	**Sig.**
Small (<14.33m^2)	29	0.103	
Large (>14.33m^2)	35	0.112	
Total			0.290

7.1.3 Case Study Project 3

This project involved 55 apartments over 3 storeys and across a complex of five separate buildings (of which only 3 buildings were included in the study). As for earlier projects, an overview of gross crane time and its subgroups during cassette installation is provided in Figure 10. The main subgroup of net crane time represents a strong 85.88% and as previously noted, is used for calculating installation productivity. Net crane time involved a total of 60 crane cycles relating to upper floor cassettes (these crane cycles represented 58% of the total installed cassette area of the 3 buildings). Other much lower and peripheral contributors included unexpected stoppages 9.23% crane operation attributes 3.97% and miscellaneous handling of other materials 0.93%. As stated earlier, these items represent a mix of random, unexpected or site-specific issues that project managers should separately consider and make allowance for, on a project by project basis.

As an example of this, and as apparent in Figure 10, crane operation attributes (including crane set up and takedown time) were very low[7] and to some extent this was a function of the fixed hammerhead tower crane used on this project (refer to Table 1 for further details). It was able to reach all lifting requirements from its centralised site location and its permanent presence meant that it could be easily and quickly deployed for dedicated cassette lifting activities (Note: aspects of this are discussed in comparative terms under section 8).

As an example of the random and unexpected nature of events, it can be seen in Figure 10 that *unexpected delays* were relatively high on 12/11/2015 compared to other days of installation. Upon reviewing the time lapse video it was apparent that scaffolding being erected along the side of the building caused lost cranage productivity time; there were also delays where the installation team needed to finish internal walls in order to support the cassettes. Even so, neither of these instances were directly related to normal prefabricated timber cassette installation processes – hence showing the need to consider such issues separately and as part of broader based project planning.

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[7] This comment does not necessarily mean that crane operation attributes were low for the overall project, just in terms of prefabricated timber installation processes.

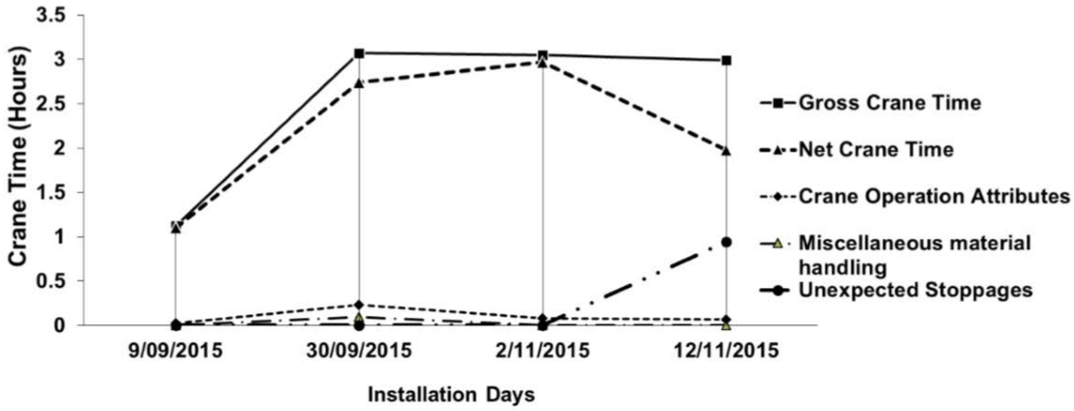

Figure 10: Project 3 gross crane time including breakdown of net crane time and lesser contributors to gross crane time.

A line chart of the 60 crane cycles contributing to net crane time is shown in Figure 11: . As per the previous case studies, the figure delineates outlying data (maximum 24m:36s and minimum of 3m:36s) from the trimmed data set within which represents 44 cycles (73%) of the overall data set). As per the previously reported projects, the trimmed dataset was checked using the Shapiro-Wilk normality test to ensure that it was indeed, normally distributed[8]. Figure 11: also denotes the values defining the range of the trimmed dataset (being 4m:12s to 9m:20s). Reasons for the long/slow outliers were individually analysed using the video data and trends included:

- Cassettes that were incorrectly placed and/or required re-positioning, or due to incorrect set out.
- Cassettes that required excessive time to nestle the panel into a confined closing space.

[8] Here, the Sig. value of 0.083 (refer to Table 10) was greater than the chosen alpha level (0.05), therefore the null hypothesis that the data comes from a normally distributed population was accepted.

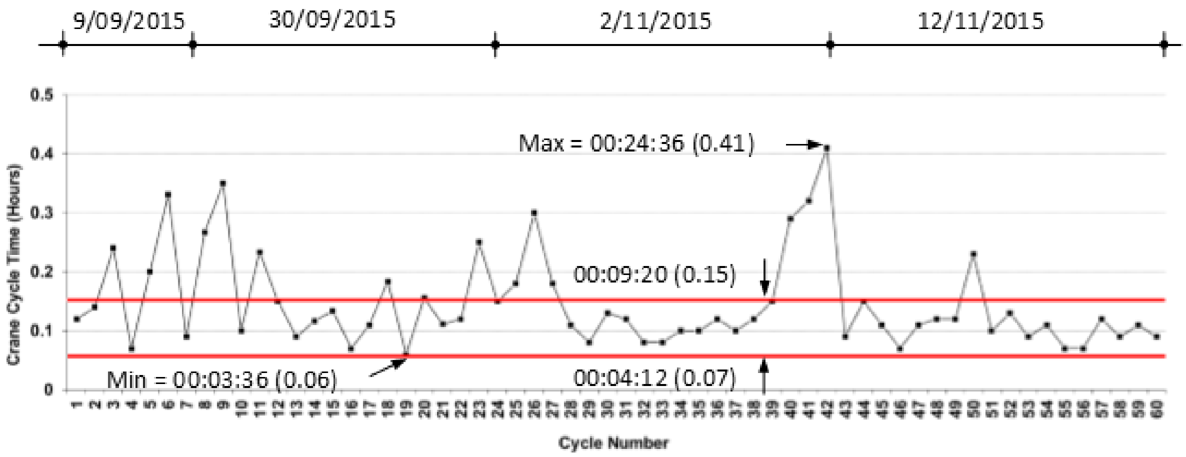

Figure 11: Project 3 line chart showing cassette crane cycle times (i.e. cycles contributing to net crane time).

Using both the overall dataset and the trimmed dataset a variety of descriptive statistics are presented in Table 10. Some key points of interest include:

- The mean crane cycle time across all cycles was 9 minutes and the median cycle time was 7 minutes and 12 seconds.
- The mean crane cycle time from the trimmed sample was 6 minutes and 36 seconds and the median cycle time was 6 minutes and 36 seconds.

Table 10: Project 3 descriptive statistics for crane cycle times (including overall and trimmed datasets).

Statistic	**Overall dataset (total number of measured cycles)**	**Trimmed dataset (i.e. after trimming outliers)**
Sample size	60	44
Mean time (hours)	0.15 (9m:0s)	0.11 (6m:36s)
Median time (hours)	0.12 (7m:12s)	0.11 (6m:36s)
Range	0.35 (21m:00s)	0.09 (5m:24s)
Skewness	1.55	0.18
Value of Shapiro-Wilk Test	0.000 (Alpha level 0.05)	0.083 (Alpha level 0.05)

Note: Hours are expressed using both decimal number notation and time notation.

Measured productivity rates based on net crane time are presented in Table 11 for the overall dataset of crane cycles. The Table also includes a breakdown of this productivity into individual components such as the trimmed dataset productivity and the outlier productivity.

Table 11: Project 3 cassette installation productivity rates.

Data recording days	**Area installed**	**Crane productivity**		**Crane loading crew productivity e.g. driver/dogman**			**Installation crew productivity i.e. carpenters & riggers**		
	(m^2)	**Net crane time (hours)**	**Crane Productivity (m^2/net crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**
9/09/2015	109.00	1.10	99.09	2	2.20	49.55	3	4.80	22.71
30/09/2015	240.00	2.74	87.60	2	5.48	43.80	3	9.72	24.69
2/11/2015	240.00	2.97	80.81	2	5.94	40.40	3	10.41	23.05
12/11/2015	240.00	1.98	121.21	2	3.96	60.61	3	7.44	32.26
Overall dataset calculations	**829.00**	**8.79**	**94.31**		**17.58**	**47.16**		**32.37**	**25.61**
Trimmed dataset only	**574.30**	**4.77**	**120.49**		**9.53**	**60.24**		**18.68**	**30.74**
Outliers dataset only	**254.70**	**4.02**	**63.31**		**8.05**	**31.65**		**12.48**	**20.42**

Notes:

1. Installation crew hours includes net crane time and where required, any time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

For instance, reading from Table 11, time measured for the overall dataset was 8.79 hours and involved laying 829m^2 of cassettes, thus resulting in an *overall* productivity rate of 94.31m^2/hour. The trimmed dataset shows less time at 4.77 hours, a lower measured area at 574.30m^2, but ultimately a higher *trimmed* productivity rate of 120.49m^2/hour. The outliers achieved a much lower productivity rate of only 63.31m^2/hour.

As a basis for benchmarking, the trimmed dataset findings achieved 27.75% higher productivity that the overall dataset and 90% higher productivity than the outliers – again reinforcing the importance of adopting a controlled crane cycle and reducing outliers in order to increase productivity.

Drawing further on Table 11 and as per previous projects, labour productivity again focuses on the installation crew (see for instance footnote 5 on page 32 for details regarding this) and subsequently the overall dataset came in with a crew rate of 25.61m^2/man hour and for the trimmed dataset 30.74m^2/man/hour.

Following analysis trends from previous projects a t-test was undertaken using the trimmed (normally distributed) dataset to test if crane cycle times differed for different cassette sizes. Again, the frequency distribution was used to split cassettes sizes into two groups whereby small cassettes were less than 13.26m^2 (average: 5.40 m^2) and large cassettes were greater than 13.26m^2 (average: 17.87 m^2). The test was run using a 95% confidence intervals (CI) for the mean difference. The test (refer to Table 12) shows that a statistically significant difference was found for different cassette sizes – the Sig. value of 0.018, falls below the 0.05 alpha value which means the null hypothesis that the crane cycles for cassette size are equal, must be rejected, a finding that differs from the same test when applied to Project 2. It was found that the crane cycle time for installing larger cassettes (0. 115± 0.024 hours) were significantly higher than crane cycles for installing small cassettes (0. 098± 0.020 hours)

Table 12: Project 3 t- test of crane cycle time for different cassette sizes (refer to Appendix B for SPPS generated statistics table).

Cassette size	**N**	**Mean**	**Sig.**
1 (<13.62m^2)	17	.0976	
2 (>13.62m^2)	27	.1152	
Total			0.018

7.1.4 Case Study Project 4

This project involved a freestanding row of 2, two storey townhouses. The relatively small and simple scale of this project meant that gross crane time for floor cassette installation took place over a short 2:33 hour time period. Net crane time was the main subgroup of interest which contributed 76% to gross crane time. This involved a total of 10 floor crane cycles (there were actually 14 cassettes involved in the installation but 4 very small cassettes were piggy-backed onto crane cycles for larger cassettes, then man handled into place from the floor deck).

Other contributors to gross crane time included unexpected stoppages 16%, crane operating attributes 4%, and miscellaneous materials 4%. As previously noted, these items were a function of crane selection and project specific events. In explaining these issues further, waiting time was particularly apparent at the beginning and end of the crane period on-site, and whilst this merits comment because of its input to the above percentages, it was still relatively minor in terms of actual time. Further, it also had no real impact on the productivity of the installation crew because the waiting took place in a way that didn't impact on work flow. This project also provided a different crane selection to other sites. It used a relatively small all-terrain mobile crane for lifting the cassettes (refer to Table 1). This required very low crane operating attributes i.e. low setup and take down time was apparent as the machine did not use outriggers and was nimble to manoeuvre. This situation also differed insofar as requiring the crane to crawl/carry the cassettes over approximately 40m from the delivery truck location to the work face. Whilst this added marginally to each crane cycle time and required the dogman to stabilise the load with webbing straps whilst crawling, it was still a relatively straightforward process and was achievable due to the small scale of the project.

A line chart of the 10 crane cycles is shown in Figure 12. The figure delineates outlying data from the trimmed data set within. Even so, the small and variable nature of the sample meant that it was not possible to create the trimmed dataset as a normal frequency distribution[9]. Instead, the trimmed dataset was created purely on the basis of viewing long crane cycles on the time lapse video, then determining if the work processes involved were of a standard repetitive nature or included aspects that were random, unexpected or atypical. With regard to this, the figure shows both the maximum outlier (18m:00s) and minimum outlier (7m:36s) times. It also denotes the values defining the chosen range of the trimmed dataset (being 7m:00s to 14m:00s). The trimmed dataset represents 7 cycles

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[9] The small sample failed the Shapiro-Wilk test of normality and therefore prevented the ability to carry out ANOVA and t-tests as undertaken for other projects.

(70%) of the overall data set with outliers representing the remaining 30%. Reasons for the outliers were individually analysed using the video data and focused purely on slow cycles as follows:

- Double handling of cassettes (i.e. cassettes set-down near the delivery truck area in order to implement the desired installation sequence).
- Minor trouble hooking, unhooking, and placing of specific panels.
- Piggy-backing small cassettes onto larger cassettes caused a slightly slower cycle but the overall efficiency of this was apparent as the installation crew could then separately handle these small panels into position – thus minimising the total number of crane cycles.

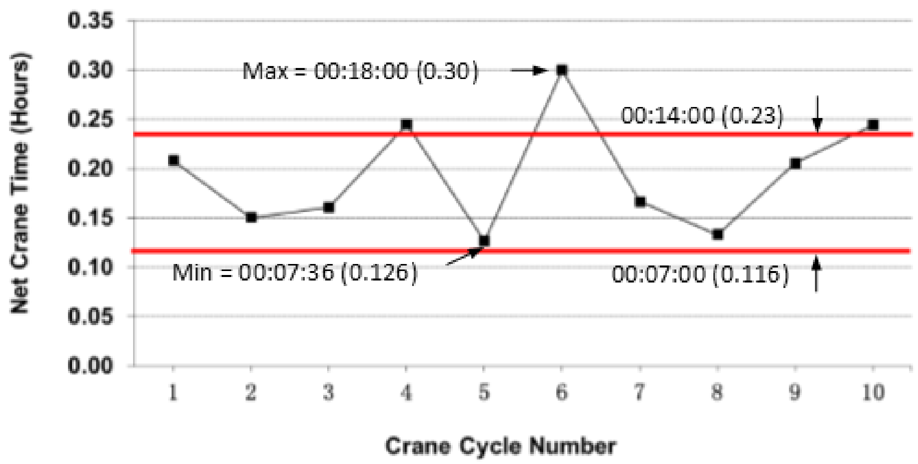

Figure 12: Project 4 line chart showing cassette crane cycle times (i.e. cycles contributing to net crane time).

Using both the overall dataset and the trimmed dataset a variety of descriptive statistics is presented in Table 13. Some key points of interest include:

- The mean crane cycle time across all cycles was 11 minutes and 24 seconds and similarly the median cycle time was 11 minutes and 24 seconds.
- The mean crane cycle time from the trimmed sample was 9 minutes and 36 seconds and similarly the median cycle time was 9 minutes and 36 seconds.

Table 13: Project 4 descriptive statistics for crane cycle times (overall and trimmed datasets).

Statistic	**Measured sample (a total number of the measured cycles)**	**Trimmed sample (i.e. after trimming outliers)**
Sample size	10	8
Mean time (hours)	0.19 (11m:24s)	0.16 (9m:36s)
Median time (hours)	0.19 (11m:24s)	0.16 (9m:36s)
Range	0.17 (10m:12s)	0.08 (4m:48s)

Note: Hours are expressed using both decimal number notation and time notation.

Measured productivity rates based on net crane time are presented in Table 14 for the overall crane cycle dataset. The Table also includes a breakdown of this productivity into individual components such as the trimmed dataset productivity and the outlier productivity.

For instance, reading from Table 14, time measured for the overall dataset was 1.94 hours and involved laying 137.60m^2 of cassettes, thus resulting in an overall productivity rate of 70.87m^2/hour. The trimmed dataset shows less time at 1.15 hours, a lower measured area at 99.80m^2, but ultimately a higher trimmed productivity rate of 86.82m^2/hour. The outliers achieved a much lower productivity rate of only 47.88m^2/hour.

The trimmed dataset can be used for ongoing benchmarking purposes and in this context achieved 22.5% higher productivity than the overall dataset and 81% higher productivity than for the outliers.

Table 14: Project 4 cassette installation productivity rates (data recorded 3/12/14).

	Area installed	**Crane productivity**	**Crane loading crew productivity e.g.**	**Installation crew productivity i.e.**

				driver/dogman			carpenters & riggers		
	(m^2)	Net crane time (hours)	Crane Productivity (m^2/net crane hour)	Crew size (No.)	Crew time (hours)	Productivity (m^2/man hour)	Crew size (No.)	Crew time (hours)	Productivity (m^2/man hour)
Overall dataset calculation	**137.60**	**1.94**	**70.87**	**3**	**5.83**	**23.62**	**3**	**9**	**15.92**
Trimmed dataset only	**99.80**	**1.15**	**86.62**	**3**	**3.46**	**28.87**	**3**	**5**	**18.38**
Outlier dataset only	**37.80**	**0.79**	**47.88**	**3**	**2.37**	**15.96**	**3**	**3**	**11.76**

Notes:

1. Installation crew hours includes net crane time and where required, any time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

7.2 Productivity Analysis for Pre-Clad Wall Panels (Case Study Project 2)

This aspect of the study focused on pre-clad and pre-sheathed walls applied over conventional lightweight stud framing (including walls with pre-installed window and door units). These assemblies facilitate fast attainment of weatherproofing during construction and constitute a more pre-finished panel than the more commonly available prefabricated open stud wall panel construction.

Such assemblies proved difficult to find, and subsequently only a single case study is reported upon. It is the same "Case Study 2" project used in the floor cassette study. As mentioned previously, this project involved 12 townhouses across two separate buildings (refer to Table 1 and Section 7.1.2 for other details about this case). On this project, external and internal dividing walls were craned into position (Note: other internal walls were the simple un-clad open stud panels, mentioned above, and have not been dealt with in the study as much of the work involved simple man-handling of the panels with relatively little cranage involved). Pre-cladding fell under two different scenarios: ground floor walls simply involved an OSB sheathing; upper floors walls involved fibre cement sheet cladding[10]. As mentioned previously (Section 7.1.2), this project made use of a delivery truck mounted crane which was inherently efficient for the small, low lift nature of this project.

Unlike the earlier study of cassettes, a breakdown of gross crane time was not used in this study – instead, the focus was purely on net crane time. This is because gross cane time was found to often involve quite a number of other activities (mainly moving stacks of internal open stud panels and crane waiting time whilst workers broke the stack up, and man-handled small panels into position). The extent of this meant that cranage sessions were quite mixed and it therefore seemed more relevant to focus purely on net crane time (for pre-clad panel installation) rather than provide a full breakdown of other activities.

Given the above, net crane cycle time involved a total of 116 crane cycles (including pre-clad wall panels for both the ground floor and first floor levels). A line chart of the 116 crane cycles, including the time for each cycle, is shown in Figure 13. As per previous

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[10] A site laid external brick veneer skin ultimately covered the ground floor OSB sheathing; a site applied acrylic render was applied over the first floor fibre cement sheeting.

conventions, the figure delineates outlying data from the trimmed data set within which was verified as conforming to a normal distribution using the Shapiro-Wilk test[11].

With regard to this, the figure shows both the maximum outlier (24m:19s) and minimum outlier (2m:20s). It also shows the values that denote the range of the trimmed dataset (2m:20s to 12m:36s). The trimmed dataset represents 96 cycles (83%) of the overall data set (with outliers representing the remaining 17%). Reasons for the outliers were individually analysed using the video data and trends included:

- Slow cycles were mainly characterised by: wind related causes such as difficulty hooking up panels, getting a sling or webbing around panels or increased back propping of panels. Fitting panels in to bounded or closed spaces also caused extra time.
- Fast cycles occurred where small panels were involved and were not slowed down by fit problems.

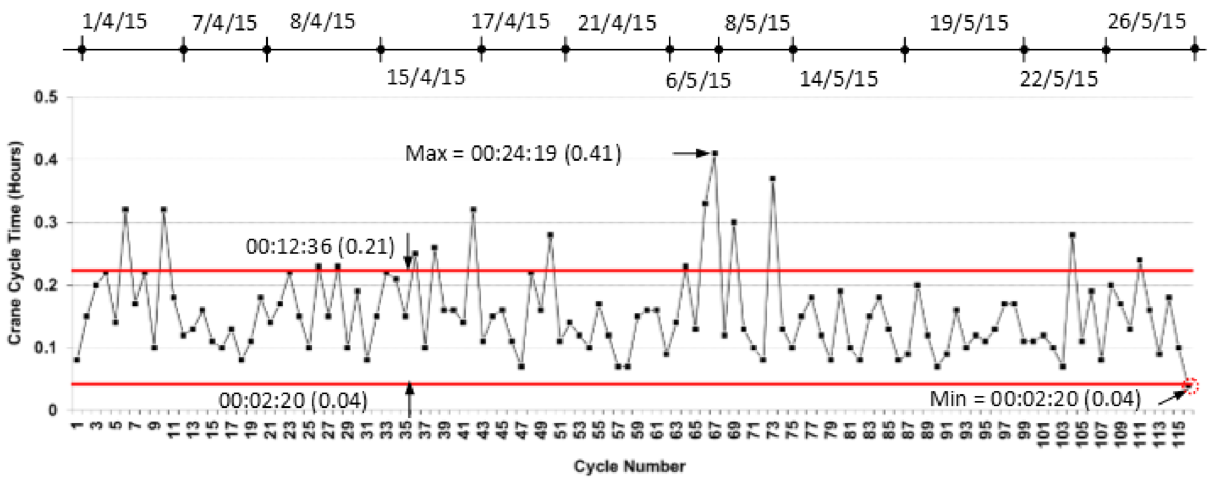

Figure 13: Project 2 line chart for pre-clad wall panel crane cycle times (i.e. cycle times contributing to net crane time).

Using both the overall dataset and the trimmed dataset a variety of descriptive statistics are presented in Table 15. Some key points of interest include:

- The mean crane cycle time across all cycles was 9 minutes and 11 seconds the median cycle time was 8 minutes and 24 seconds.

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[11] Here, the Sig. value of 0.065 (refer to Table 15) was greater than the chosen alpha level (0.05), therefore the null hypothesis that the data comes from a normally distributed population, was accepted.

- The mean crane cycle time from the trimmed sample was 7 minutes and 41 seconds the median cycle time was 7 minutes and 48 seconds.

Table 15: Project 2 descriptive statistics for wall crane cycle times (overall and trimmed datasets).

Statistic	**Measured sample (a total number of the measured cycles)**	**Trimmed sample (i.e. after trimming outliers)**
Sample size	116	96
Mean time (hours)	0.153 (9m:11s)	0.128 (7m:41s)
Median time (hours)	0.140 (8m:24s)	0.130 (7m:48s)
Range	0.37 (22m:12s)	0.17 (10m12s:)
Skewness	1.314	0.104
Value of Shapiro-Wilk Test	0.000 (Alpha level 0.05)	0.065 (Alpha level 0.05)

Note: Hours are expressed using both decimal number notation and time notation

Measured productivity rates based on net crane time are presented in Table 16 for the overall crane cycle dataset. Of note, productivity is expressed in term of installed area per hour. Table 15 also includes a breakdown of this productivity into individual components such as the trimmed dataset productivity and the outlier productivity.

In the overall dataset, time equated to 17.84 hours and involved laying 1189m^2 of cassettes, thus resulting in a productivity rate of 66.65m^2/hour. For the trimmed dataset, less time was involved at 12.37 hours and a lower measured wall length of 958m^2, but ultimately a higher (trimmed) productivity rate of 77.47m^2/hour. In contrast, outliers on their own only achieved a productivity rate of 42.16m^2/hour.

Using the trimmed dataset as a best practice benchmark, it can be said that it achieved 16.23% higher productivity than the overall dataset. It also achieved 83.75% higher productivity than the outlier productivity. As for cassettes, this reinforces the benefits of adopting a controlled crane cycle and reducing outliers in order to optimise productivity.

Table 16: Project 2 pre-clad wall installation productivity rates (based on area).

Data recording days	Area installed	Crane productivity		Crane loading crew productivity e.g. driver/dogman			Installation crew productivity (i.e. carpenters & riggers) based on wall area		
	(m^2)	Net crane time (hours)	Crane Productivity (m^2/crane hour)	Crew size (No.)	Crew time (hours)	Productivity (m^2/man/hour)	Crew size (No.)	Crew time (hours)	Productivity (m^2/man/hour)
1/04/2015	138.07	2.22	62.19	1	2.22	62.19	3	9.66	14.29
7/04/2015	106.92	1.00	106.92	1	1	106.92	3	6	17.82
8/04/2015	138.07	1.91	72.29	1	1.91	72.29	3	8.73	15.82
15/04/2015	95.69	2.08	46.01	1	2.08	46.01	3	9.24	10.36
17/04/2015	71.21	1.26	56.52	1	1.26	56.52	3	6.78	10.50
21/04/2015	82.90	1.35	61.41	1	1.35	61.41	3	7.05	11.76
6/05/2015	66.92	1.24	53.97	1	1.24	53.97	3	6.72	9.96
8/05/2015	106.92	1.33	80.39	1	1.33	80.39	3	6.99	15.30
14/05/2015	125.74	1.44	87.32	1	1.44	87.32	3	7.32	17.18
19/05/2015	100.31	1.64	61.16	1	1.64	61.16	3	7.92	12.66
22/05/2015	71.21	1.06	67.18	1	1.06	67.18	2.5	11.65	6.11
26/05/2015	85.00	1.31	64.89	1	1.31	64.89	3	6.93	12.27
Overall dataset calculations	**1188.97**	**17.84**	**66.65**		**17.84**	**66.65**		**94.99**	**12.52**
Trimmed dataset only	**958.34**	**12.37**	**77.47**		**12.37**	**77.47**		**72.68**	**13.18**
Outliers dataset only	**230.63**	**5.47**	**42.16**		**5.47**	**42.16**		**22.30**	**10.34**

Notes:

1. Installation crew hours includes net crane time and where required, any time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

Labour productivity can also be read from the above tables. As per the cassette analysis, emphasis is mainly directed towards installation crew productivity (see for instance footnote 5, page 33, for details regarding this). Subsequently, installation crew productivity for the overall dataset came in at 12.52m^2/hour and for the trimmed dataset 13.18m^2/hour. As discussed under previous projects, these rates are mainly useful in comparing installation crew performance and in comparing prefabricated methods to more traditional labour-intensive construction methods of construction.

Measured productivity rates for the same items in Table 16, but based on wall length instead of wall area, are presented in Table 17 for the overall crane cycle dataset. Here, time for overall dataset equated to 17.84 hours and involved laying 456.65m of cassettes, thus resulting in a productivity rate of 25.60m/hour. For the trimmed dataset, (Table 17) less time was involved at 12.37 hours and a lower measured wall length of 369.17m, but ultimately a higher (trimmed) productivity rate of 29.84m/hour. As shown in Table 17, outliers on their own only achieved a productivity rate of 15.99m/hour.

The trimmed dataset achieved very similar results to the wall area calculations including 16.56% higher productivity than the overall dataset and 86.61% higher productivity than the outlier productivity.

Labour productivity for the overall dataset came in at 4.81m/hour and for the trimmed dataset 5.08m/hour.

Table 17: Project 2 pre-clad wall installation productivity (based on wall length).

Data recording days	Length Installed	Crane productivity		Crane loading crew productivity e.g. driver/dogman			Installation crew productivity (i.e. carpenters & riggers) based on wall length		
	(m)	Net crane time (hours)	Crane Productivity (m/crane hour)	Crew size (No.)	Crew time (hours)	Productivity (m/man/hour)	Crew size (No.)	Crew time (hours)	Productivity (m/man/hour)
1/04/2015	50.39	2.22	22.70	1	2.22	22.70	3	9.66	5.22
7/04/2015	39.02	1.00	39.02	1	1.00	39.02	3	6	6.50
8/04/2015	50.39	1.91	26.38	1	1.91	26.38	3	8.73	5.77
15/04/2015	39.22	2.08	18.86	1	2.08	18.86	3	9.24	4.24
17/04/2015	29.19	1.26	23.16	1	1.26	23.16	3	6.78	4.30
21/04/2015	33.97	1.35	25.17	1	1.35	25.17	3	7.05	4.82
6/05/2015	24.42	1.24	19.70	1	1.24	19.70	3	6.72	3.63
8/05/2015	39.02	1.33	29.34	1	1.33	29.34	3	6.99	5.58
14/05/2015	45.89	1.44	31.87	1	1.44	31.87	3	7.32	6.27
19/05/2015	41.11	1.64	25.07	1	1.64	25.07	3	7.92	5.19
22/05/2015	29.19	1.06	27.53	1	1.06	27.53	2.5	11.65	2.51
26/05/2015	34.84	1.31	26.59	1	1.31	26.59	3	6.93	5.03
Overall dataset calculations	**456.65**	**17.84**	**25.60**		**17.84**	**25.60**		**94.99**	**4.81**
Trimmed dataset only	**369.17**	**12.37**	**29.84**		**12.37**	**29.84**		**72.685**	**5.08**
Outliers dataset only	**87.48**	**5.47**	**15.99**		**5.47**	**15.99**		**22.305**	**3.92**

Notes:

1. Installation crew hours includes net crane time and where required, time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

Similarly, it was again decided to test for differences in crane cycle time potentially brought about by different wall panel sizes. As previously, the frequency distribution of panel sizes was divided into two similar proportions whereby small panels were less than 9.71m^2 (average: 5.80 m^2) and large panels were greater than 9.71m^2 (average: 14.16 m^2). Further to this, another t-test was undertaken to determine if crane cycles times differed for different floor levels including ground floor and first floor installations. All of these tests were based on using the trimmed (normally distributed) dataset.

The results of the first t-test (refer to Table 18) shows that there was a statistically significant difference in the crane cycle time for the two different wall panel sizes – the Sig. value of 0.0.000, falls lower the 0.05 alpha value which means the null hypothesis that the crane cycles for different wall panel size are equal, must be rejected. It was found that crane cycle time for installing larger cassettes (mean 0.143 ± 0.035 hours) was significantly higher than crane cycles for installing small cassettes (mean 0.115 ± 0.034 hours).

Still further, the second t-test (refer to Table 19) shows that there was no statistically significant difference between the crane cycle time for ground floor versus first floor installations – the Sig. value of 0.703, falls above the 0.05 alpha value which means the null hypothesis that the crane cycles for each level are equal, must be accepted.

Table 18: Project 2 t-test of crane cycle time for different wall panel sizes – refer to Appendix B for SPPS generated statistics table.

	N	**Mean**	**Sig.**
Small (<9.71m^2)	48	0.114	
Large (>9.71m^2)	48	0.142	
Total			0.000

Table 19: Project 2 t-test of crane cycle time for different floor levels.

	N	**Mean**	**Sig.**
Ground Floor	44	0.130	
First Floor	52	0.127	
Total			0.703

7.3 Productivity Analysis for CLT Panels and Engineered Beams (Case Study Project 5)

The solid nature of CLT panels represents a different construction scenario to the previously analysed lightweight cassette and pre-clad wall framing scenarios. These panels are heavier in weight and require greater attention to temporary bracing, wind and cranage operations on-site.

Unfortunately, only one such building was available during the period of the research project being case study Project 5 (also refer to Table 1). It involved a large, architect designed, 2 storey residential dwelling which included some curved beams and panels, and was situated on a steeply sloping site with limited site access. Panels were used on the two floor levels and in addition, the roof level above (3 levels in total). Further, a number of prefabricated engineered beams were used as part of the roof construction (these included Glulam beams made as by-products of the CLT process).

The panels and beams were obtained from an overseas supplier and all cut-outs (such as door and window openings) were included in the offsite fabrication. The only exception was a large and particularly deep (1200mm deep) curved box beam which was partially fabricated in Australia and included 3 segments, measuring approximately 25m in combined length. Most of the other beams were 400mm deep.

A large mobile crane (refer to Table 1) was utilised from the very front of the narrow fronted site (which involved difficult access down a narrow dirt track). This and the fact that the entire superstructure was made from CLT meant that it made sense for the crane to stay continuously on-site for the entirety of the panel and beam installation process. The lack of site space and overhanging trees created an inability to move or change the crane siting from its location just inside the front boundary. The crane was also notably used for other miscellaneous lifting processes whilst on-site which have been excluded from the CLT productivity calculations.

Data analysis for this case study used the same methods detailed previously in Section 7.2. These methods are applied separately for floor, wall, and beam installations.

Interpreting from Figure 14, the main subgroup of net crane time is again important because it is used for productivity measurement. It represents 44.30% of gross crane time and involved a total of 105 crane cycles relating to floor and wall panels and beams. For this project, other contributors to gross crane time were more significant relative to other projects – primarily miscellaneous handling of other materials at 34.36% was much higher than on other projects because the small nature of this project meant that the crane fulfilled multiple tasks. Following this, crane operation attributes represented 16.25%, and unexpected stoppages 5.09%.

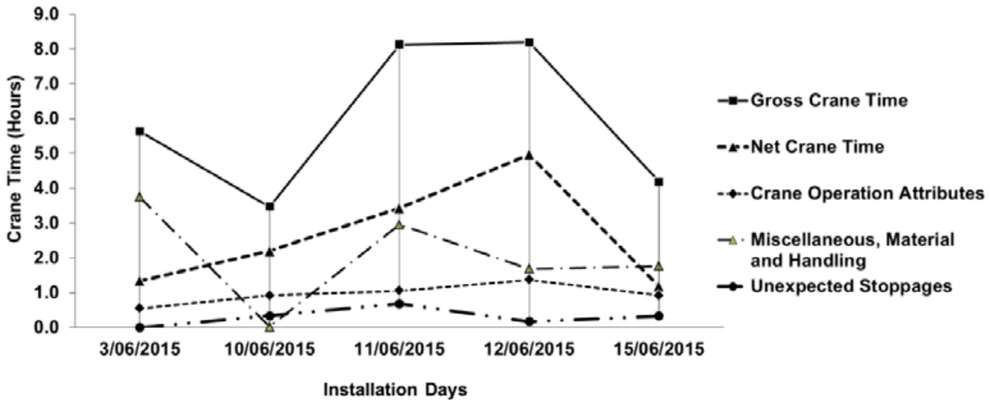

Figure 14: Project 5 gross crane time including breakdown of net crane time and lesser contributors to gross crane time.

7.3.1 CLT Floor Panels

Net crane time for floor panels involved a total of 33 crane cycles as shown in the line chart in Figure 15. Again, the overall dataset has been expressed in terms of outliers and a trimmed dataset within. Even so, the small and variable nature of the sample meant that it was not possible to create the trimmed dataset as a normal frequency distribution (refer to Shapiro-Wilk test result in Table 20 where Sig. values of 0.01 is lower than the chosen alpha level (0.05), thus indicating that the trimmed dataset is not normally distributed). This prevented the ability to carry out ANOVA and t-tests as undertaken for other projects. Instead, the trimmed dataset was created purely on the basis of viewing long crane cycles on the time lapse video, then determining if the work processes involved were of a standard repetitive nature or included aspects that were random, unexpected, or atypical. This was considered to still be useful in helping to identify the main repetitious work process. With regard to this, only a single outlier (29m:00s) was the result of a critical steel support beam being slightly out of position which significantly slowed the ability to place the panel. Ultimately, the trimmed dataset (between the parallel red lines) represented 32 cycles (being a very high 97%) of the overall data set. The range of the trimmed dataset was 1m:30s to 15m:00s.

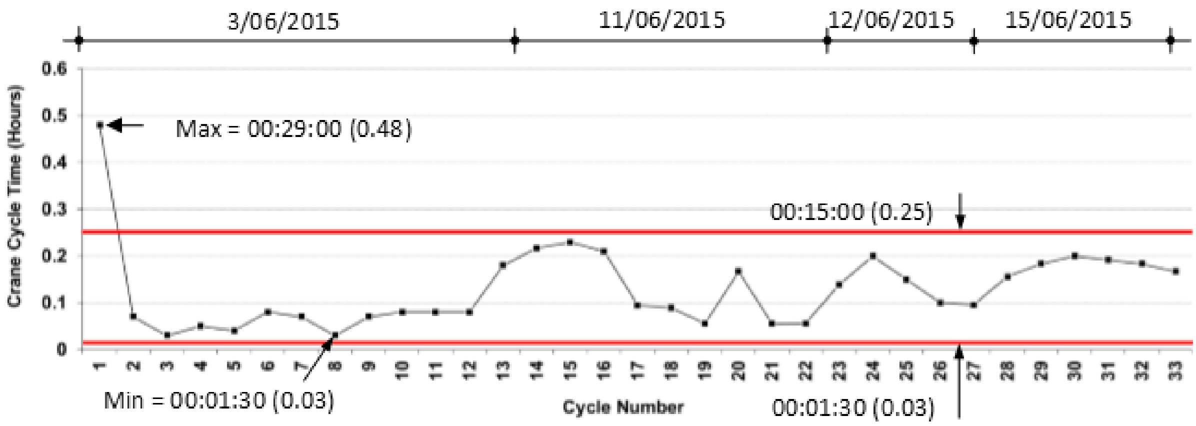

Figure 15: Project 5 line chart showing CLT floor panel crane cycle times (i.e. cycle times contributing to net crane time).

Using both the overall dataset and the trimmed dataset a variety of descriptive statistics are presented in Table 20. Some key points of interest include:

- The mean crane cycle time across all cycles was 7 minutes and 48 seconds and the median cycle time was 6 minutes.
- The mean crane cycle time from the trimmed sample was 7 minutes and 8 seconds and the median cycle time was 5 minutes and 42 seconds.

Table 20: Project 5 descriptive statistics for floor crane cycle times (overall and trimmed datasets).

Statistic	Measured sample (a total number of the measured cycles)	Trimmed sample (i.e. after trimming outliers)
Sample size	33	32
Mean time (hours)	0.130 (7m:48s)	0.119 (7m:8s)
Median time (hours)	0.100 (6m:0s)	0.095 (5m:42s)
Range	0.45 (27m:00s)	0.20 (12m,00s)
Skewness	1.992	0.279
Value of Shapiro-Wilk Test	0.000 (Alpha level 0.05)	0.010 (Alpha level 0.05)

Note: Hours are expressed using both decimal number notation and time notation.

Measured productivity rates for CLT floor panels are presented in Table 21 for the overall dataset and Table 21 for the trimmed dataset[12]. In the first instance, time equated to 4.28 hours and involved laying 342.25m^2 of floor panels, thus resulting in an overall productivity rate of 80.03m^2/hour. For the trimmed situation, less time was involved at 3.8 hours, a lower measured area at 322.25m^2, but ultimately a higher trimmed productivity rate at 84.88m^2/hour. Of note, the trimmed dataset only achieved a marginally higher productivity rate of 6.06%, compared to the overall dataset. Of note amongst these figures, installation on 3/6/15 involved a particularly high installation rate and this was observed, using the time lapse video, to be because most large panels (10 to 23m^2 panel area) were installed on this day. As per analysis for other prefabricated panels, this observation supports the view that larger panels tend to deliver higher installation productivity.

[12] Given that only a single outlier exists for this activity (equating to a productivity rate of 41.65m^2/hour), a dedicated table is not considered appropriate for this activity nor is it addressed in the commentary

Table 21: Project 5 CLT floor panels productivity installation rates.

Data recording days	Area installed per day	Crane productivity		Crane loading crew productivity e.g. driver/dogman			Installation crew productivity i.e. carpenters & riggers		
	(m^2)	Net crane time (hours)	Crane Productivity (m^2/net crane hour)	Crew size (No.)	Crew time (hours)	Productivity (m^2/man hour)	Crew size (No.)	Crew time (hours)	Productivity (m^2/man hour)
3/06/2015	182.59	1.34	136.26	2	2.68	68.13	5	6.70	27.25
11/06/2015	87.63	1.31	66.87	2	2.62	33.43	5	6.55	13.37
12/06/2015	20.81	0.45	46.24	2	0.90	23.12	3	1.35	15.41
15/06/2015	51.22	1.18	43.55	2	2.35	21.78	5	5.88	8.71
Overall dataset calculations	342.25	4.28	80.03	-	8.55	40.01	-	20.48	16.71
Trimmed dataset only	322.25	3.80	84.88	-	7.59	42.44	-	18.08	17.82
Outliers dataset only	19.99	0.48	41.65		0.96	20.83		2.40	8.33

Notes:

1. Installation crew hours includes net crane time, and where required any time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

7.3.2 CLT Wall Panels

Net crane time for wall panels involved a total of 52 crane cycles, as shown in the line chart in Figure 16. A trimmed dataset was created but due to the small and variable nature of the sample, it was not possible to create this as a normal frequency distribution (refer to Shapiro-Wilk test result in Table 22) and instead, the trimmed dataset was created using the same methods described under CLT floor panels (section 7.3.1). On this basis, and reading from Figure 16: , it can be seen that the trimmed data set represents 45 cycles (87%), of the overall dataset. Only a small number of outliers existed with all relating to long cycles (maximum 36m:00s long). Reasons for these long outliers revolved around extra work involving:

- The need to back-prop adjacent panels before the intended panel could be installed.
- The panel not being flush with floor and therefore needing on-the-spot adjustments.
- Extra drilling required to align the connection between panels.
- Adjustment of surrounding lower and side panels to accommodate placement of the closing panel.

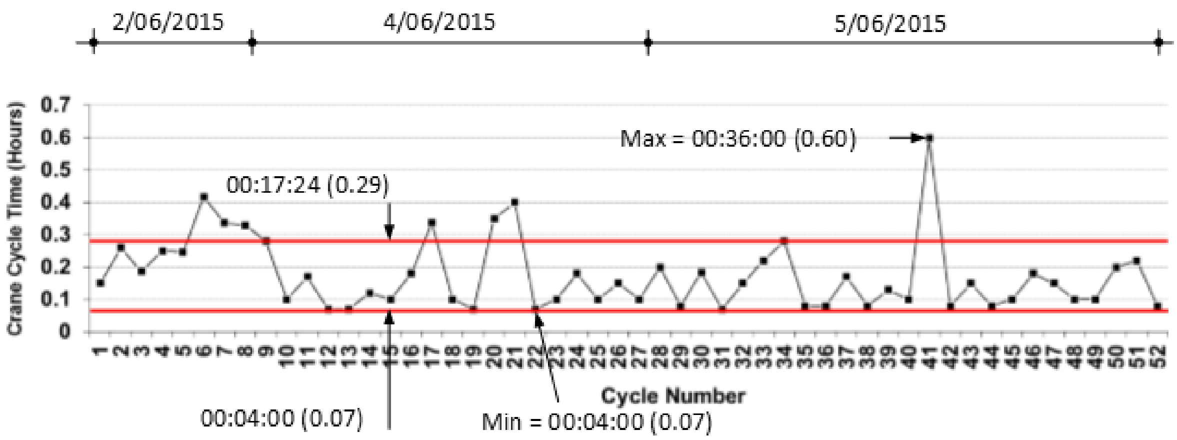

Figure 16: Project 5 line chart showing wall panel crane cycle times (i.e. cycle times contributing to net crane time).

Descriptive statistics for both the overall dataset and the trimmed dataset are presented in Table 22. Some key points of interest include:

- The mean crane cycle time across all cycles was 10 minutes and 12 seconds and the median cycle time was 9 minutes.
- The mean crane cycle time from the trimmed sample was 8 minutes and 24 seconds and the median cycle time was 7 minutes and 12 seconds.

Table 22: Project 5 descriptive statistics for wall panel crane cycle times (overall and trimmed datasets).

Statistic	Measured sample (a total number of the measured	Trimmed sample (i.e. after trimming outliers)

	cycles)	
Sample size	52	45
Mean time (hours)	0.17 (10m:12s)	0.14 (8m:24s)
Median time (hours)	0.15 (9m:0s)	0.12 (7m:12s)
Range	0.53 (31m:48s)	0.21 (12m:36s)
Skewness	1.61	0.726
Value of Shapiro-Wilk Test	0.000 (Alpha level 0.05)	0.000 (Alpha level 0.05)

Note: Hours are expressed using both decimal number notation and time notation.

Measured productivity rates are first presented in terms of wall area and then in terms of lineal metres.

In terms of wall area and based on the overall dataset (Table 23) it can be seen that time equated to 9.09 hours and involved laying 241.6m^2 of wall panels which resulted in an overall productivity rate of 26.59m^2/hour. Table 23 shows that for the corresponding trimmed dataset analysis, less time was involved at 6.32 hours, a lower measured area at 207.48m^2, but ultimately a higher productivity rate at 32.85m^2/hour. The productivity rate for outliers was much lower at 12.32m^2/hour. Of note, the trimmed dataset achieved 23.5% higher productivity than the overall dataset.

Table 23: Project 5 CLT wall installation productivity rates (based on area).

Data recording days	Area installed per day	Crane productivity		Crane loading crew productivity e.g. driver/dogman			Installation crew productivity i.e. carpenters & riggers		
	(m^2)	**Net crane time (hours)**	**Crane Productivity (m^2/net crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man hour)**
2/06/2015	32.55	2.18	14.95	2	4.35	7.48	5	10.88	2.99
4/06/2015	90.48	3.05	29.70	2	6.09	14.85	5	15.23	5.94
5/06/2015	118.57	3.86	30.69	2	7.73	15.35	3	11.59	10.23
Overall dataset calculations	**241.60**	**9.09**	**26.59**	**-**	**18.17**	**13.29**	**-**	**37.71**	**6.41**
Trimmed dataset only	**207.48**	**6.32**	**32.85**		**12.63**	**16.42**		**25.06**	**8.28**
Outliers dataset only	**34.12**	**2.77**	**12.32**		**5.54**	**6.16**		**12.65**	**2.70**

Notes:

1. Installation crew hours includes net crane time and where required, any time for preparatory and trailing activities.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

Wall productivity in terms of length (lineal metres of wall installed) is presented for the overall dataset in Table 24 and shows that the net crane time equated to 9.09 hours and involved laying 144.98m of wall length, thus resulting in an overall productivity rate of 15.96m/hour. Table 24 shows the corresponding analysis for the trimmed dataset which involves a higher productivity rate of 20.58m/hour. Of note, the trimmed dataset achieved 29% higher productivity than the overall dataset.

Table 24: Project 5 CLT wall installation productivity rates (based on wall length).

Data recording days	Length installed	Net crane time		Crane loading crew e.g. driver/dogman			Installing crew i.e. carpenters & riggers		
	M	hours (expressed as number)	Productivity based on net crane time m/hour	Workers	Hours	Productivity m/hour m/hour	Workers	Hours	Productivity m/hour
2/06/2015	20.37	2.18	9.36	2	4.35	4.68	5	10.88	1.87
4/06/2015	51.68	3.05	16.96	2	6.09	8.48	5	15.23	3.39
5/06/2015	72.93	3.86	18.88	2	7.73	9.44	3	11.59	6.29
Overall dataset calculations	**144.98**	**9.09**	**15.96**	**-**	**18.17**	**7.98**	**-**	**37.71**	**3.84**
Trimmed dataset only	**129.98**	**6.32**	**20.58**	**-**	**12.63**	**10.29**	**-**	**25.06**	**5.19**
Outliers dataset only	**15.00**	**2.77**	**5.42**	**-**	**5.54**	**2.71**	**-**	**12.65**	**1.19**

Notes:

1. Installation crew hours includes net crane time and where required, any time for preparatory and trailing activities where required.
2. Hours are expressed using decimal number notation.
3. Productivity calculations are based on net crane time (i.e. crane cycles devoted purely to prefabricated timber installation).

7.3.3 Prefabricated Engineered Beams

Net crane time for engineered beams involved a total of 20 crane cycles as shown in Figure 17. With regard to this, a trimmed sample was obtained and was sufficient to meet the requirements of a normal distribution[13]. It represents 16 cycles (80%) of the overall data set (with outliers representing the remaining 20%). With regard to this, slow outlier cycles were the main area of concern – the maximum outlier took a long 1h:46m. Reasons for the outliers were individually analysed using the video data and adhered to a consistent reason primarily caused by:

- Lifting three long and deep (1200mm deep) curved boxed beams which needed to be joined to form a continuously curved (25m long) load bearing beam supported only at two extreme ends, hence creating a complex and high tolerance process.
- Installation of a 9m propped cantilevered beam which had a complex connection in terms of the cantilevered supporting the cantilevered end of another beam – again a complex and high tolerance process.

Given these reasons, it is considered best to think of these outliers as representing a special subgroup of beams characterised by special shapes, complex connections, and high tolerances that subsequently take longer to install than straight and relatively simple situations.

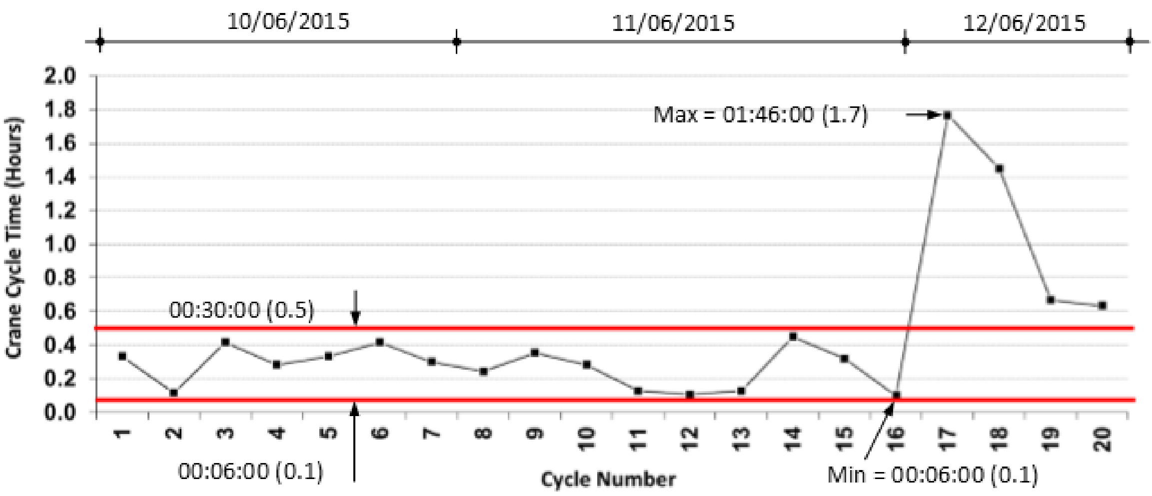

Figure 17: Project 5 line chart for beam installation crane cycle times (i.e. cycle times contributing to net crane time).

Using both the overall dataset and the trimmed dataset, descriptive statistics are presented in Table 25. Some key points of interest include:

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13 Using the Shapiro-Wilk test, the Sig. of 0.103 (refer to Table 25) was greater than the chosen alpha level (0.05), therefore it can be accepted as being normally distributed. A Q–Q plot was also applied

- The mean crane cycle time across all cycles was 26 minutes and 31 seconds and the median cycle time was 19 minutes and 30 seconds.
- The mean crane cycle time from the trimmed sample was 16 minutes and 12 seconds and the median cycle time was 17 minutes and 24 seconds.

Table 25: Descriptive statistics for Project 5 beam crane cycle times (overall and trimmed datasets).

Statistic	**Measured sample (a total number of the measured cycles)**	**Trimmed sample (i.e. after trimming outliers)**
Sample size	20	16
Mean time (hours)	0.442 (26m:31s)	0.27 (16m:12s)
Median time (hours)	0.325 (19m:30s)	0.29 (17m:24s)
Range	1.67 (100m:00s)	0.35 (21m:00s)
Skewness	2.306	-0.180
Value of Shapiro-Wilk Test	0.000 (Alpha level 0.05)	0.103 (Alpha level 0.05)

Note: Hours are expressed using both decimal number notation and time notation.

Measured productivity rates based on net crane time, are presented in Table 26. The Table also includes a breakdown of this productivity into individual components such as the trimmed dataset productivity and the outlier productivity.

For instance, reading from Table 26 time measured for the overall dataset equated to 8.83 hours and involved laying 84.58m of beam length, thus resulting in an overall productivity rate of 9.58m/hour. The table shows corresponding analysis for the trimmed dataset which involved less time at 4.32 hours, a lower measured length at 48.78m, but ultimately a higher productivity rate at 11.30m/hour. Of note, the trimmed dataset achieved 18% higher productivity than the overall dataset. It also achieved 42.5% higher productivity than the productivity associated with outliers (7.93m/hour) as also shown in Table 26. These findings are consistent with earlier analysis in this report, and to reiterate, these findings support that the trimmed dataset findings represent a benchmark productivity that adopts a relatively controlled crane cycle and reduces outliers. In this case, it more specifically excludes complex and high tolerance beam situations which based on this very limited and non-generalisable dataset, may take in the order of 42% longer to execute.

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for verification purposes, which supports the data being normally distributed.

Table 26: Project 5 beam installation productivity rates (based on beam length).

Data recording days	**Length installed per day**	**Net crane time**		**Crane loading crew e.g. driver/dogman**			**Installing crew i.e. carpenters & riggers**		
	m	hours (expressed as number)	Productivity based on net crane time m/hour	Workers	Hours	Productivity m/hour m/hour	Workers	Hours	Productivity m/hour
10/06/2015	24.46	2.20	11.12	2	4.40	5.56	4	10.80	2.26
11/06/2015	24.32	2.12	11.50	2	4.23	5.75	5	13.08	1.86
12/06/2015	35.80	4.52	7.93	3	13.55	2.64	3	15.05	2.38
Overall dataset calculations	**84.58**	**8.83**	**9.58**	**-**	**22.18**	**3.81**	**-**	**38.93**	**2.17**
Trimmed dataset only	**48.78**	**4.32**	**11.30**		**8.63**	**5.65**		**23.88**	**2.04**
Outliers dataset only	**35.80**	**4.52**	**7.93**		**13.55**	**2.64**		**15.05**	**2.38**

Measured productivity rates have also been calculated based on beam area (single beam face only) primarily because this allows comparison with wall and floor area measurement. In other respects this approach tends to be less useful and less intuitive. Notwithstanding the above, the overall dataset for beam area presented in Table 26 shows that time equated to 8.83 hours and involved laying 53.9m^2 of beams, thus resulting in an overall productivity rate of 6.10m^2/hour. The table shows corresponding analysis for the trimmed dataset which involved less time at 4.32 hours, a lower measured area at 18.24m^2, and resulted in a lower productivity rate at 4.23m^2/hour compared to the overall dataset. Of note, the trimmed dataset achieved only 96.3% productivity of the overall dataset which contrast significantly with earlier trends in the overall analysis. This was because the overall dataset included the previously discussed large and curved beams which involved a much increased beam area.

Finally, and as mentioned above, outliers could more correctly be described as representing a special category of complex and high tolerance beam installation. As shown in the table the situations yielded a productivity rate of 7.9m^2/hour and for the same reasons as above (i.e. large beam surface area), this category achieved a 53.5% higher productivity than for the trimmed dataset.

Whilst the above findings show an interesting anomaly where productivity is measured on beam area, it is generally considered a poor measure of beam productivity for daily usage – especially given that most beams are much longer than they are deep.

Table 27: Project 5 beam installation productivity rates (based on area).

Data recording days	**Area installed per day**	**Net crane time**		**Crane loading crew e.g. driver/dogman**			**Installing crew i.e. carpenters & riggers**		
	m^2	hours (expressed as number)	Productivity based on net crane time **m^2**/hour	Workers	Hours	Productivity m/hour **m^2**/hour	Workers	Hours	Productivity m2/hour
10/06/2015	9.35	2.20	4.25	2	4.40	2.12	4	10.80	0.87
11/06/2015	8.89	2.12	4.21	2	4.23	2.10	5	13.08	0.68
12/06/2015	35.66	4.52	7.90	3	13.55	2.63	3	15.05	2.37
Overall dataset calculations	**53.90**	**8.83**	**6.10**	**-**	**22.18**	**2.43**	**-**	**38.93**	**1.38**
Trimmed dataset only	**18.24**	**4.32**	**4.23**	**-**	**8.63**	**2.11**	**-**	**23.88**	**0.76**
Outliers dataset only	**35.66**	**4.52**	**7.90**	**-**	**13.55**	**2.63**	**-**	**15.05**	**2.37**

8. Qualitative Findings – Supply Chain Interviews and Site Observations

Findings from the interview data coupled with site observations are provided in bullet point form and under selected areas of content below. These findings aim to add context to the previous quantitative findings and identify key areas that need to be addressed by the practitioner in order to ensure optimum productivity when installing prefabricated timber construction.

Pre-Construction, Offsite Production Issues:

- Early pre-fabricator involvement typically improves the cost effectiveness of both offsite and on-site production processes.
- The economics of offsite production revolves around skill in panelising the building layout into a limited number of repetitious assemblies. Economies of scale and structural efficiency are important. Some specific issues include:
  - Regarding economies of scale – cassettes are commonly sized in multiples of floor sheet sizes to minimise the need for specialised cutting and to avoid unusable offcuts.
  - Regarding structural considerations – long span situations may require intermediate beams hidden within the depth of cassettes to retain a flat plane appearance which can add to cost and fabrication complexity.
- There is need to manage dimensional tolerances in prefabricated assemblies but this varies according to site needs:
  - High tolerance floor sheets – as used in fabrication of floor cassettes – facilitate an accurate cassette shape which reduces tolerance creep on-site.
  - Joints between assemblies and set-downs for wet areas and balconies require key attention – simplicity is important.
  - Pre-clad and CLT walls may encounter tolerance problems where floor flatness is poor.
- Delivery logistics are important where:
  - Delivery schedules must coincide with site based work flows.

- Particularly wide cassettes (e.g. greater than 3.0m) may cause delivery problems by invoking the need for a truck escort and limited road usage times. This tends to cost more and restricts site work flow options.
- The method of stacking the cassettes on delivery trucks in correct order of installation, avoids double handling on-site.

Onsite Construction Processes

- Timber assemblies are lightweight relative to concrete construction but crane selection is still important subject to loading scenarios and site specific variables. Whilst large cranes offer certain scale based advantages, bigger cranes than necessary are often slower to manipulate. Operator visibility and sense of space is important which is often easier on small projects, or easier using remote crane operation. The main options observed during this research include:
  - Delivery truck mounted cranes: These offer fast set up and take down times. They do not incur “float costs”. Careful sequencing of deliveries avoids the need for multiple changes to setup locations once on-site. This approach can subsequently offer a high ratio of net crane time, to gross crane time. Even so, usage of this approach is best suited to relatively small sites, close access to the building footprint area, lightweight assemblies, relatively low loads, and low reach situations.
  - Mobile cranes: These generally take longer to set up and takedown than the above, but this can be mediated by setting up for multiple days where continuous work flow is possible or; in light load and short reach situations all terrain wheeled cranes present an alternative that does not involve usage of outriggers. To avoid time wastage, mobile crane and materials deliveries may need to be carefully coordinated where site storage of panels is not possible. Mobile cranes increasingly become a necessity on medium to larger sites where longer reach and higher loading capability are required.
  - Fixed cranes: These cranes potentially have very low setup time at least within the confines of prefabricated timber installation activities. Reach and load carrying capacity are generally greater than for the other options but there is greater need for pre-planning of loading scenarios. Manoeuvrability will also vary with hammerhead versus luffing crane options (including boom and jib angles). This approach potentially provides a high ratio of net crane

time to gross crane time. In general, this approach mainly applies to larger projects where economies of scale and long term use are applicable.

- Pre-construction planning is key including attention to joint detailing, delivery schedules, unloading sequences, expected productivity rates and work flows on-site.
- Incorrectly sequenced panels cost time and money on-site. Issues include:
  - Picking up a piece more than once costs crane time.
  - (Notwithstanding the above), small assemblies are often placed on top of the delivery so as not to destabilise the bottom, but this places them out of installation sequence. Such panels are often then piggybacked onto large cassettes, later in the installation process, so as not overly impact on installation productivity.
  - Large-scale temporary storage can be problematic on tight sites and is less efficient than a coordinated just-in-time delivery, where possible.
- Preferred on-site installation practices include:
  - Placing longer and straight cassettes on perimeter line firts, creates a reference set-out line for following panels.
  - Best to lay panels in a continuous laying pattern, rather than setting up separate clusters that ultimately create the need for tightly bound closing panels.
  - Use a ratcheting tool “turfer” to draw large and heavy wall panels together to make tight joints possible and to avoid tolerance creep.
  - Installation crews to have balanced workflows with a view to ensuring each worker is fully deployed – this is best achieved creating a rhythm around the crane cycle time. Less critical activities (such as nailing/screwing off) can be deployed to trailing activities after the crane is finished. Crew sizes are generally small but must be sized to assist optimum crane cycle efficiency.
    - An example for CLT includes a crew supervisor who locates panels, a second person to assist, a third person to help the dogman to load/direct panels, a fourth person for bracket installation and additional fixings, and a fifth person to handle temporary bracing poles (for wall panels). More crew may be required on larger projects.
    - An example for floor cassettes and pre-clad wall panels includes a crew supervisor who locates panels, a second person who assists,

and a third person for bracket installation, additional fixings and miscellaneous help. More crew may be required on larger projects.

- Climatic conditions effect crane installation speed. Specific issues include:
    - Wind is mainly a problem for pre-clad wall panels due to the amount of wind exposed surface area. The problem manifests more as height increases. Floor cassettes are somewhat less affected because of the much lower profile to the wind.
    - Rain prevents progress – surfaces become too slippery to work safely; pre-clad walls with absorbent claddings may become considerably heavier to lift.
- In order to create perceivable value to clients and head contractors, care must be taken to ensure prefabricated construction cost effectively delivers a building faster in overall terms. To do this, care must be taken to ensure systems synergistically and efficiently interface with traditional site processes such as brickwork, eaves and gutter installation, external render, painting, and scaffolding (where applicable).

Safety Onsite

- Safety requirements vary according to regulatory requirements, risk assessment, location and project size. This in turn has ramifications for site processes which will in turn impact on productivity output.
- Crew sizes are relatively small for prefabricated construction hence reducing safety risk and allowing greater focus on a reduced number of people.
- Prefabricated timber floor systems can be designed as underfloor erection systems to avoid workers working at height.
- Some floor cassette systems utilise lifting bracket set into the assembly, and once these assemblies are in place, there is potential to reuse the brackets as anchor points for the likes of safety harnesses.
- When slinging or attaching panels to the crane hook of the delivery truck, the top of the stack may be quite high and subsequently care needs to be taken is setting up appropriate safe work procedures.

9. Combined Findings and Conclusions

Panelised prefabricated timber construction offers a fast and productive site installation process. Cranage provides the lead resource, as it dictates the speed of installation – therefore optimising crane time is central to optimising productivity.

As a subset of gross crane time, the study purposely focused on net crane time as the basis for measuring productivity, being the time dedicated to crane cycles involved directly in installing prefabricated timber panels (521 cycles were measured relating to the installation of 5,592m^2 of panels plus a limited number of beams).

Other contributors to gross crane time were found to include unexpected stoppages, miscellaneous handling of other materials, and crane operation attributes (setup time, take down time, and scheduled breaks)[14]. The former two included random events and issues unrelated to prefabricated timber installation productivity. The latter area is of potentially higher relevance to installation productivity but assessment of this tends to be particularly site specific and dependent on holistic crane selection criteria. Such criteria often go beyond the pure needs of prefabricated timber installation and relate to project-wide issues. Subsequently, a project specific additional allowance should be considered for crane operating attributes if perceived to impact on installation productivity rates.

Crane cycles contributing to net crane time were measured on each project and analysed under two scenarios including: the overall dataset of cycle times and a trimmed dataset within. This latter scenario purposely removed especially fast and slow outlier cycles from the overall dataset, mainly to provide a normally distributed dataset. In principal, the trimmed dataset also provides an idealised benchmark of what could be achieved if crane operation could be managed in a more predictable and controlled process that avoided lengthy outlier cycles. For instance, based on the projects studied careful pre-planning, tolerance control, and design detailing could serve to avoid most of the lengthy outlier cycles observed on-site.

Trends drawn from t-test analysis indicate that in three out of the 4 situations tested, there was evidence of crane cycle times varying according to panel size, whereby larger panels took longer than smaller panels to install (based on comparison of mean values for each group). Even so, it is noteworthy that despite this test, in real terms it is evident the difference in cycle times for large and small panels was very minor - large and small panels only differed in cycle time by 0m:47s, 1m.0s and 1m:41s respectively, across the three

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[14] Gross crane time is the overall crane time deployed for a given activity; unexpected stoppages includes waiting time.

situations. Further, this extra time for large panels was more than offset by the increased area installed – hence providing a better result in productivity terms. For instance, across the three situations, large panel sizes ranged from being a minimum of 60% larger and maximum of 230% larger, than small panel sizes for each respective project (refer pages 35, 41 and 46 for details). Subsequently, a small amount of extra crane cycle time for large panels resulted in a much greater amount of panel area being installed. To some extent, the fourth case showed similar trends albeit that no statistically significant difference was detected between large and small panels. For instance, the cycle times were in statistical terms the same, but the large panels (being on average 144% larger than small) meant that as above, a much greater area was installed in the same time period (refer page 57 for details). Future research should check and further validate this finding because it suggests that where possible, architectural designs are best converted to panel layouts that optimise large panels as they provide higher installation productivity.

On a separate issue, ANOVA and t-tests show no statistically significant difference in terms of crane cycle times vary according to the installation of different floor levels. This is most likely because the 2 and 3 level buildings used in this research did not sufficiently vary in height to detect such differences. The situation may change on taller buildings. In such instances, it is expected that wind will probably be the main issue affecting crane cycle times on taller buildings more so than crane lifting speeds[15].

Labour productivity mainly works in a supportive way with the crane. The greater the synchronisation between the two, the better the overall productivity. The crane crew is often supplied as a fixed part of the overall crane package (often involving a crane operator and a dogman). The dogman is important where necessary to help guide and direct loads especially on wind effected days, and where driver visibility is poor. Remote crane operation is a useful variant that can assist driver visibility, sensitivity, and coordination of operations – it therefore potentially provides improved productivity for this aspect of site processes. Notwithstanding crane crew involvement, the installation crew was the main labour variable of interest because it was independent of the crane operation, could be up-scaled or down-scaled according to perceived need, but still had to work in a highly synchronised way with the crane. It was found that only small installation crews were required on the sites studied: the crew for the pre-clad wall panel project ranged from 2-3 workers, crews for cassette projects ranged from 3-4 workers, and the crew for the CLT project still only involved a

[15] For instance, perusal of the technical specifications of commonly available mobile cranes indicate winch speed in the vicinity of 115m/min which could therefore traverse floor levels quickly, albeit that to hoist at high speed, cranes may only be lifting at 30% of capacity and without significant wind issues impacting on the load.

relatively small 5 workers. It is considered that adding more workers to installation crews may not necessarily provide directly proportionate increases in productivity. Whilst this may change marginally for larger projects, or where teams carry out a broader variety of tasks than described in this report, crew sizes are still expected to remain small relative to more labour intensive methods.

Under most circumstances, crane productivity measurements are thought to be the most appropriate way to consider productivity in common project situations. Installation crew productivity rates are thought to be less useful in this context but are still useful for more detailed comparison where comparing crew performance between prefabrication projects or; where comparing prefabrication projects with traditional labour intensive construction.

Average (mean) productivity rates are perhaps the easiest way to interpret findings from the study. In an overall sense, the combined cassette, pre-clad wall, and CLT floor/wall/beam data equates to a general panel average of 67.4m^2/crane hour (based on overall dataset) and 79.8m^2/crane hour (trimmed dataset). Even so and for greater accuracy, differences for specific panel types are discussed under dedicated headings below. Trends within this study need to be verified by a larger sample, but indicate that a potential relationship exists whereby floor panel installation productivity is somewhat faster than the general panel average; wall panel productivity tends to be slower than the general average (logical reasons for this are discussed under relevant sub-headings that follow).

For all of these panel types it was found that variances within each respective group were a function of multiple variables including the size of the project, the appropriateness and inherent efficiency of the chosen prefabrication system, delivery logistics, and the prevailing on-site work environment (including work flow, wind, site access, rain, meeting safety requirements). The efficiency and appropriateness of crane selection is also particularly important and to some extent responds directly to the former issues. Nimble, fast, and repeatable crane cycles are central to the achievement of productivity. It was found that particularly slow outlying crane cycles reduced productivity rates significantly. In absolute terms, this impacts on larger projects more so than smaller projects (all other variables being equal).

Floor/Roof Cassette Installation Productivity

Table 28 provides an overview of cassette productivity rates relating to the 4 cassette installation projects in the study. Here, the average rate was 83.1m^2/crane hour (overall dataset) and 100.1m^2/crane hour (trimmed dataset). Labour productivity rates for installation crews were on average 20.9m^2/man/hour (overall dataset) and 24.2m^2/man/hour respectively (trimmed dataset).

For benchmarking crane productivity and based on the trimmed dataset, cassettes provided 25% higher productivity than the previously mentioned general panel average above (79.8m^2/crane hour).

Table 28: Overview of combined cassette productivity installation rates.

Descriptive statistics	**Area installed**	**Crane productivity**		**Installation crew productivity i.e. carpenters & riggers**		
	(m^2)	**Net crane time (hours)**	**Crane Productivity (m^2/crane hours)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man/hour)**
Overall dataset mean	1425.34	20.51	83.1	3.5	86.23	20.9
Trimmed dataset Mean	1114.72	13.35	100.1	3.5	56.63	24.2

Pre-Clad Wall Panel Productivity

Table 29 provides an overview of productivity rates from the single pre-clad wall project studied. Understandably, it is difficult to make broad generalisations based on such a small sample. Of note, productivity rates are provided in terms of wall area, but wall length rates are also provided in Section 7.2. On this basis, the average installation productivity rate was 66.65m^2/crane hour (overall dataset) and 77.47m^2/crane hours (trimmed dataset). Labour productivity rates for the installation crew averaged 12.5m^2/man hour and 13.18m^2/man hour, respectively.

Table 29: Overview of combined pre-clad productivity installation rates.

Descriptive statistics	**Area installed**	**Crane productivity**		**Installation crew productivity i.e. carpenters & riggers**		
	(m^2)	**Net crane time (hours)**	**Crane Productivity (m^2/crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man/ hour)**
Overall dataset Mean for pre-clad wall	1188.97	17.84	66.65	3	94.99	12.52

productivity						
Trimmed dataset Mean for pre-clad wall productivity	958.34	12.37	77.47		72.68	13.18

For benchmarking crane productivity (based on the trimmed dataset), pre-clad walls provided 3% lower productivity than the general panel average. Whilst this finding is thought to be logical since wall installation includes increased surface area exposed to wind during cranage, greater time and accuracy required in aligning and positioning walls, greater problems from poor floor flatness tolerances, less assistance from gravity during placement and greater need for temporary bracing, a larger sample of pre-clad wall projects is required to more accurately and confidently quantify productivity.

CLT Floor, Wall, and Solid Timber Beam Productivity

As with pre-clad walls, the single project studied for CLT means broad and confident generalisations about installation productivity rates are not possible. Notwithstanding this, Table 29 provides an overview of productivity rates from the case study. Of note, rates are provided in a mix of areas (for floors and walls) and lengths for beams. For comparative purposes, alternative units of measure for walls (based on wall length) and beams (based on beam face area) are also provided in Section 7.3.

CLT Floor Panels

The average installation productivity rate for CLT floor panels was 80.03m^2/crane hour (overall dataset) and 84.88m^2/crane hour (trimmed dataset). For labour productivity, the CLT floor panel installation rate was 16.71m^2/man hour (overall dataset) and 17.82m^2/man hour (trimmed dataset).

For the purposes of benchmarking crane productivity (based on the trimmed dataset above), CLT floor panels provide 6.4% higher productivity than the general panel average and this above average productivity rate is consistent with cassette floors. This supports the proposition that floors panels provide higher installation productivity than wall panels.

CLT Wall Panels

Reading from Table 29, the average installation productivity rate for CLT wall panels was 26.59m^2/crane hour (overall dataset) and 32.85m^2/crane hour (trimmed dataset). For labour productivity, the CLT wall panel installation rates were 6.41m^2/man hour (overall dataset) and 8.28m^2/man hour (trimmed dataset).

For the purposes of benchmarking crane productivity (based on the trimmed dataset above) the CLT wall panels provided somewhat lower productivity than the general panel average. Reasons for this include those already mentioned for pre-clad walls but in addition, the extra weight of CLT potentially adds to the subsequent need for more rigorous bracing and tools for cramping panels together. Odd shaped walls associated with this project potentially also impacted on the productivity measured. As stated previously, this single case study is insufficient to know if the measured productivity is representative of what can generally be expected on a broader sample of projects – a larger sample of CLT wall projects is required to more accurately, and confidently quantify and qualify installation productivity albeit that such projects were not available during this research study.

Table 30: Overview of combined productivity installation rates for CLT floor panels, CLT wall panels, and engineered beams

Descriptive statistics	**Area installed**	**Crane productivity**		**Installation crew productivity i.e. carpenters & riggers**		
Floor and wall panels	**(m^2)**	**Net crane time (hours)**	**Crane Productivity (m^2/net crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m^2/man/ hour)**
Mean productivity for CLT floor panels (based on overall dataset)	342.25	4.28	80.03	-	20.48	16.71
Mean productivity for CLT floor panels (based on trimmed dataset)	322.25	3.80	84.88	-	18.08	17.82
Mean productivity for CLT wall panels (based on overall dataset)	241.6	9.09	26.59		37.71	6.41
Mean productivity for CLT wall panels (based on trimmed dataset)	207.48	6.32	32.85		25.06	8.28
Beams	**(m)**	**Net crane time (hours)**	**Crane Productivity (m/net crane hour)**	**Crew size (No.)**	**Crew time (hours)**	**Productivity (m/man/ hour)**
Mean productivity for engineered beams (based on overall dataset)	84.58	8.83	9.58	-	38.93	2.2
Mean productivity for engineered beams (based on trimmed dataset)	48.78	4.32	11.30	-	23.88	2.0

Engineered Beams

Beams are typically measured by length rather than area. As shown in Table 29, the average installation productivity rate for engineered beams was therefore 9.6m/crane hour (overall dataset) and 11.30m/crane hour (trimmed dataset). For labour productivity, the CLT wall panel installation rates were 2.17m/man hour (overall dataset) and 2.04m/man hour (trimmed dataset). Complex, curved and deep beams influenced these results. It is expected that quite different results would be obtained if systematically installing long span beams according to a standard and repetitive layout, as may occur in the likes of office building construction. Unfortunately, such buildings were not available during this study.

Findings from Interviews and Site Observations

Interviews and site observations provided context to the above productivity rates. Key areas include:

- A specific need for care in pre-construction and offsite production planning including early pre-fabricator involvement, providing economies of scale in offsite production, designing-in structural efficiency into panel and beam layouts, providing accurate dimensional tolerances, and providing thoughtful delivery logistics.
- Understanding work flow on-site including careful thought around pre-construction planning, crane section, preferred on-site installation practices, and managing the impact of climate conditions.
- Safety requirements vary according to regulatory requirements, risk, size and location. This in turn effects site processes which impact on productivity output.

Recommendations and Future Work

A key arising issue from the above is simply the need to gather more project data to help verify the findings from this project - especially regarding CLT installation. More broadly, it is apparent that from a client and building supply chain perspective, prefabricated timber construction competes with traditional methods as a means to an end in providing a fast and weather resistant shell for the building. Usage of individual assemblies such as floor cassettes help achieve this and are a step in the right direction, but ongoing work should focus on more holistic structure/envelope solutions - such as the more complete floor, wall and roof solutions commonly provided by the likes of CLT systems. For instance, prefabricated systems in general must create a value proposition that works for the entire construction process including the delivery of fast delivery process in terms of the structure/envelope of the entire project rather than for individual elements (as analysed in this study). In another instance, it must synergistically fit-in with facade and MEP systems in order to provide an overall productive system. Finally, timber prefabrication systems must aim to re-engineer or reduce less value adding parts of the building process – especially, expensive temporary works such as scaffolding. In this process, productivity benchmarking against traditional construction methods should be undertaken in order to prove the benefits of prefabricated timber in an evidence based way.

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Appendix A

Interview questions.

Item	**Interview questions**
Consent question (asked and audio recorded for all participants)	Thanks for reading through our information sheet. Now that you have an understanding of the research project, would you be prepared to participate in a brief interview about this project (i.e. the project being investigated)?
Role of person being interviewed	Content questions
FACTORY SCHEDULER/ PLANNER	1. Please tell me about the process of planning and scheduling the production of prefab panels for this project? (If required) What about delivery logistics?
	2. Tell me about the main criteria you use when determining panel size and panel weight for a project?
	3. In your opinion can the current planning and scheduling be improved in any way?
	4. What are the major decisions at manufacturing stage that potentially impact on on-site productivity?
	5. Does design complexity affect the productivity of installing prefabricated panels on-site?
	6. In your opinion what are the main constraints in the overall process of prefab panel construction? (As required) what about manufacturing, delivery and erection issues.
	7. What improvements can you suggest for the jointing of panels to make it a better result (on-site)?

Item	Interview questions
TIMBER ERECTOR, **SITE MANAGER and/or HEAD CONTRACTOR**	1. From your experience how does prefabricated timber construction compare to traditional construction methods in terms of site productivity?
	2. What are the main constraints in the overall process of delivery and erection, that effect productivity?
	3. Can you suggest any improvements to make it a better result on-site? (As required): • What about the jointing of panels • What about planning, scheduling, storage and delivery methods?
	4. Describe how much design complexity affects the productivity of installing prefabricated panels on-site?
	5. What do you believe is the best crew size and composition to provide the best productivity? (If required) Can you explain the logic behind your thinking?
	6. What are the main variables that affect productivity on-site? (prompts) weather, design changes, deliveries, storage, jointing, planning
	7. How does panel construction compare with traditional construction with regard to the safety methods used?
CRANE DRIVER/ OPERATOR	1. What could improve your crane cycle time for erecting the panels?
	2. What are the main constraints in your part of the process that affects productivity? (As required):

Item	**Interview questions**
	• What about the current storage location and the delivery schedule, • What about the weather?
	3. Given that crane movements tend to dominate the installation process, what do you believe is the best crew size (or number of crews) to get the best result? (If required) Can you explain the logic behind your thinking?
	4. Can you suggest any improvements to the current methodology to achieve higher productivity on-site?

Appendix B

SPPS generated statistics tables as referenced in the body of the main report.

Table 31: Project 1 ANOVA test of crane cycle time for installing cassettes on different building levels.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	83045.552	2	41522.776	2.835	.063
Within Groups	1611033.528	110	14645.759		
Total	1694079.080	112			

Table 32: Project 1 t-test of crane cycle time for installing for installing different cassette sizes

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
CraneCycleTime	Equal variances assumed	.045	-.0128752	.0063400
	Equal variances not assumed	.045	-.0128752	.0063535

Table 33: Project 2 t-test of crane cycle time for installing different cassette size.

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
CraneCycle	Equal variances assumed	.290	-.009497	.008898
	Equal variances not assumed	.287	-.009497	.008844

Table 34: Project 3 T- test of crane cycle time for installing different cassette size.

		t-test for Equality of Means		
		df	Sig. (2-tailed)	Mean Difference
AverageCraneCycleTime	Equal variances assumed	42	.018	-.01754
	Equal variances not assumed	38.935	.014	-.01754

Table 35: Project 2 t-test of crane cycle time for installing different wall panel sizes.

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
NetCraneCycle	Equal variances assumed	.000	-.02812	.00713
	Equal variances not assumed	.000	-.02812	.00713

Table 36: Project 2 t-test of crane cycle time for different installing walls on different floor levels

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
NetCraneCycle	Equal variances assumed	.703	.00295	.00772
	Equal variances not assumed	.700	.00295	.00765