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Trialling the Value of RFID Technology in Prefabricated Timber Construction

Project number: PNA381-1516

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Forest & Wood Products Australia

Trialling the Value of RFID Technology in Prefabricated Timber Construction

Prepared for

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Executive Summary

The project addresses Forest and Wood Products Australia's investment plan for increased use of prefabricated timber in multi residential and commercial buildings. Realizing the full benefits of prefabricated timber systems in construction of multistorey buildings is reliant on integration and efficiency along the upstream logistics and supply chain. Therefore, the purpose of this research is to determine the potential value that use of Radio- Frequency Identification Technology (RFID) can add to prefabricated timber construction and to undertake basic development of a RFID tracking model in assisting this task. The methods used in this study, not only build upon knowledge obtained from the previous literature but also include industry interviews, lab and primary technological setup, detailed field trial design, and field trial. The investigations showed that the value proposition of RFID tracking system tends be strongest where there exist large scale and vertically integrated supply chains, logistics complexity between a limited number of discrete but partnered supply chain links, and/or internal logistically based complexity problems. Accordingly, five distinct value adding stages of RFID application were found in incoming delivery logistics, factory production of panels, outgoing delivery logistics, onsite installation, and third parties who may inspect the finished construction work.

RFID offers automated processes where fixed readers are used in a pre-defined process. This can be at least partially utilised in prefabrication factory environments. However, the ability for high levels of automation is thought to be more limited onsite due to the temporary nature of sites and associated investment. Instead, handheld readers are more likely to be used in the short term and therefore require operators, training, and allocation of staff. Moreover, Ultra-High Frequency (UHF) technology was found to provide the best technology for RFID when used in prefabricated construction contexts, but care must be taken in the ability and accuracy of tag reading where tags/panels are exposed to excessive moisture or metal substances. Finally, the technology was found to be under-utilised where used purely as an isolated tool by workers for digitally cross checking tags against hard copy timber panel lists. Commitment needs to be placed in using the technology as a strategic tool for monitoring productivity and controlling processes along the supply chains through its date and time stamping features.

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1 INTRODUCTION

The present project addresses FWPA's investment plan for increased use of timber in multi residential and commercial buildings. It focuses on prefabricated systems and the use of *Radio- Frequency Identification Technology* (RFID) to extend the advantages of timber construction, especially in terms of logistics and supply chain integration of prefabricated timber construction. The wireless tags and readers inexpensively store and transfer small amounts of data for automatically identifying, tracking, checking, inspecting and providing quality assurance data for the likes of large CLT panels, wall frames and floor cassette assemblies.

The technology can be used to assist in marshalling of components for logistics and factory based processes. For site, the technology can help contractors to plan the order and sequence of deliveries, check the completeness of deliveries, determine how much work has been installed onsite, and trigger the release of subsequent deliveries. As an instance, RFID technology enables tracking of deliveries in order to ensure logistics are executed as planned and hence, can provide information of process flow, early warning on likely delays and triggering of mitigating actions for deadline management. Once the building is occupied, the tags can be used to assist maintenance regimes and recycling upon the eventual demolition of the building (Note: as discussed later in the report, the research found that this remains an undeveloped part of the value proposition of RFID technology in so far as requiring greater demand from building owners).

The purpose of this research is to determine the potential value proposition that RFID offers prefabricated timber construction and to undertake basic development of a RFID tracking model in assisting this task. The proposed research may provide several benefits including increasing competitiveness of prefabricated timber/wood construction when compared to traditional and improving the delivery chain for those undertaking the logistics in medium to large scale projects. In order to achieve these outcomes, the following objectives were established:

1. Identify appropriate user groups and then identify where different phases of the construction supply chain process can be tracked and traced using RFID technology,
2. Identify the potential benefits for the user groups;
3. Integrate RFID technology with timber construction software to deliver a means for real-time tracking;
4. Address timber/wood specific data recording needs including structural, sustainability, work process and facilities management requirements.
5. Develop a model process of the novel integrated technology and implement the tracking process at a lab or controlled implementation scale (i.e. field trial the proposed system on a project and analyse practical values and challenges).

The intended impacts from the project include:

1. An improved opportunity for the timber industry to gain benefit from new technologies in order to increase productivity using semi-automated methods.
2. Provide quick and accurate data on timber logistics and offsite/onsite processes, to assist fabricators and contractors in their decision making.
3. Provide a means of linking key data flows across key participants in the prefabricated timber/wood supply chain
4. Prevent incomplete, lost or misplaced deliveries in offsite and onsite processes.

The emphasis of this research is more on the practical *implications* of the use of RFID technology rather than *quantification* of efficiency along the supply chain of prefabricated timber construction.

2 BACKGROUND AND LITERATURE REVIEW

Poor productivity is often cited as being an ongoing problem in the construction industry. The use of advanced digital technology and offsite prefabrication are seen as the two key areas of improvement (KPMG International, 2016). Timber construction is well positioned to take advantage of both trends in the industry. To some extent, this is a natural progression for the timber while it enters new multistorey building markets, because prefabricated timber has potential to excel over traditional construction methods. To complement this scenario, RFID technology can potentially play a significant role. It is a type of auto-identification technology and refers to the process of indexing information of physical objects (such as timber panels and assemblies) and using radio frequencies to transfer information from the object to interested users. RFID can thus be used to automate information systems through supplying field data read from RFID tags attached to the abovementioned objects by using RFID readers operated by users. It involves the use of wireless tags used to store and transfer small amounts of data for automatically identifying and tracking objects. Users can read and write information to the tags which are quite cheap. RFID readers can take the form of dedicated equipment or attachments to smart phones. The technology has gained traction in the supply chains of various industries including logistics and shipping (Ramanathan et al. 2014), retail (Loebbecke, 2005), medical (Chao et al. 2007), and mining (Mahmad et al. 2016).

In construction, there is currently a much lower level of uptake relative to other industries. Even so, previous research has shown the potential of RFID applications in areas such as labour management (Navon and Goldschmidt 2003), construction tool tracking (Jaselskis and El-Misalami 2003, Goodrum et al. 2006), pipe spool tracking (Jaselskis and El-Misalami 2003, Song et al. 2006), machine maintenance records (e.g. time of inspection, the personnel who conducts the checking, conditions of the machines, and repair work done), prefabricated precast components (Demiralp et al. 2012) and logistics management of structural steel projects (Chin et al. 2008).

One of the benefits of RFID technology over the likes of barcodes, is that the reader does not need to be very close to the tag in order to read information. For instance, if an insitu timber frame is concealed by overlying layers of construction, the information can still be read off the tag which makes it useful for post construction checking. The reader can also read multiple objects at once, hence making it possible to interpret an entire stack of wall frames or cassette floors, quickly, as they leave the yard for delivery to site, rather than scanning each one.

The unplanned, uncontrolled and dynamically occurring events that typify construction projects create a significant need for real-time information sharing amongst project participants and hence, justify the potential relevance of RFID technology (Sardroud 2012). One example is Chin et al. (2008), who examined the application of RFID in steel construction by using it to identify production, delivery and on-site erection information on a steel member unit basis. Their experiment showed that the use of RFID offers more accurate logistics and reduces risks in terms of lost materials and lost schedule time. Further problems with material management that can be addressed by RFID technology include: lost or damaged materials, unnecessary multiple handlings, materials not being procured, materials not received, and out of sequence material deliveries (Razavi and Haas 2011). Still further, low levels of information integration can be improved with the use of RFID for materials, tool tracking and document management (Sardroud 2012, Elghamrawy & Boukamp 2010). Lee et al. (2013) similarly recognized that tracking and providing real-time information on materials, tools, equipment, documents and life cycle information would serve to make construction processes easier. Linked to this, cost coding for tagged objects is another area of potential benefit achievable with RFID technology (Lu et al. 2011).

Hinkka and Tatila (2013) suggest that if materials are RFID tagged then material tracking management systems can provide information on the progress of construction onsite, by simply walking around onsite with an RFID reader in-hand. The information read from RFID tags would give more precise estimates of percentages of work completed based upon the quantity and type of delivered/installed goods thus enabling automated billing (Lee et al. 2013). In mining, RFID has been successfully used to control Personal Protective Equipment (PPE). For instance, tags attached to PPE identify when a worker passes through RFID reader gates stationed throughout the mine; the tag carries the vital information of the worker wearing the PPE as well as the information related to the PPE, thus ensuring that essential PPE components are worn by workers when entering a mine (Mahmad et al. 2016).

Adding to the above, Demiralp et al's (2012) case study of precast concrete used simulations to determine that a cost saving of approximately 3% on projects was possible where prefabricated concrete panels were fitted with RFID tags prior to entering the supply chain. The savings were from: (1) the reduced number of missing panels, and thus reduced remanufactured panels; (2) the reduced number of incorrectly delivered/identified panels, and hence, the decreased number of material double movements; and (3) the reduced durations of certain activities, resulting in decreased labour costs (Demiralp et al, 2012).

In applying the above to prefabricated timber construction, it would seem that the importance of logistics increases with the scale of prefabrication operations. Because manually assembling many small objects onsite has been changing to handling a lesser number of large and value added prefabricated objects offsite, where care is needed in ensuring an efficient work flow from factory to site assembly (Forsythe and Carey 2017). Concerning logistics management of prefabrication, RFID technology can potentially:

- Identify and track large prefabricated panels/assemblies with graduated checking of incoming raw material deliveries, factory processing, factory storage, delivery logistics, installation sequencing, insitu placement and quantification of work complete for progress and billing purposes.

- Read through multiple layers of construction thus allowing retrospective compliance checking/inspection of objects encapsulated within the construction.

(Forsythe and Carey 2017)

3 TECHNOLOGY OVERVIEW

RFID technology tracks objects in accordance with defined process locations. Tags attached to the object allow a read and write capacity whereby small amounts of information about the object can be sent from the tag to a reader unit. The tags (which in technical terms are actually transponders), include a minute computer chip with an inbuilt antenna. Tags are embedded as cards, stickers, and other form factors that can be easily attached to the object that will be tracked. The data transmits between tags and RFID unit using radio waves, thereby giving details about the object. This commonly involves a time and date stamp reading at specific locations in a defined process which identifies where the object is, at a given point in time (Forsythe and Carey 2017). The RFID reader can be connected to the cloud to assist with data storage, access and management. Figure 1 shows the configuration for a typical RFID system.

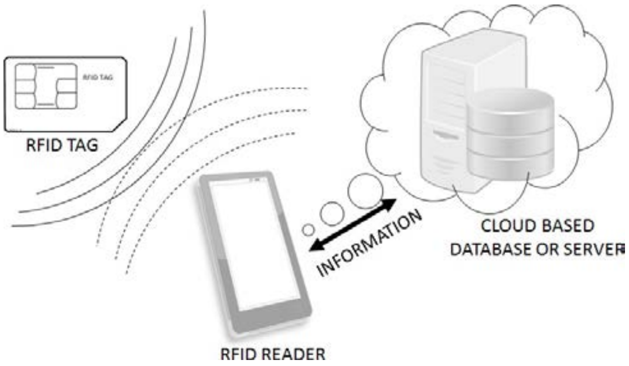


Figure 1: RFID process

The RFID tag circuit comprises at least two key components:

1. An integrated circuit which:
    a. Stores and processes information
    b. Modulates and demodulates a radio frequency signal
    c. Collects DC power from the incident reader signal
2. An antenna for receiving and transmitting the signal.

Tag information is stored in non-volatile memory but for inexpensive tags (the tags ultimately used in this study costed $0.30 each), memory is limited and may only be in the order of 50 characters which prompts the need for the previously discussed cloud database to manage the bulk of the data storage. The RFID tag can also include either fixed or programmable logic for processing the transmission and sensor data respectively. Since RFID tags have individual serial numbers, an RFID system can discriminate among several tags that may be within range of the RFID reader and read them simultaneously.

In concert with the above, an RFID reader emits electromagnetic waves from its antenna. These waves are then picked up by the antenna of the RFID tag circuit. The electrical power induced in the antenna powers the Tag's chip. Upon powering, the RFID tag transmits information wirelessly back to the reader's antenna which is then interpreted (decoded and processed) by the reader and subsequently relayed (for instance) to a computer as useful information.

Further, an Electronic Product Code (EPC) is one common type of data stored in a tag. When written into the tag by an RFID printer, the tag contains a 96-bit string of data. The first eight bits are a header which identifies the version of the protocol. The next 28 bits identify the organization that manages the data for this tag; the organization number is assigned by the

EPCGlobal consortium. The next 24 bits are an object class, identifying the kind of product; the last 36 bits are a unique serial number for a particular tag. These last two fields are set by the organization that issues the tag. Rather like a URL, the total electronic product code number can be used as a key into a global database to uniquely identify a particular product (Vacca 2009). Ideally, companies using RFID tags *en masse,* would typically purchase a tag printer which allows them to assign a unique serial number for an object, in a way that compliments their internal operations and systems.

3.1 RFID Technology Types

RFID tags come in two types:

- **Passive** – is solely powered by the incoming electromagnetic waves generated by the RFID reader, triggering a signal that is captured by the Tag's antenna. This allows the circuit to be simplified and the chip form factor to be very small, but limits its signal propagation capabilities, data storage and processing, and its ability to support more power demanding modules (such as humidity and temperature sensors or GPS technology).
- **Active** – contain their own internal power source (a battery), permitting increased propagation range by the tag which emits a signal to the RFID reader. The increased power also allows the tag to support a range of sensors and modules (e.g. sensors and/or GPS). However, the addition of a power source increases the tag's form factor. Practical limitations like battery life also lead to subsequent issues in terms of operational life and access for replacement.

A comparison of the two tag technologies is provided in Table 1.

Table 1: Comparison of passive and active RFID technology

Characteristics	*Active*	*Passive*
Power	Battery operated	No internal power
Required Signal Strength	Low	High
Communication Range	Long range (100m+)	Short range (3m)
Data Storage Range	Large read/write data (128kb)	Small read/write data (128b)
Per Tag Cost	Expensive: > 100 times more expensive than cheap passive tags	Cheap e.g. $0.30 for basic tags
Tag Size	Varies depending on application	"Sticker" to credit card size
Fixed Infrastructure Costs	Lower – cheaper interrogators	Higher – particularly fixed readers
Best Area of Use	High volume assets moving within designated areas ("4 walls") in random and dynamic systems	High volume assets moving through fixed choke points in definable, uniform systems
Application in Building Industry	Post-construction phase for facility management and preventive maintenance	Pre-occupancy phases for logistics management and construction progress monitoring

Notes:

- Source: Interpreted from http://www.atlasrfid.com/jovix-education/auto-id-basics/active-rfid-vs-passive-rfid/
- Cost data changeable and presented mainly for assessing proportional costs differences.

Of the two technologies, passive tags are much less expensive than active tags and hence, provide greater potential for uptake and entry level adoption. Since this is most consistent with the objectives of this project, passive technology has formed the focus of this study. Of note, such technology can be easily paired with barcodes and QR code technology, thus allowing data interchange within logistics systems, as may occur inside a product supply chain. Active tags are, however, more expensive and commonly used for long-term post-occupancy purposes such as preventive maintenance and facility management. Such applications were out of the scope of this study.

3.2 Advantages and Disadvantages relative to competing technologies

A competing technology with a history of similar applications in the construction industry is barcode. The RFID technology offers certain advantages and disadvantages over cheaper bar code technology. Common themes regarding this are reported by many service providers and are widely available on the internet. For instance, an edited list comparing the two technologies is created below and reflects information shown commonly by multiple RFID service providers (White et al., 2007; inLogic TM, accessed 10/08/2018).

Table 2: Comparison of RFID versus Barcode technology (Adopted from Atlas RFID solutions, accessed 10/12/2017)

Characteristics	*RFID*	*Bar code*
Read Rate	High throughput. Multiple (>100) tags can be read simultaneously.	Very low throughput. Tags can only be read manually, one at a time.
Line of Sight	Not required. Items can be oriented in any direction, as long as it is in the read range, and direct line of sight is never required.	Definitely required. Scanner must physically see each item directly to scan, and items must be oriented in a very specific manner.
Human Capital	Virtually none. Once up and running, the system can potentially be completely automated.	Large requirements. Labourers must scan each tag.
Read/Write Capability	More than just reading. Ability to read, write, modify, and update.	Read only. Ability to read items and nothing else.
Durability	High. Much better protected, and can even be internally attached, so it can be read in very harsh environments.	Low. Easily damaged or removed; cannot be read if dirty or greasy.
Security	High. Difficult to replicate. Data can be encrypted, password protected, or include a "kill" feature to remove data permanently, so information stored is much more secure.	Low. Much easier to reproduce or counterfeit.
Event Triggering	Capable. Can be used to trigger certain events (like door openings, alarms, etc.).	Not capable. Cannot be used to trigger events

Given the above, it can be seen that RFID technology has certain advantages over bar code technology (albeit that the two can be blended where appropriate to do so). Even so, but there are still additional issues specific to RFID technology, which require attention in order to ensure appropriate usage of the technology in prefabricated timber construction applications. These include:

- There is a trade-off between material penetration and range. Lower frequencies have better material penetration, but poorer read range. Higher frequencies have better range however with poorer material penetration.
- Readers struggle picking up information when passing through metal and water environments.
- Although RFID tags can be particularly robust (especially passive tags), they are susceptible to a number of physical issues, including mechanical damage, moisture damage, and deterioration of the adhesive or the housing used.
- Tag and/or reader collision can occur when numerous tags in the same area respond at the same time. This tends to occur if a large number of tags are simultaneously read

together in the same frequency. The reader is then unable to differentiate between each tag's signal and confuses the reader.

In the ongoing research, there is a need to test, choose and check that appropriately reliable methods are developed and used to suit the context of prefabricated timber construction. There are other technologies, such as SIM chips and Zigbee, with functionalities comparable to RFID technology. Such technologies are mainly used for automated machine to machine communication and are reliant on availability of WiFi or wireless networks and presence of battery-powered devices (Naticchia et al. 2013). Therefore, they have currently only gained limited uptake in the construction industry compared to RFID and barcode technologies.

4 RESEARCH OVERVIEW

4.1 Research Objective

To realize the full benefits of prefabricated timber in construction of multi residential and commercial buildings, efficiency along the upstream logistics and supply chain is critical. Therefore, the central aim of this research is to determine the potential value that RFID can bring to prefabricated timber construction and to undertake basic development of a RFID tracking model in assisting this task.

4.2 Research Methods

The methods used in this research study, not only build upon knowledge obtained from the previous literature but include a number of mixed methods, as listed below:

1. Industry Interviews
2. Lab and preparatory technological design
3. Detailed field trial design
4. Field trial.

The method used for each, and related findings, are presented under respective headings in details below.

5 STAGE 1 RESEARCH- INDUSTRY INTERVIEWS

5.1 Method

Industry interviews involved a total of 17 interviews followed by content analysis of the data obtained. The majority were audio recorded for content analysis although for a limited number of cases, recording of interviewers was not possible at the request of the interviewee or due to locational circumstances. Of the 17 interviews, 10 Australian interviews were conducted with a view to understanding different prefabrication contexts, related supply chains and the relative need/interest in RFID technology within the Australian context. In general, efforts were made to capture interviews which covered different perspectives of RFID technology across the breadth of the prefabricated timber panel supply chain. These include timber design software companies that create and manipulate design information; timber fabricators who undertake offsite production; logistics operations involved in transporting panels from one link in the supply chain to the next; construction contractors who install the prefabricated timber onsite and must prove compliance concerning the installed panels; property developers who may have a value added use for the technology.

In order to ensure interviewees had at least a basic level of understanding about the technology, they were provided an online briefing video prior to conducting the interview. Interviewees were asked semi-open questions in a conversational style where most were undertaken face-to-face and took place at the interviewee's work place. Content analysis was then undertaken on the obtained data. Areas covered in the interviews included:

1) Company background and explanation of work undertaken
2) Potential benefits of RFID technology in operations
3) Current procedures for the type and transfer of information/documentation
4) Problems that exist in the supply chain process in terms of tracking items
5) Current technologies used for tracking objects
6) Potential to reduce/simplify communications and traditional documentation

In addition to the Australian context, 7 international interviews (with targeted companies in technically advanced regions of timber building industry encapsulating Scandinavia, Central Europe and Canada) were conducted to determine usage and application elsewhere, as a basic means of benchmarking application in Australia. These involved interviews and site visits at medium to large scale timber prefabrication plants.

5.2 Interview findings

The perspectives of those interviewed varied widely according to differences in their supply chain involvement. As an initial step, three identifiable types of information flows were found to exist:

- Product information (i.e. product features relating to sustainability, quality, and compliance)
- Process dynamic information (i.e. active decision support of production/logistics/construction process management)
- Feedback during the service life of the end product (i.e. potential for information pertaining to building operation, inspection, durability and maintenance)

The findings presented below are either direct quotes from interviewees, shown in quotation marks, or excerpts of discussions with them edited by the authors to infer meaning and improve readability.

The interviews found that to build aggregated value along the full length of these combined stages, it was apparent that there needed to be demand/desire to replace existing systems with more efficient ones. There was also a need to introduce tagging early in the above processes in order to retain information lineage throughout.

For those new to the technology in Australia, it was apparent that interviewees showed a degree of nervousness about the cost versus benefit of the technology. For instance, some already had their own ad hoc object tracking systems in place. Others had well-developed internal systems where one example included smartphone photography that could be uploaded to a database and was used at various points in logistics processes which enabled time, date and location stamping of the product at defined parts of the process (mainly storage and delivery points). Such a developed system meant that the company involved did not necessarily want to change this for the RFID technology.

The concern was also raised that the RFID tags did not contain enough memory space to be a freestanding source of information storage - the tag only links to cloud-based information.

The link to cloud database subsequently raised information security issues for the interviewee referring to questions such as "Who controls, maintains and owns the cloud database?", "Will it be transferred to the eventual owners of the building once construction is completed?" and "Will the owners and/or property managers be prepared to pay for access to this information?".

In terms of main-flow detached and semi-detached housing production, a number of interviewees doubted the value proposition on RFID technology given that houses were relatively small and design differentiated projects, that may limit the ability to systematise and fully leverage the potential of the RFID technology.

Other perspectives were more positive. Interestingly, one interviewee involved in vertically integrated offsite-to-onsite operations of medium to large scale buildings, saw benefits in matching the RFID technology with their internal database and photogrammetry system whereby semi-completed panels in their factory production processes could be photographed before being closed in by overlying linings, and then the RFID technology could be used to provide access to this information onsite, by compliance inspectors. Another interviewee from a similar context in terms of large and vertically integrated offsite-to-onsite operations, saw considerable value in the RFID technology for their business which involved close partnering with overseas material suppliers. They also extensively used digital design technology to link to factory production which created the environment for potential synergy and efficiency in linking logistics, factory production, inventory management and site operations. Of note, they had trouble in the past surrounding logistics and so, had an express need to address this issue. They saw the RFID technology as providing a flow of information based around panelised objects that could be digitally linked to the building design.

Both of these above examples had one feature in common: viewing construction as a centralised production like process and doing so for larger scale building projects.

Along a separate vein but still revolving around the theme of vertical integration, an interviewee who was located towards the end of the supply chain was a large contractor/developer of both volume housing, apartment developments and master planned estates. For them, there would be clear benefit if the technology could allow property owners and managers to access as-built drawings, warranties, engineering certificates, plant and equipment operating information, and maintenance information. Clearly, this extends well beyond timber construction but it does serve to highlight where downstream demand in the supply chain for RFID technology is likely to come from and what they want from it.

Overseas, large prefabricated housing manufacturers (including those with vertically integrated design, construction, and sales operations) were not especially using RFID technology but instead, were using akin barcode and QR code technology. This was mainly geared to materials management concerning incoming delivery and incoming inventory control (e.g. timber deliveries, window unit). Another usage was in the monitoring of panel fabrication production lines. For instance, pre-cut materials were delivered to the first panel production station with a bar coded job sheet attached. As the panel passed from one station to the next, the tag was read by the worker at each station to record arrival/departure times from that station, thus providing a clever and yet simple means for monitoring production throughput, meaning that productivity within the factory could be easily measured.

Surprisingly, relatively little interest was shown by the interviewees in using RFID to store sustainability and recycling information about a panel. It seems that they did not see this as important enough to pursue since they mainly thought of the RFID technology as an efficiency or cost saving production technology. The Australian interviewees stated that this may change if reporting of sustainability data became mandatory due to regulatory requirements or if the likes of Green Star rating systems became commonplace and hence related information was sought by building owners.

In overview, a significant finding from the above is that the degree of fragmentation typically in construction supply chains means that where there are only small and/or individual benefits at each link in the supply chain, there is insufficient impetus to foster a strong value proposition for RFID technology. In such instances, it lacks a "champion" to foster implementation. Instead, the value proposition tends to be strongest where there is an inclination towards integration across supply chain participants. Specific examples of this include:

1. *Large scale and vertically integrated supply chains:* The value proposition is strongest where an individual company spanning multiple links in the supply chain. This opens up the possibility of the abovementioned links extending from incoming logistics, to factory production, to inventory control, to site operations. Whilst the value proposition could extend even further along the chain to ongoing property owners/managers and third-party inspectors, the current degree of fragmentation from construction to ownership means the value proposition in most instances, will be more tenuous (albeit that this may change with time).
2. *Logistics between a limited number of large supply chain linked companies that work in an ongoing and integrated way:* Here, the RFID technology appears to most easily be implemented in links pertaining to *en masse* suppliers of timber materials who work closely with the likes of large timber fabricators in a systematised way.
3. *Large scale internal logistics problems:* This simply relates to internally dedicated tracking systems within the likes of large scale fabrication companies that deal with repetitious processes and products on a significant economy of scale.

It is considered from the above that the most promising area for further development and field testing is in the context of item 1 above, i.e. *Large scale and vertically integrated supply chains*, as this appears to offer the best value proposition in applying the RFID technology to prefabricated timber construction. This is subsequently pursued further in the ongoing research.

6 STAGE 2 RESEARCH: LAB TESTING AND TECHNOLOGICAL CAPACITY BUILDING

6.1 Method

During stage 2, the researchers used basic lab testing to develop preliminary setup surrounding the design and usage of RFID systems. Development followed the below procedure:

1. Liaisons and technical discussions with RFID hardware suppliers.
2. Selection of RFID technology including lab mock-ups and tests to ensure the feasibility of RFID hardware and consumables arrangements; lab testing of sample RFID tags and reader options for various material combinations
3. Exploration of RFID app development options and software design considerations; this included a feasibility study of developing standalone apps suited to prefabricated timber construction requirements in conjunction with consideration of customising off-the-shelf options.

6.2 Lab testing and capacity building findings

In general, it was recognised that there was a specific need for the technology to deal with two different environments including factory and construction site contexts. The former tends to involve relatively close proximity between the reader and tagged objects; the latter tends to require longer range proximity and may also not have the luxury of a reliable Wi-Fi network onsite to relay data to/from cloud databases. Technology must be chosen accordingly and an initial issue with regard to this, was the choice between three categorically different RFID solutions including: Low Frequency (LF), High Frequency (HF), and Ultra-High Frequency (UHF) technologies. Review of these options indicated that UHF appeared to provide the most potential for the needs of the project, as influenced by the following features:

- UHF provides the longest read distances (>2m) which is useful given that scanning of panels may take place on trucks and forklifts with relatively high stack heights above the ground. Ergonomics and speed of inspection must also be taken into account.
- A high degree of flexibility in read/write range, which can be altered by dialing-in a different setting using the reader's on-board antenna and by using different tag geometries.
- A high degree of flexibility in tag types to suit different usage scenarios,
- UHF permits multiple tags to be scanned concurrently (LF and HF only permit one at a time),
- UHF tags possess the highest capacity of data storage in comparison to LF and HF

However, UHF technology also possesses its own share of challenges which need to be managed for implementation in the system. These are:

- No universally accepted standard for UHF RFID. Each region (US and EU) have their own set of standards for UHF RFID which operate in separate frequency ranges. However, from our research, "global-standard" readers (able to be read in the both US and EU frequencies) do exist.
- Heightened risk of interference. Due to the high propagation ranges achieved, UHF risks bouncing signals off surfaces and back onto itself, thus scrambling and disrupting RFID signals.
- (Because of the above) it fairs poorly with metal materials and water. High moisture content in timber and rain may impact on tag reading – especially work undertaken in open areas such as onsite operations and open storage areas.

6.2.1 Tag selection issues

As alluded to above, there is a wide selection of tags on offer, however, a number of central fitness for purpose criteria required of the prefabricated timber construction context, are covered below:

1. Stick on paper tags represent a common and low-cost form of tag. These are, however, unlikely to be durable enough for exposed weather conditions and construction site conditions – more durable tags made with a synthetic outer layer have greater potential. Stapling is also likely to provide a more reliable fixing method whilst still offering a low cost solution.
2. Care needs to be taken in selecting tags where read without a clear line of sight or where passing through the likes of materials such as plasterboard, membranes, claddings and sarking materials as may occur in the prefabrication of closed panel production. Basic testing must be undertaken, as reported later in this stage of the research to affirm suitability.
3. Tags may need to store critical data about the panel which is to stay with the panel. This may include core descriptors of the panel/assembly (e.g. predominant materials used, strength, weight, hazardous materials, dimensional data, and inspection dates). Decisions need to be made when selecting tags as to the extent of data realistically stored in on-board memory (if any), or if all such data should be deployed to a cloud database.

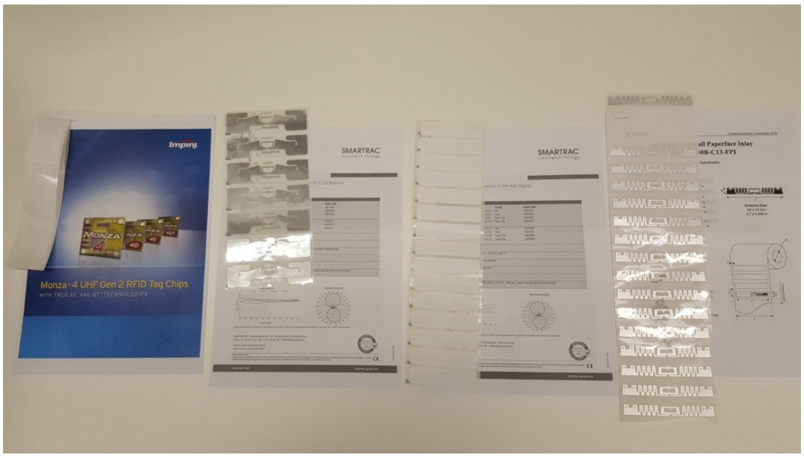


Figure 2: Example of UHF self-adhering tags

It is also apparent from the current state of the technology that it does not provide a perfect (100%) read rate from tags. For instance, one "dead tag" potentially breaks the lineage of data transfer. This poses a potential reliability problem in certain usage scenarios, perhaps where multiple tags are read at one time and subsequently an unread panel may go unnoticed. To mitigate this problem, systematic checking can be employed during reading operations against reference lists, to prompt the need for re-reading attempts. An example solution is to place multiple tags on panels to improve the read rate, albeit this creates a degree of built-in redundancy in the number of tags required. The genuine necessity for such measures needs to be carefully assessed.

6.2.2 Reader hardware

Handheld readers commonly cost in the range of $1,200 to $2,800 and offer flexible usage but also require manual operation – hence meaning workers must be engaged for such tasks as part of their skill set. Fixed readers are more expensive and commonly fall in the range of $4,300 to $6,000 but also afford increased automation as workers are not required for day-to-day reading operations. Gate readers offer an even more expensive option, in the order of $10,000 to $12,000, but in addition to automated operation, these readers also offer the ability to manage large and stacked loads of panels as may be carried by trucks and forklifts.

To obtain a better understanding of reader expectations, initial laboratory-based UHF trials were undertaken using two types of RFID readers as described further below,:

1. **TSL1128 Bluetooth handheld reader (Source: https://www.tsl.com/products/1128-bluetooth-handheld-uhf-rfid-reader/)**: this allows for close range reading and writing of tags (specification rated range for reading and writing of 4m and 1.33m respectively) with variable antenna power control via software development kits. The unit must be linked to a smartphone or tablet as it does not have an on-board screen. All major mobile platforms interface with this device and it can connect to online databases via a variety of computing devices (via serial port, Bluetooth or Sim card connections). Such units allow flexible and mobile usage on the factory floor, construction site, and during building inspections without any need to change existing infrastructure at these locations. Care needs to be taken in setting the antennae read distance/angle so as not accidentally read non-targeted tags.

2. **IMPINJ Speedway R240 RAIN wall mounted RFID reader** (Source: https://support.impinj.com/hc/article_attachments/115001225024/ProductBrief_Impinj_SpeedwayFamily_6.19.17_FINAL.pdf): this wall mounted reader operates on 24VDC, and has customizable antenna for read ranges of ~100m (as per specification). However, it's higher performance and read range requires significantly greater support from other hardware including a physical connection to a dedicated computing device via USB cable and hardwired power outlet. This not only adds additional hardware costs but also, the value proposition of such hardware is more geared to permanent factory or inventory installations, than temporal onsite conditions. Notwithstanding this, such units still have a degree of flexibility in application including mounting to the side of open shipment cages, shipping trucks, gates, or made portable for wide area scanning. Once setup, the unit offers an automated solution at a lower cost point and some ability to adjust or move the reader, relative to a dedicated gate reader.

Figure 3: TSL1128 Bluetooth handheld reader

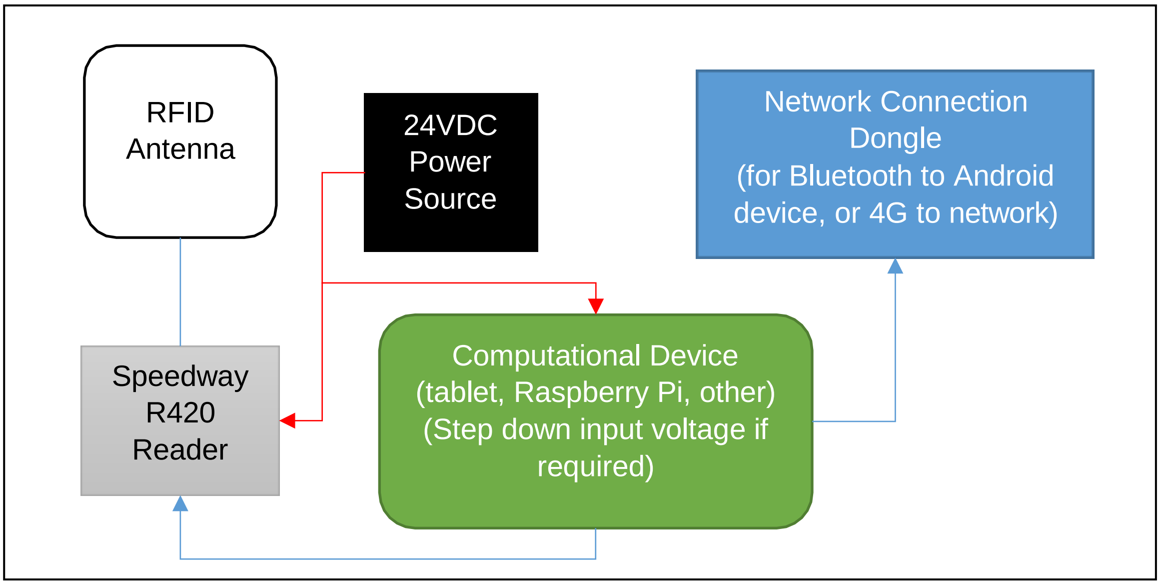


Figure 4: Diagram of wall reader arrangement including necessary support hardware

For the “proof-of-concept” ambitions of this project, it was decided that the ongoing research should focus on handheld readers which were considered most appropriate, especially because of their flexibility in filed usage and addition, due to the budgetary limits of the project.

6.2.3 Exploration of App development versus off-the-shelf options

Exploration was also undertaken into development of standalone Android Apps as the “brains” to capture, read and send data between the likes of the above handheld unit, and a cloud database.

Here, a range of data was considered for storage and retrieval from the system when interacting with fabricated, stored or installed panels. Due to the limitation of the RFID tag storage capacity (<50 characters), only critical data could be stored on the tags, and all remaining data required cloud database storage.

Two options were considered for the storage of cloud data in an online and independent platform including consideration of:

1. Use of Amazon Web Services’ Relational Databases (RDS) and cloud storage services (C3): this allows the use of relational databases and SQL queries for storing and retrieving data, but requires the development of an app host with developed functionality for an application to interact with the database,
2. Use of Google Firebase’s real time database and online storage: this allows real time updates. Firebase’s real time database uses a NoSQL database and follows a JSON structure.

Firebase was pursued further as a viable option coupled with feasibility development of 3 related Android apps which could operate in conjunction with smartphone or tablet functionality, as follows:

App 1: Interface between the reader (TSL1128) and an Android device. This allowed understanding the behaviour of a handheld RFID reader, the ability to assess read-and-write capabilities of UHF RFID readers, and understanding the storage and retrieval of data in both software and on an RFID tag. Primary uses of this app were to read and write strings to the tag; to allow physical experimentation to determine range characteristics of the RFID tag reader, and to assess its performance through typical construction materials.

App 2: Interface between Android device and an online database for storing and viewing data. This app determined the upload and download capabilities in Android, and was assessed through a messaging app using Google Firebase. Changes to the database were automatically detected and updated through its message display capacity in the database.

App 3: Interface between RFID hardware and database using Android device. This app assessed the integration of both hardware and online databases. This included data recording at specific stages in the supply chain, storing and retrieving project data from an online database, document viewing, and QR code reading.

Initial development work was undertaken regarding these Apps, but it was soon realised that a significant impediment to the longer-term feasibility of such development was the potentially large amounts of data handling (onsite and in factory) – especially if using the RFID technology for the likes of calling up drawing details and other design information. This amount of data transfer would likely cause significant slowness when using the proposed platforms, and so further development was considered too risky to pursue given the budgetary constraints in resolving data transfer issues.

An equally significant lesson was the realisation that RFID systems are as much about providing an integrated package of hardware, service delivery, and well-maintained database systems, as the individual software apps used in the system. Here, existing providers had already developed their own packages albeit this still required customisation of their off-the-shelf systems – mainly around customisation of apps, cloud database structure, hardware selection and tag selection. Ultimately, it was concluded that using such companies represented a more sustainable and serviceable outcome for the project and potentially the longer term needs of the timber construction industry as well. Subsequently, this approach was used for ongoing field development and testing – as reported in Stage 3 of the research.

6.2.4 Testing of read range through various materials

As indicated previously, RFID performance can be reduced by the interaction of signals with metal plus the ability to read through materials (due to closed panels or where there is not a direct read line of sight for the tags). Subsequently, the final aspect of this stage of the research prompted lab experiments on common building materials pertaining to such issues. Lab experiments included testing of high frequency (HF) RFID equipment followed by Ultra-high Frequency (UF) RFID equipment. These aimed to provide an indication of the types of complications that may be faced in the field with metals and assorted timber materials, and also underpin the validity of using UHF over the likes of HF technology.

This first set of HF experiments aimed to test the penetrability of the RF signal through a number of construction materials. For this test, an Arduino R3 micro-controller board with a small read range MFRC522 HF RFID (13.56MHz) reader module was used. Materials were placed in the space between the tag and the reader. The test scanned through a number of materials including metals. If the tag could no longer be read, the distance between the RFID reader and tag was reduced until the tag could be read. The control sample had a maximum read distance of 30mm. Whilst this short range was not indicative of hand units that would be used in the field, it was convenient for comparison with metals compared against other materials.

As seen in Table 3, test results show that various sheet timber materials had no effect on the readability of HF RFID tags and RFID signals passed through easily and undistorted. Any thickness of steel, however, completely blocked the RFID signals such that the reader could not detect the RFID tag which agreed with findings by others (Violino, 2005). Aluminium sheet was also assessed and found that this also caused the tag to be unreadable.

Table 3: HF reader tests; including metal and other common materials

Test Material	Material Thickness (mm)	Successful Read range (mm ±1mm)
None (Control)	N/A	30
Plywood (Pine)	12	30
	24	30
Steel	1	0 (unreadable at any range)
Aluminium	0.5	0 (unreadable at any range)
	0.2 (Foil)	0 (unreadable at any range)
Particleboard Flooring	18	30
Formply	17	30

It is suspected that this problem was due to the generation of eddy currents as RF waves are inducted through the metal material, thus retarding the signal to an unusable state (http://propagation.ece.gatech.edu/ECE3025/opencourse/MSF/MagRFID.pdf). What was of further interest was that the metal material did not need to be placed between the tag and reader to disrupt the RFID signal. When the tag was mounted to the metal material, the tag could not be read at any distance or direction. The tag could not be detected until it was removed from the metal surface. Obviously, this potentially effects panels using metallic claddings, metallic sarking layers or other significant metal parts in panel assemblies. Care in placement is, therefore, important and should be on a clear timber face away from significant metal components.

Secondary testing was similarly undertaken involving UF RFID equipment as may be more commonly used in the field (the TSL 1128 Bluetooth UHF RFID Hand Reader and INVENGO UHF RFID plastic Tags were used). The results show the stark contrast in read range relative to the HF read tests presented previously. As presented in Table 4, a much longer read range was possible and this was true for both sheet timber and a variety of structural timber options. This suggests that the read range for timber materials at over 1.5m and up to 2.1m is likely to be workable for many factory and site scenarios. Even so, it is apparent that as material thickness increases, read range decreases albeit this is not in a linear an easily explainable way. To maximise read range, it seems sensible to face mount tags on panels and where possible, aim for direct or relatively unimpeded read-line.

Table 4: UHF reader range tests including multiple timber materials

Penetration Material	Material thickness (mm)	Successful Read Range (mm ±1mm)
No material (Control)		2164
OSB	6	2160
Particleboard flooring	18	2158
Formply	17	2156
Seasoned Hardwood	35	1544
Seasoned Softwood	17	1565
H2 Treated Softwood Framing	35	1569
CLT	62	1566

LVL	45	1583
Glued Laminated Softwood	64	1854
Glued Laminated Hardwood	64	1855

Figure 5: Testing read range through different materials and different thicknesses using UHF reader

7 STAGE 3 RESEARCH: DETAILED FIELD DESIGN

This section presents the detailed design of a RFID tracking system tailored before trialing within a real world case scenario.

7.1 Method

This stage of the research involved more purposeful development of the Stage 1 and 2 findings to suit specific field application. A case study scenario was set up with *Strongbuild* who *are a* vertically integrated construction contracting business with a design office, offsite factory production facility, and onsite contracting operations. They specialise in prefabricated CLT and timber framed construction solutions (including fabrication of floor cassette panels, closed wall frame panels, roof trusses, interior fitout joinery, importation and machining of CLT panels and manufacture of bathroom pods). Consequently, a substantial amount of a building can be delivered within their scope of prefabricated methods. The company is a leader in large scale timber buildings including apartments, aged care, institutional and housing construction sectors. Of note, CLT panels are imported on a large scale from Europe via shipping containers and are mainly used on larger projects of 6 storeys or more.

The company uses highly automated methods of factory fabrication that synthesise 3D architectural modelling (e.g. Archicad) and file-to-factory digital technologies (e.g. Cadworks) to drive CNC cutting and computer integrated fabrication lines. The company also has an ERP system for production flow monitoring. To gain a better understanding of the context and operational needs of the company, the following data gathering methods were used:

- Multiple visits were undertaken to both their factory production facility and a number of active construction sites. The sites variously involved installation of floor cassettes and CLT floor/wall panels on buildings up to 10 storeys in height and involving up to 3000 panels within a given project. In general, this research allowed mapping of processes from incoming raw materials, to factory, to site. The visits aimed to validate and adjust earlier assumptions in the research process. Observations could be made of complications (both systematic and one-off occurrences), as well as the scale of measurement and detection required by the RFID system. Site video footage was also captured and viewed to better understand logistics concerning onsite operations.
- Concurrent to the above, detailed interviews were undertaken with a spectrum of Strongbuild staff to better understand and refine needs. This included staff from design management, site installation, project management, IT, project deliveries, production management and overarching strategic management.

In parallel with the above, there was a need to find RFID suppliers and services providers who could meet the needs of the project. A number, both locally and internationally, were explored for providing hardware, app, cloud and tag requirements to assist with the field trial. From this process, RAMP RFID (https://www.ramprfid.com) were chosen to work with UTS and Strongbuild in this capacity. They became involved in the both site and factory visits to provide advice and guidance in the development of the system design which included:

- Use of passive UHF Gen 2 RFID tags to securely attach to CLT panels and similar items
- Use of mobile UF RFID handheld readers capable of reading multiple tags for tracking the movement of product through the various stages of delivery, factory and site (Note: such readers can also read bar codes and QR codes). These Android readers are used for onsite tag assignment, order dispatch and receipting, and stocktaking with search functionality. Also, they include Wi-Fi and Sim card functionality for internet connection to the cloud database.
- Customisation of their off-the-shelf Loca.Fi cloud database supply chain tracking platform. It is an object tracking system which collects data from RFID hardware for alerts, analysis or integration into third party's systems. It offers broad based utility but requires customisation to suit specific user needs. It uses Microsoft technologies with data being securely stored in a Microsoft SQL server database. The web front end is accessible from desktop, tablet and mobile devices.

The following schematic is indicative of the RFID System architecture.

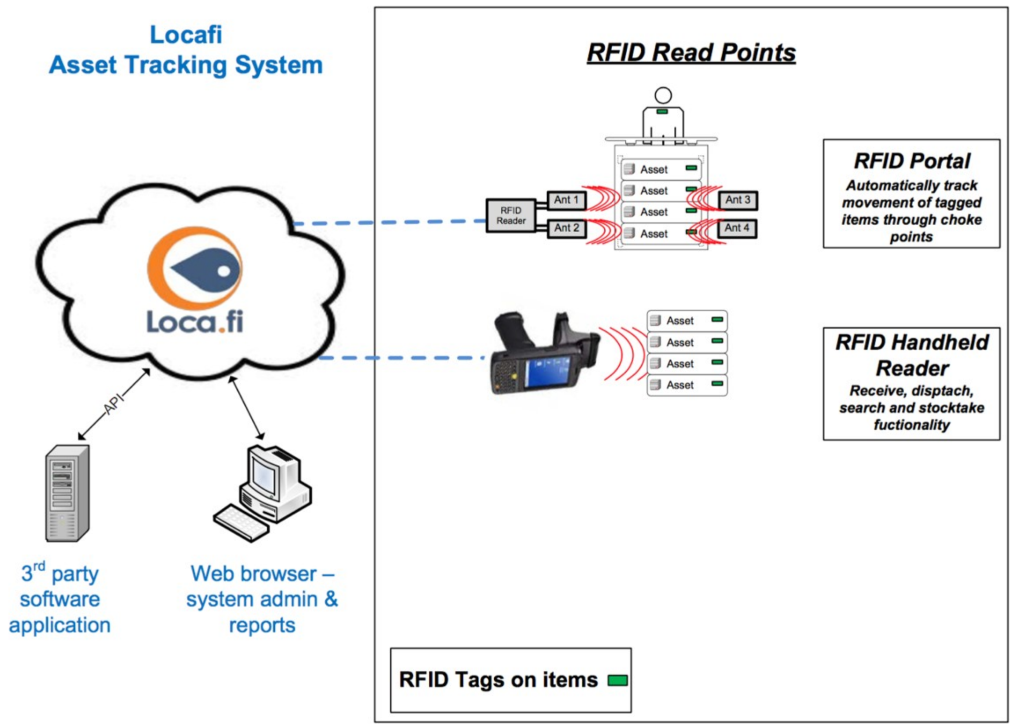


Figure 6: Components of an integrated RFID tracking system

7.2 Detailed Design Findings

In working with Strongbuild, there was a focus on high-impact efficiencies. Key areas included:

1. Avoiding wasted time arising from delivery logistics, especially finding panels quickly and efficiently in-process.
2. Identifying potential points in the factory, to onsite processes that could add value and remove wasted work effort.
3. Defining when and where to read or write to the RFID system in the field. Among other things, this includes:
    a. Pulling down panel information from shipping manifests
    b. Pulling down panel information from the Cadwork panelisation model of the building project
    c. Time and date stamping to show that an assembly has passed through defined process locations to determine throughput and productivity
4. Determining how to structure and display readings for practical purposes and for various levels of interest (factory or site personnel, internal management information, and external parties)
5. Determining what information should be stored
6. Determining operating characteristics such as the placement, scalability and performance of the RFID system.

The choice to use RAMP's Loca.fi system created both design constraints and opportunities around these criteria. For the field trial, it's cloud-based approach held the advantage of standalone simplicity as distinct from needing to connect to StrongBuild's existing ERP system (including avoidance of information privacy and security issues). Further, the cloud database provided mobility insofar being connectable via Wi-Fi or 3/4G networks – where the latter would potentially suit onsite usage.

Observing the installation of panels on Strongbuild's sites helped improve understanding of the nature of the processes involved (refer to Figure for an overview of the scale of floor panel installation). From such observations along with the findings from earlier stages of the research, it was decided that tags should be stapled onto the panel edges (edges are typically in the range of 80mm to 200mm thick for CLT panels). This offered the most adaptable and standardisable location for field testing through which the likelihood of damage to tags and interrupted reads were minimized. Different tag types were trialled for suitability relative to environmental factors, form factor, and read range. Though this is discussed more fully later in the field trial findings, the basic chip remained relatively constant and utilised an Impinj Monza R6 Dogbone chip, shown in Figure 7.

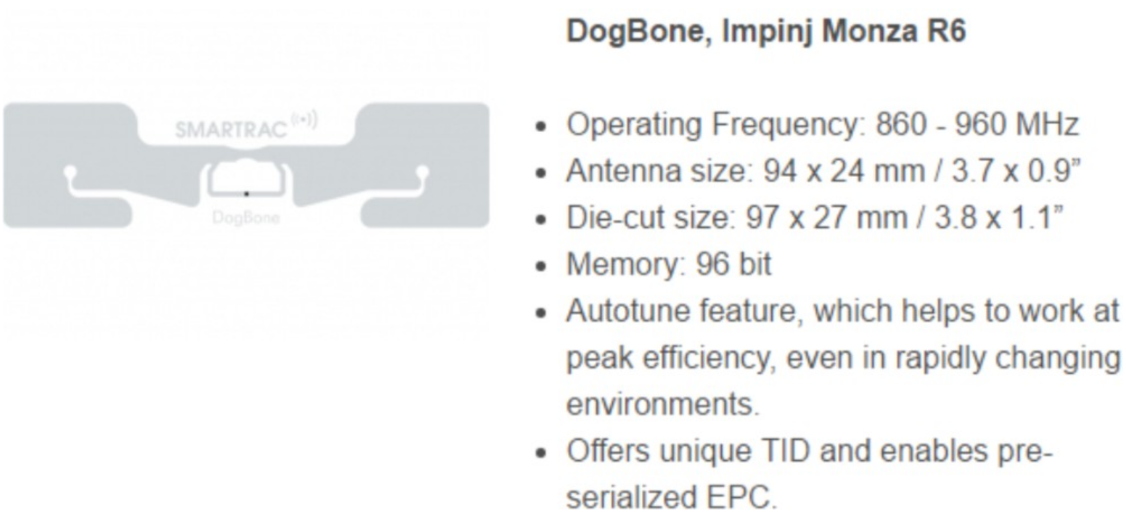


Figure 7: Monza R6 Tag chip

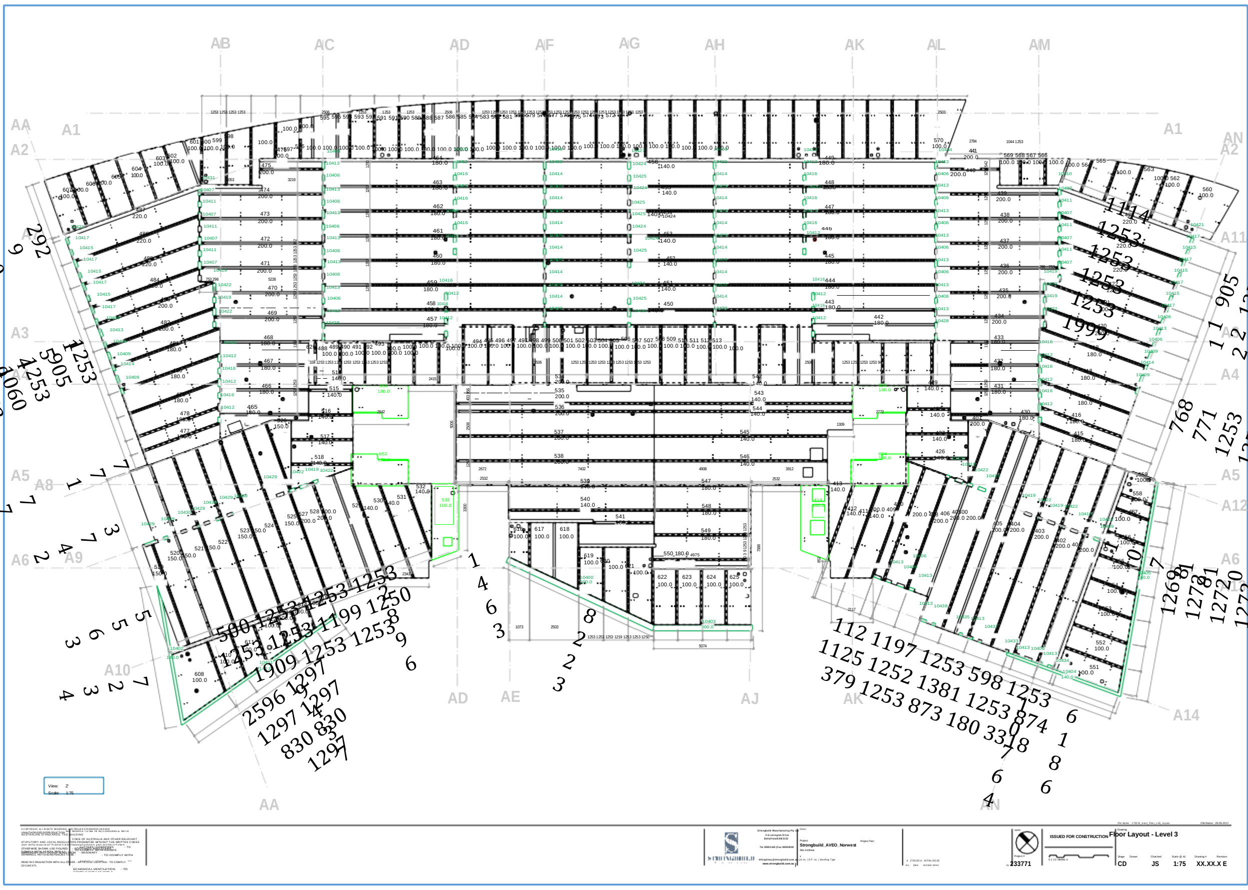


Figure 8: Indicative floor panel layout from a multi-storey residential building project

In addition to the above, it was found that site panel deliveries potentially came to site from different sources. These include machined panels from Strongbuild's factory and raw panels packed in shipping containers, coming directly from external logistics storage, after being shipped from Europe.

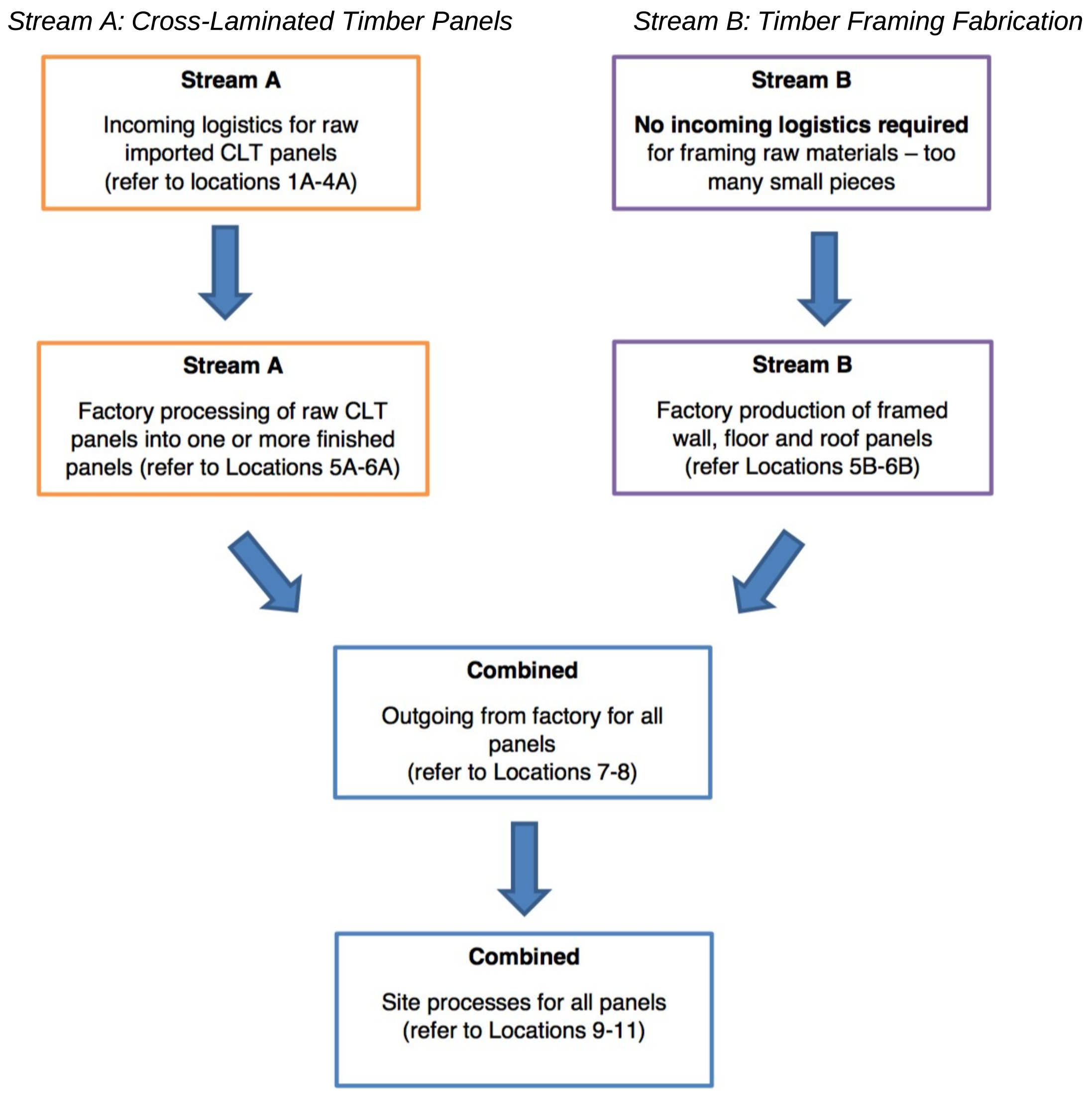
In this latter instance, large areas of land around the site were needed to unpack the shipping containers, because they had been originally packed for shipping economy and not for sequenced installation needs onsite. It was apparent that whilst this process worked for the site in question, the same would not normally be true on tight urban sites where the building footprint occupies most of the available site space, thus creating a more obvious need for the use of the RFID technology to manage delivery logistics and keep double handling to a minimum. Even so, it was apparent that the RFID technology could still bring other efficiencies to the site in question in reducing sighting of panels, checking, double handling and re-sorting panels for installation needs. The general site scenario including the staging area for lifting panels is shown in Figure 9.

Figure 9: CLT Construction site with staging area (lower right)

Four key phases were identified relating to Strongbuild's interest in the RFID technology covering both CLT panels (as used on the site shown in Figure 9) and framed panels (as used on other projects). These phases included incoming delivery logistics for raw materials; factory production of panels; outgoing logistics of finished panels; site delivery and site installation. There were two variants of the main process for RFID application, each taking a different stream in terms of incoming delivery logistics and factory production, while their outgoing logistics and site installation are then combined into a common process:

1. Raw CLT panels are imported from oversees. Such panels need to be tagged at the source (e.g. Binderholz in Austria) and tracking is then commenced once delivered to Australia. This includes delivery to the docks in Sydney, followed by shipment to a logistics storage facility (Enfield), and then dispatched to Strongbuild's storage area for incoming panels (Norwest factory). Once delivered, the raw panels are machined/cut into one or more finished panels in the factory in preparation for delivery to site.
2. Framed panels are made in the Strongbuild factory from a kit of many smaller parts (noggings, studs, plates, insulation, OSB, plasterboard) which in general terms, are not worth tagging because it requires significant integration investment while the added value of tracking the production stage is little. Tagging is only worthwhile once the kit of parts are assembled into larger scale panelised elements.

The arrangement of the over-arching process is shown below in Figure 10 and acts as a high level framework. This is then broken down into more specific details under dedicated headings that follow.



Locations Legend:

Arriving points

- Location 1: Australian unpacking yard
- Location 3: Factory's raw material storage area
- Location 5: Production station
- Location 7: Factory's finished product storage area
- Location 9: Construction site stagging area
- Location 11: In-situ

Leaving points

- Location 2: Australian unpacking yard
- Location 4: Factory's raw material storage area
- Location 6: Production station
- Location 8: Factory's finished product storage area
- Location 10: Construction site stagging area

Figure 10: Overview of RFID reading locations for CLT (Stream A) and Framing fabrication (Stream B)

7.2.1 Reading Locations for Incoming Logistics

A key issue for incoming logistics of CLT panels (Stream A) concerned the ability to verify that all panels in a shipping container were present, as per the provided shipping list from the CLT supplier in Europe. Another requirement was to be able to quickly sort through containers and packs to find the required packs/panels for staged delivery to Strongbuild for processing or to go directly to site.

As a general overview of Stream A, imported CLT typically comes in shipping containers each containing about 4 to 6 packs; each pack contains about 4 to 6 individual panels each being approximately 1,200mm wide by up to 12,000mm long. Tag numbers must be generated by the CLT supplier (in this case, by Binderholz in Austria) including a shipping container tag, pack tags and individual panel tags in a way that there is the ability to cross reference each tagging layer.

The appropriate number of reading locations varies according to the value each provides in logistics processes. For instance, tracking panels whilst at sea involves relatively high setup costs and tracking by third party service providers once in Australia also carries additional cost and so best kept to a minimum. The latter is particularly the case with Strongbuild as they employed a logistics company to manage the customs clearance process and then hired another company to unpack the containers at the docks and take the panel packs away to a separate holding yard, until ultimately being delivered to Strongbuild’s yard. Therefore, outsourced RFID readings involve extra hardware and extra participants in the overall RFID process. Whilst this is not a new phenomenon in other industries, it does mean that careful consideration is required concerning the value of each reading location because of the amount of work, cost and complexity involved. In order to keep uptake of the technology simple, it was ultimately decided that only a reading at the holding yard was necessary primarily to check the container’s content received from overseas, and secondarily to assist in sorting selected deliveries to go to Strongbuild’s yard.

In enacting this in the field trial, Strongbuild staff tagged a number of packs and panels at the holding yard. Mid to long term, these tags would ideally be placed by Binderholz in Austria and hence, once panels arrived in Australia, they could be checked easily.

Accordingly, the location and timing of RFID date/time stamp readings for incoming logistics of imported CLT was as shown in Figure 11.

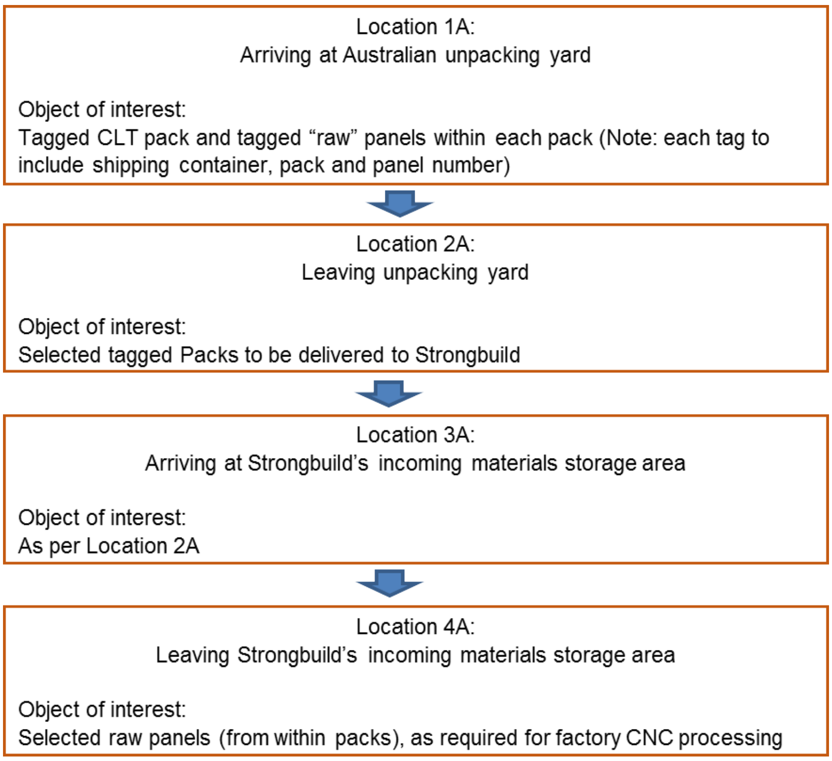


Figure 11: Stream A RFID reading locations for incoming delivery logistics

7.2.2 Reading Locations for factory production

Interest in date/time stamping locations during factory production focused on production performance indicators as follows:

- Measuring production and productivity based on factory throughput (example: panels/day).
- Checking project estimates against actual performance (example: estimates of how long factory production should take compared against how long it actually takes).
- Monitoring production on how far advanced panels are in the production stages with a view to identifying bottlenecks.

With regard to the above, RFID reading locations were mapped for the previously defined A and B streams as each was found to involve separate production processes. Of note, Stream A ostensibly involved picking selected CLT panels from the incoming storage area (refer to Figure 11) and then bringing the panels into the factory for processing by the CNC cutting machine (i.e. the Hundegger). Importantly, these raw panels (including attached tags) are converted into one or more finished panels. Consequently, re-tagging is required once finished panels are cut, to reflect where the finished panels will go in the building and in order to assist delivery and installation onsite.

In practically undertaking this process, the Cadwork software used by Strongbuild was found to provide the best tool for creating identifier numbers on the new tags for finished panels. It is a secondary 3D software that converts the primary 3D architectural model of the building into a "file-to-factory" panelised version. The CADwork software provides a spreadsheet file containing an individual identifier code for every panel in the building, as per the example shown in Figure 12. This can be used to generate individual RFID tags for each finished panel. A data export can then be undertaken from Cadwork to the RAMP RFID cloud database and this can be used to print tags accordingly. There is virtually no limit on the number of panel attributes that can be transferred from Cadwork to the RAMP RFID database. Generally, a unique serial number; identifying type of panels (wall or floor), floor level number, and section number; panel dimensions, and weight are main attributes of interest that were exported to the could database.

Figure 12: Spreadsheet printout of panels in the AVEO project from Cadwork software

No. production list	Group	Subgroup	Name	Material	Quantity	Real height [mm]	Real width [mm]	Real Length [mm]	Comment	User2	User3	User4	User5	User6	User7	User8	User9	User10
178	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	140	1250	3141	CLT 140/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
179	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	140	1250	2244	CLT 140/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
180	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	140	384	2219	CLT 140/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
181	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2269	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
182	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2269	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
183	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2216	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
184	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2216	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
185	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2289	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
186	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	3089	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
187	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	3069	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
188	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	3069	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
189	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	783	3089	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
190	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	3069	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
191	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2812	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
192	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2812	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
193	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2812	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
194	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	1250	2812	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Double Hole & Loop	
198	02 - LEVEL 02 FLOOR	F - 0001	BBS Fichte	BBS Fichte	1	100	80	2812	CLT 100/5s	Floor	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	No Lifting System	
201	03 - LEVEL 02 WALLS	W - 2001	BBS Fichte	BBS Fichte	1	140	686	3080	140-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
203	03 - LEVEL 02 WALLS	W - 2002	BBS Fichte	BBS Fichte	1	140	836	2860	140-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
206	03 - LEVEL 02 WALLS	W - 2004	BBS Fichte	BBS Fichte	1	160	1250	3060	160-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
207	03 - LEVEL 02 WALLS	W - 2004	BBS Fichte	BBS Fichte	1	160	1173	3060	160-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
208	03 - LEVEL 02 WALLS	W - 2005	BBS Fichte	BBS Fichte	1	160	507	3060	160-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
209	03 - LEVEL 02 WALLS	W - 2006	BBS Fichte	BBS Fichte	1	160	338	2620	160-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
210	03 - LEVEL 02 WALLS	W - 2006	BBS Fichte	BBS Fichte	1	160	1250	3080	160-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
211	03 - LEVEL 02 WALLS	W - 2006	BBS Fichte	BBS Fichte	1	160	629	1415	160-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
212	03 - LEVEL 02 WALLS	W - 2006	BBS Fichte	BBS Fichte	1	160	924	3080	160-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	
213	03 - LEVEL 02 WALLS	W - 2008	BBS Fichte	BBS Fichte	1	140	259	3060	140-5s BBS 125	Wall	Falz 56 | 28	NH-C	NH-C		5s	beidseitig gehobelt	Hebeschlaufe	

For framed panels in Stream B, Cadwork is used to cut the parts for each frame i.e. studs, plates, and other smaller pieces, and then drive the automated work undertaken at the various stations in the frame production line. The locations for RFID readings for Streams A and B are shown in Figure 13. In both instances, there is a need to read the tags at the start of the panel production process (where the finished panel does not physically exist yet) and then again upon completion. These tags also remain in place on the finished panel to assist outgoing logistics, site installation and any uses beyond this point in time as per previous discussion about compliance inspection and asset management.

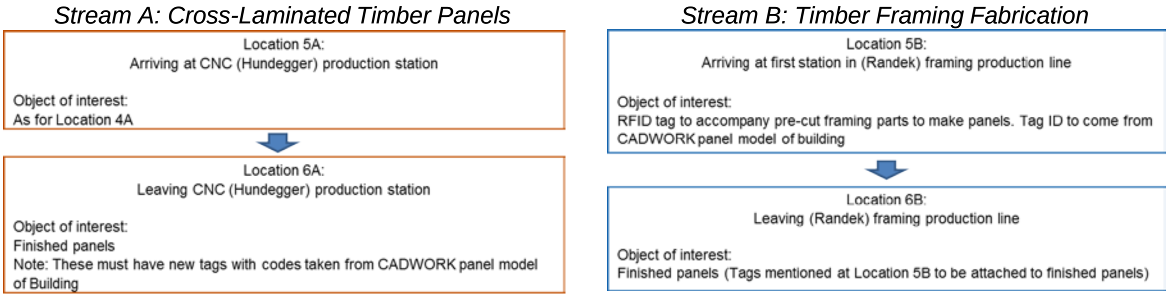


Figure 13: Production Line Reading Locations for Stream A and B

If required, Stream B can be expanded into a more detailed sub-process than shown in Figure 13 to better reflect frame fabrication which involves multiple workstations in fixing members, placing insulation, and fixing plasterboard layers. Inclusion of these stages would be useful where intending to measure productivity at individual stations for the purposes of identifying bottlenecks in the overall frame production process.

7.2.3 Reading Locations for Outgoing Delivery Logistics

Outgoing logistics concerned 1) knowing when finished panels entered storage in preparation for site delivery, 2) knowing where those panels were located within storage, and then 3) being able to pick panels and prepare for deliveries to site. Despite these targeted stages, for simplicity of technology uptake during the field trial, Strongbuild focused upon taking RFID readings upon receiving finished panels into factory storage area (item 1) and as soon as dispatch of deliveries to site (Item 3), as shown in Figure 14.

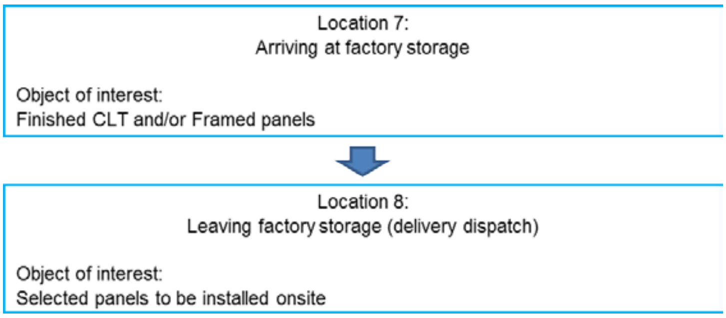


Figure 14: RFID reading locations during outgoing logistics

In addition to these reading locations, an extended use of the RFID technology concerned the ability to help compile panels on delivery trucks for delivery to site in the correct stacking order; this was found to be particularly important to ensure that onsite installation occurred smoothly and according to the intended assembly sequences onsite, as pre-determined from an onsite installation plan. Methods for doing this require attention to detail in picking panels from storage, for delivery, and in coordination with site needs. For this, it was found that the previously mentioned Cadworks software could help facilitate the process via the QR code generated for each individual panel (refer Figure 15). This code potentially allows coordination between the design office, factory and site because the codes can be both cross referenced to RFID tags on panels as well as creating sequenced picking lists according to site needs. For instance, simply cutting and pasting QR codes into a sequenced order could be used to match up tagged panels with stacking order.

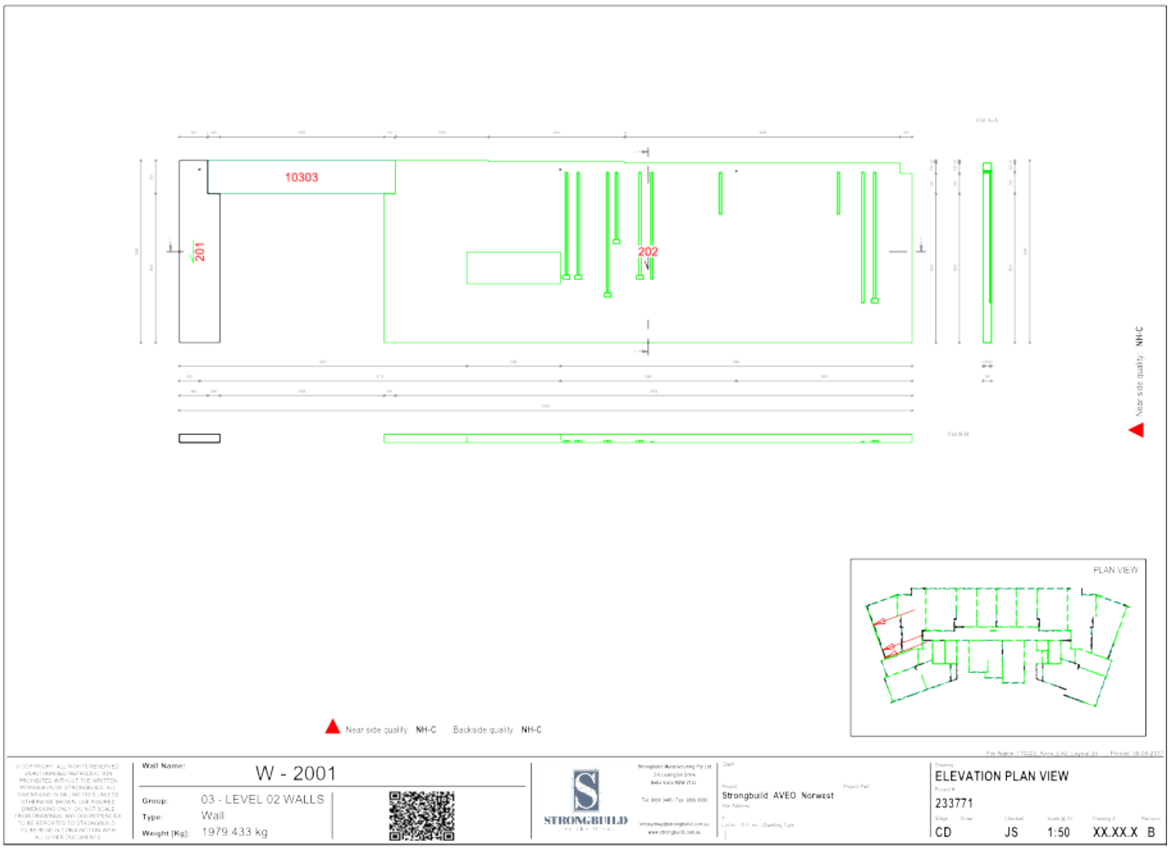


Figure 15: 2D panel drawing of specific panels

7.2.4 Reading Locations Onsite

Key issues for site usage of RFID technology revolved around:

1. (As previously mentioned) Panels deliveries being in correct stacking order to suit the required site installation sequence. This is to achieve fast installation, avoid confusion,

avoid wasted effort, idle time while finding the right panel and avoiding double handling of panels.
2. Knowing if particular panels had been delivered to site and if so, where they can be found
3. Measuring onsite installation productivity and completed work for progress payments
4. Identifying and hoisting the right panel and avoidance of double handling
5. Knowing where a panel should be installed
6. Being able to view panel design detail

The first of these points can be addressed using the same QR code methods mentioned under the previous heading. With regard to the other issues mentioned in the list, a key initial decision was whether to stick with handheld reader usage or to also consider usage of gate reader. In consideration of this, gate readers potentially automate the panel reading process as trucks enter the site, but such an approach tends to be more suited to fixed production facilities more so than the temporary nature of building construction sites. In addition, not all material suppliers may want to be involved in the RFID technology.

In seeking an automated approach further, consideration was given to mounting a reader on the crane boom to capture the main materials movements, primarily during panel installation cycles. Whilst this has mid to long term potential as a measure of productivity, feasibility problems include the boom being too far away from the tackle where panels are hooked up; mounting the reader on the terminal tackle may be a better option but may still not be stable enough given the long pendulum effect of wire drop, the continual movement in the tackle head, and thus, the possibility of damage to the RFID reader. Though this approach has longer term potential, it was decided against including it in the field trial.

Subsequently, hand held readers were considered the best option for initial implementation purposes. Even so, the lack of automation meant site staff must be trained and allocated responsibility for taking readings, thus triggering a need to keep the number of readings to a minimum. This may typically when panels are first lifted off the delivery truck (a reading that could be taken by the crane dogman) and then upon final installation (a reading could be taken during actual installation or as part of an overall set of readings at the end of the day, by an allocated worker on the live deck). Intermediate points may also be taken according to need. For instance, unless panels are installed directly off the delivery truck (i.e. Just-In-Time approach), they effectively require double handling and so each movement may involve additional readings. An example is where packs of panels were lifted to the main deck and then a second lift was used to move individual panels from the deck to the final insitu location.

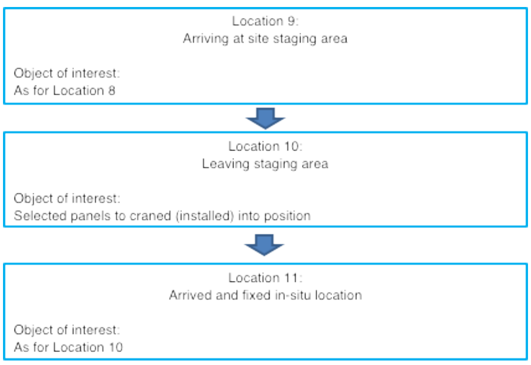


Figure 16: Reading Locations Onsite

In trying to identify the most useful readings, much can be accomplished by focusing on panel crane cycles because it was found that this acts as a strong measure of productivity accomplished in a days work. Such readings could be developed to discern cycle time and the area of each panel lifted, and from this, it is relatively easy to calculate productivity rates based on area installed over time taken to install (i.e. m^2/hour). In practice, this level of detail is perhaps only necessary when undertaking detailed work studies to find out if an existing process could be improved upon or supplanted by more productive approaches. It is envisaged that the crane cycle readings at the beginning of each lift, could realistically be undertaken by the crane "dogman" who will already be in close proximity to the panels during lifting operations.

A note separate to the field trial is the progressive ability to use smartphone and tablet devices with RFID technology. For instance, the Cadwork information mentioned previously can potentially be used more intuitively and carpenters installing panels will be able to call up detailed PDF drawings for panels on their smartphone/tablet, such as the example shown in Figure 15.

7.2.5 Other considerations

Other readings depend on the extent to which third parties are included in the system's reporting capabilities. For instance, quantity surveyors approving progress payments for the client, could quantify completed work, and inspectors could approve compliance. In the short term, this level of inclusion is thought to lack uptake however, the advent of readers attached to smartphones could make this more realistic.

Linked to this is the possibility of tags with sufficient on-board memory for core information to stay with the object rather than being deployed to cloud-based storage. Of note, such data could include physical properties of panels including:

a. Size: thickness, length, width, and volume
b. Area: gross area and net area (with windows, doors, openings deducted)
c. Construction type: framed or mass timber:
d. Dominant material type: timber species, CLT GLT, LVL, plywood, oriented strand board
e. Design density in kg/m3
f. Special characteristics: # of lamellas, lamella thickness
g. Stress grade
h. Surface finish grade: industrial, industrial &finished, finished both sides
i. Adhesive type (for engineered timber materials only)
j. Surface coatings
k. Main connector
l. Termite/fungal treatment

Other information which would require much greater memory and is perhaps less achievable in the short term includes:

- safety and sustainability compliance verification
- on-site installation sequence, lifting method, fixing details, propping layout, bracing layout
- photographs and details that may be required by certifiers

- inspection approval (i.e. inclusive of name, company, date of inspection, and outcome)

7.3 Conclusions

From the previous analysis, it was possible to identify and customise RAMP's standard Loca.fi database structure to suit the project's needs, including the read locations mentioned previously. Whilst this utilised Strongbuild's situation as a backdrop, generic naming described earlier, aimed to provide broader based generalisability that could be used by others involved in prefabricated timber construction, in a similar manner.

8 STAGE 4 RESEARCH - ACTIVE FIELD TRIALS.

Trialing of the RFID tracking system under a real-world case scenario was undertaken during the factory production and onsite construction of a seven-storey residential apartment complex, being constructed by Strongbuild. The complex consisted of CLT floors and walls, as well as framed walls. The field trial focused specifically on the supply chain of CLT panels albeit that the technology could also equally be used on framed panels as well. Importantly, and as mentioned previously, Strongbuild has a vertically integrated delivery system in which design office, factory manufacturing, and construction site, work together to deliver building projects. In the case project, raw CLT panels were imported from Austria for factory processing, into finished panels. This typically involved large/long raw panels being cut into smaller (finished) wall and floor panels and then delivered to site for installation. The field trial of RFID technology, thus, aimed to evaluate its value across different execution stages of the case building project. The findings are presented and discussed with an emphasis on the lessons learnt and the challenges confronted during the trial stage.

8.1 Method

The research team used the RFID tracking flowcharts shown in Figure 10 (refer section 7.2.) to set up the apparatus and experiment with the viability of the system. This involved:

1. ***Installation of the RFID equipment and related commissioning work:***
   This involved installation, set up, and testing of RFID hardware, namely readers and tags. Two handheld readers were set up and utilized. Larger readers and more automated (e.g. gate readers) were not used due to the relatively small scale of the project. Other technical and non-technical issues surrounding this are explained further, later in the report. Moreover, two types of RFID tags were tested on single panels and packs of panels including both raw and finished panels.
2. **Induction training of the RFID equipment for workers involved in factory, logistics and site processes:**
   The research team and the RFID technology partner, RAMP RFID, conducted two training workshops for Strongbuild staff in its factory. The first workshop primarily focused on the use, operation, and troubleshooting of the hardware systems over the supply chain of CLT panels. This involved hands-on exercises where the operation team undertook initial tests using the RFID tags and readers across the factory, from the raw panel storage area to the finished panel dispatch area.

The second workshop was dedicated to working with the features of the cloud-based software tracking system, Loca.fi. This session, in particular, provided training on customizing read locations, data collection points, inventory checks, time performance analysis, and reporting features of the software platform.

3. **Monitoring of implementation**
   Once Strongbuild started trialling the technology on the case project, the research team documented the implementation through factory visits and regular offsite progress checking. Emphasis was placed on three locations including the raw panel arrival yard, production line workshop, and the finished panel storage/dispatching yard. The visits involved identifying tagged panels in terms of physical locations, cross referencing between pack and panel picking lists, visual inspection of the tags (for damage), and assessing accuracy of the reads. Offsite progress monitoring aimed to ensure the RFID tags were supplied via RAMP RFID in an accurate and timely way to the factory, so as not to interrupt the supply chain tracking process.
4. **Problem analysis in practice**
   Problem analysis was performed during and after the trial phase through both observational and perception-based evaluations.
   In the observational method, the selected RFID tracking system was evaluated primarily with respect to its technical specifications and then, with regards to its impact on process efficiency. Therefore, the technical features specified for both the hardware (RFID tags and readers) and software (Loca.fi) elements were validated. For the RFID tags, the ease of use on panels, the durability against weather, movement and friction, and the read/re-write capacity were examined. For the RFID readers, the range and accuracy of the reads in indoor and outdoor environments were checked. For the software systems, the RFID reader and the web-based tracking system were examined through evaluating user-interfaces and troubleshooting methods. Finally, the effect of the selected RFID technology on process efficiency was recorded across different stages of the supply chain through perceptions of both time and manpower savings. In the perception-based analysis, staff and mangers involved in usage and uptake were asked to comment on the RFID technology in their operations and as such, the areas that need improvements were identified. These included potential improvements to the RFID hardware and software, in conjunction with diagnosis of simplifications required in the tracking process (such as reducing the number of read locations that added limited value to process efficiency but demanded extra manpower in-process).

8.2 Active Field Trial Findings

8.2.1 Tags

The RFID tags used in the trial phase were UHF passive paper-type labels with a read range of up to 12 meters, shown in Figures 17 to 19. As alluded to earlier in the report, choosing the paper-type labels had a number of pros and cons. Pros include simplified mass production of tags through an RFID tag printing system that prints and encodes labels on the back of RFID chips; paper tags also reduced the cost per tag to 30 cents which at the time of the research, represented a low price per tag in the RFID market place. As adoption of RFID technology relies on supply and purchase of thousands of RFID tags throughout a project, this small price becomes a continuous operation cost that should be kept to a minimum. Finally, the paper-type labels enabled a degree of customizability in the design of RFID tags such as dimensions of label, order, quantity, and readability (font size) of printed information on the tags.

The initial tags were 4cm×5cm self-adhesive labels, shown in Figure 17, used on the raw panels located in the outdoor storage yard of the Contractor's factory. Two problems became apparent over the use of these labels. First, the wet weather affected adhesion and thus, around 20% of the tags went missing or fell away from the panels. Apart from additional supply costs, this also led to rework in associating the right substitute tags to the right panels. The second problem was the relatively small dimensions of labels limited the amount and size of information that could be printed on the labels. Similarly, the small dimensions of labels impacted the speed of attaching labels to the panels.

Figure 17: Initial RFID tags on a raw panel (4cm×5cm)

To address the above issues, a new tag design was introduced by which the dimensions increased to 6cm×8cm which were stapled rather than adhered to the panels, as seen in Figure 18. The increased dimensions allowed pack number to be more visible for the storeman to quickly locate packs of raw panels in the incoming storage yard. Two staple fixing points were used on each label and care was required not to accidentally staple through the chip inside the label (refer Figure 18 shown in red) which impacts adversely on readability. This problem was taken into consideration when designing the RFID labels for finished panels.

Figure 18: The second generation of RFID tags on a raw panel (6cm×8cm)

The RFID tags designed for finished panels were even larger in size (8cm×10cm). This increase intended to accommodate more information and a dedicated space for staples, as seen in Figure 19. The information on the labels of finished panels referred to building number, floor level, panel type, pack number, and panel number. Although such data were stored in the chip and readable through the RFID readers, printing them on the label aimed to enable simple visual identification on the construction site. Of note, the nature of the construction site may require multiple identifications by different people where an RFID reader may not always be readily available. As shown in Figure 19, the box assigned to stapling (shown STAPLE HERE) served to increase the speed of attaching labels to finished products. These labels also allowed more and larger font information to be printed to speed up panel handling processes. Also, stability of these tags was tangibly better than earlier versions (i.e. no missed tags was reported) albeit that care in was required in placement location, in order to avoid the tag causing damage during machining or even detached during machining. As part of this and to avoid damage to the tags, it was found useful to ensure staples were driven deep enough to finish slightly below the surface of the panel.

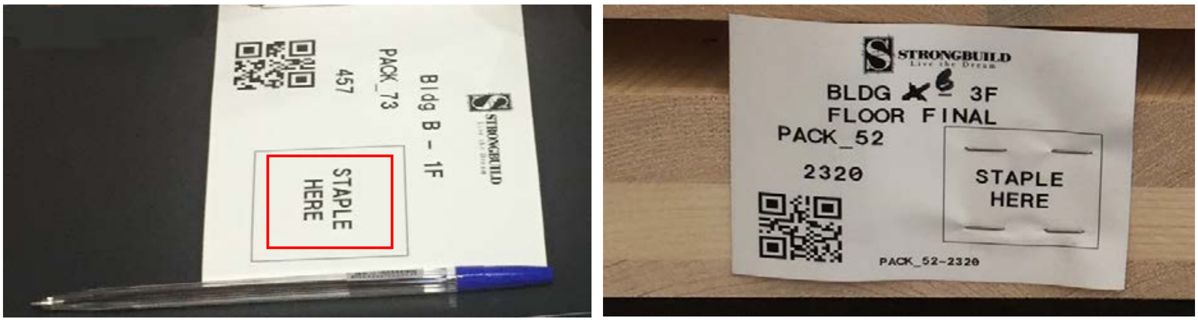


Figure 19: The final type of RFID tags designed and used on a finished panel (8cm×10cm)

8.2.2 Readers

Only two handheld RFID readers were used for tracking the panels – each with a dedicated on-board screen to simplify reading procedures. The readers used were Chainway C4000 Android UHF Gen 2 RFID readers described in Section 6.2.2., each having an approximate cost of $1800 per unit. Whilst this was appropriate for the needs of the field trial, it is worthwhile mentioning that each one requires worker input to operate and so responsibility for such tasks must be assigned accordingly – such tasks are relatively new to both factory and onsite construction processes. As mentioned earlier in the report, more expensive *fixed gate readers* provide longer range reading capacity and a higher degree automation, to the extent that the likes of forklifts and trucks can pass through a gate and have all panels read instantaneously without worker intervention. In addition, gate RFID readers are usually deployed in pairs, one at the entrance and another at the exit gate, to provide measures of overall production accuracy and efficiency. These readers were excluded from the trial due to budget limits but a basic gate reader which includes the fixed reader, antennas, consoles, and cables costs approximately $5000. Extra costs include installation and associated infrastructures expenses (such as the gate, electrical and electronic supply/ connections) and hence, an overall estimate for an installed gate reader may be ultimately be in the region of $10,000-12,000 each. Ongoing servicing is obviously at further cost. Such an approach is mainly thought to be worthwhile in factory operations, around receiving or dispatching deliveries, more so than for site operations.

Figure 20: Strongbuild factory's storage yards and tagged panels (Left: raw panel arrival, Middle: Finished panels stack up, Right: Tagged finished panels)

The handheld readers were used by the storeman and production workers to read the tags on the raw panels and the finished panels. The range of reads were up to 15 meters away from the location of tags, however, the readers were most reliably used where tags were within a 3 metre range. This was reflected in the average number of tags read per unit of time, which resulted in 32 tags/minute on average. The accuracy of reads was measured based on the percentage of the total number of tags in a certain location that could be read without need for a direct line of sight. During the trial, an average of 85% read accuracy was achieved across different read locations. Also, no significant difference was observed between indoor and outdoor reads of raw panels in terms of accuracy and speed under normal weather condition. On wet days, the reading speed of raw panels was lower and in the range of 16-24 tags/minute. In such cases, there was a need to identify the panels through a direct line of sight to the tags. In contrast, the speed of reading tags on the finished panels was higher, at 36 tags/minute. This can be attributed to two factors: the design of tags and the size of finished panels. The design of tags, discussed above, prevented any damages to the chips and helped the staff to properly attach them to the panels. The finished panels, were also smaller compared to the raw panels. This seemed to promote less uninterrupted transmission of magnetic waves from the tags to the surrounding area.

Figure 21: Examples of reading tags when direct line of sight was necessary

The handheld reader transferred the data to the web-based tracking system through the Wi-Fi network available in the factory premises. The data transfer was relatively quick in the order of 10-20 seconds after completing a round of reads. The speed of data transfer seemed to be dependent on the quality of the network and there were occasional instances when the data transfer was as slow as 2-3 minutes in processing information from the read tags. However, other factors, such as the interfaces between the app on the handheld reader and the web-based tracking software in conjunction with the programmed features of each, may have also played a role here. This was particularly noticeable because a relatively slow data processing time was observed even when the network quality was high. It should be noted that the handheld readers can also work independent of a WI-FI network, by using a SIM card (from an independent service provider) inserted into the reader, which accesses the that provider's internet network. This is a good option for construction site operation where a dedicated network may not be appropriate. Finally, the handheld readers need to be charged every second day if they are used regularly. The frequency of charging may be shorter as the reader ages.

8.2.3 Software Applications

The above-described hardware components of RFID technology were coupled with two interconnected Loca.Fi software systems, including an Android application and a cloud database.

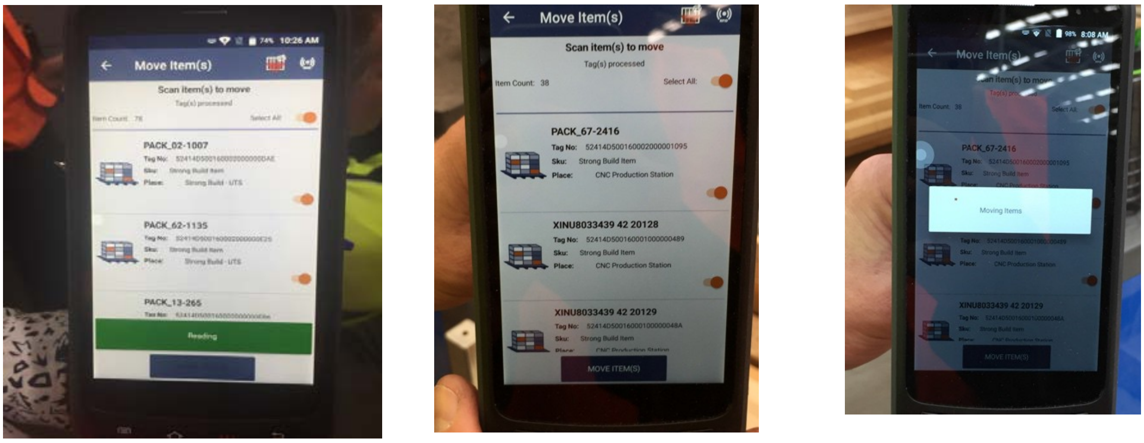


Figure 22: RFID Android App for managing readings

The Android app was installed on the handheld RFID reader and was mainly utilized to search and identify the tagged panels, stocktaking at different locations, and assigning new tags to the panels. As shown in Figure 22, this application also enabled managing movement of the panels from one location to another. As seen, once the tagged panels were identified, they were assigned to a pre-defined location (e.g. panel receiving storage area, panel processing area, outgoing storage area, incoming site storage area etc) and hence, movement of the panels along the supply chain were tracked. This feature particularly increased the efficiency of the field workers who use to spend considerable time in visual inspection of panels to find, sort and cross-reference with the pack and panel picking lists. For instance, they used the handheld reader app to list the tagged raw panels stacked for machining at the Hundegger machine station and crosschecked this with a hardcopy version of CNC picking list generated by the design team. In doing so, a tedious time-consuming job was replaced with a semi-automated fast track audit that took up to 5 minutes. The handheld reader app also helped the field workers once machining was completed and finished panels were identifiable. Here, finished panel IDs were lifted from the CADworks (BIM) model of the building which is/was used to break the architectural BIM model into a panelised cutting schedule capable of running the Hundegger and other production line machinery. The finished panel IDs were used to stack the dispatch panel packs based on a site installation sequence issued by the design team (refer Figure 23).

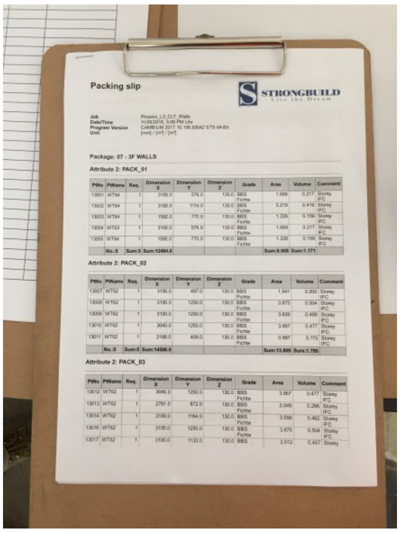


Figure 23: A sample picking list which the read panels are checked against

Figure 24 shows a screenshot of the cloud database. The database is effectively an online tracking system to store all the field information read and recorded through the handheld readers and its Android app. Such information includes both raw and finished panel attributes (such as tag serial number, pack number, panel number, dimensions, and weight), and timestamp data with respect to different locations tracked over the journey of a panel from the incoming storage yard at the factory, to the construction site. All the features of the Android app, except tag reading, were also available in the online tracking system. However, this platform mainly assisted in generating managerial reports with overall statistics on the status of the panels, as shown in Figure 24. Also, the timestamp information recorded by the handheld readers could be used to produce reports which provided time performance analytics such as waiting times along different supply chain stages (e.g. waiting time in storage or dispatching yard), production rate of machines and production rates from the beginning of a process (such as factory production) to milestone points such as delivery to site. Such reporting features were used in a limited number of runs throughout training and the trial phase. The same approach could also be used onsite to measure and monitor productivity in terms of the number of panels placed per day or the number crane lifts per day. If such information is used for monitoring and process control then corrective actions can be made, based on the insights gained from such reports.

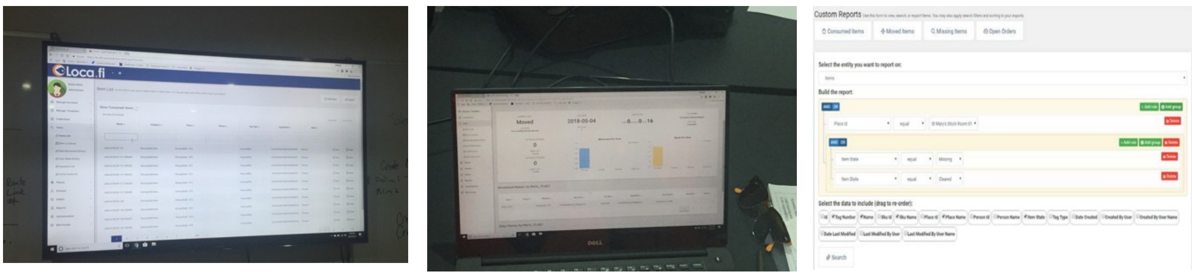


Figure 24: Screenshots of Loca.fi panel tracking and progress monitoring system

8.2.4 Perceived usefulness and challenges

Two usage contexts became apparent during the trial phase, namely for “doers” and “managers”. Doers are those who undertake day-to-day tasks in the factory or onsite, in using RFID to assist with conversion processes. Managers are responsible for controlling and monitoring these processes in a holistic and strategic way.

It was found that the first group were mostly interested in using the RFID tags and readers to make their immediate (daily) tasks easier. Although they had been given rudimentary learning of the Loca.fi cloud software, which had been designed to reflect their internal work processes, their scope of duties did not necessarily mean they were responsible for championing its implementation or committing to its broader uptake. Instead, they used the hand-readers in a relatively rudimentary way to ID specific panels and then cross check against hard copy lists of panels. There was also a tendency to not to have “too many reading locations”. This low level of usage predominated during the trial as from their point of view it was simple and expedient, albeit well below the functional potential of the system. These observations also demonstrated the need for strategically positioned managerial staff to take responsibility for broader based implementation. Taking this point further, another part of this issue that prevented optimum uptake of the full RFID system was the limited time in instituting the system as part of day-to-day procedures and across multiple work areas – usage was largely limited to factory and delivery logistics and did not include onsite processes or design team usage. It is felt that this must change and broaden to include these other departments in order to benefit from the integrated information flows offered by the RFID technology. For instance, the respective teams (design, factory, delivery and construction) need to come on board in a combined way in order to optimise usage of the RFID technology. Further, it was apparent that there were operational issues to overcome, where for example, the design team would typically advised the factory team on which panels to machine within a 24 hour period, which meant labels were difficult to provided quickly enough (by external sources such as RAMP RFID) and hence the need for having an internal tag printer available for fast printing of tags.

The second group, strategic managers, were primarily interested in time tracking of panels for production rates, bottlenecks and project throughput. At the time of completing the project, Strongbuild were in the process of extending their supply and fix service, which would be offered externally as well as internally. Full realization of this aim requires addressing some issues with the Loca.fi system. Currently, there is no direct connection between Loca.fi and Strongbuild’s ERP systems. This causes a level of manual data processing and interoperations. For instance, Loca.fi doesn’t allow uploading of the picking lists that can be automatically checked against their readers and used in the above mentioned processes. Also, Loca.fi has been featured to best work in terms of many units of the same stock whereas in Strongbuild’s projects, nearly every panel is different. This creates a level of information manipulation within the platform when generating productivity reports with respects to different types of panels involved.

9 CONCLUSIONS

RFID technology essentially concerns accessible real time information flows that stay with a given product or object (in this case, prefabricated timber panels) throughout a defined process. It provides time and date stamping at given locations in the defined process. It provides product tracking and a degree of stored information held on the RFID responder. It can also provide access to a greater range of data stored on a cloud database. Read and write capability makes it possible to update information on the tag. The reader does not need a direct line sight to the tag which means it can potentially read through minor, overlying construction materials albeit that metal layers pose significant problems. An entire delivery of panels can potentially be read at one time. These features plus the ability to build-in a degree of smart technology, are the main features that differentiate it from the likes of bar code and QR code technology (albeit that these technologies can be easily blended with RFID technology, according to need).

Whilst used commonly in many industries, it application to construction is relatively new and currently limited. Here, five distinct value adding stages of RFID application were found in this research:

1. incoming delivery logistics,
2. factory production of panels,
3. outgoing delivery logistics,
4. onsite installation
5. third parties who may inspect the finished construction work

The first three stages occur within offsite prefabrication processes and this is where the most potential is thought to lie. The fourth occurs on the construction site and this potential is reliant on specific scenarios mentioned below, especially vertical integration as distinct from the high degrees of fragmentation common in the construction industry. The fifth has potential that is conditional upon the technology first becoming common onsite.

An unlisted, but potential sixth area, involves long term facilities management but interest in this area was not particularly apparent in this research, primarily because the companies involved did not have an ongoing interest in the building after construction, and clients had yet to demand/recognise the need for such technology as a value feature of the construction. This will likely change with time in certain market sectors.

Adding to the above, this research found that the degree of fragmentation typically in construction supply chains means that small, isolated and individual benefits at each link in the supply chain are insufficient to foster a more holistic value proposition. Instead, the value proposition tends be strongest where there is:

- *The presence of large scale and vertically integrated supply chains:* The value proposition is much stronger where an individual company spans multiple links in the supply chain. This opens up the possibility of the abovementioned links extending from logistics, to factory production, to outgoing logistics, to site operations. Of note, usage of the RFID technology onsite, is thought to be of most value where it is part of a vertically integrated supply chain.

- *The presence of logistics complexity between a limited number of discrete supply chain links that undertake business in a partnered and integrated way: Here, the RFID technology appears most easily implemented between raw materials suppliers and prefabricators. This is because such processes occur in a predictable and systematised way including the use of dedicated staff/departments who deal with materials management and logistics issues. It may also apply to partnerships between prefabricators and onsite construction contractors but may be dependent on them having an ongoing flow of relatively standardised and repetitive work.*

- *The presence of large scale internal logistically based complexity problems: This simply relates to dedicated product tracking or time/date stamping problems. It is most likely to occur in the likes of large scale prefabrication companies that deal with repetitious processes and have significant economies of scale. It could also occur onsite but is dependent on the contractor committing heavily to adoption of the technology which has yet to happen in Australian contexts.*

RFID offers automated processes where fixed readers are used in a defined process. This can be at least partially utilised in prefabrication factory environments, but the ability for high levels of automation is thought to be more limited onsite (due to the temporary nature of sites and hence the lack of inclination to used fixed readers and associated investment). Hence, hand readers are more likely to be used (in the short term) and therefore require operators, training, allocation of staff and so on. The ubiquitous use of common handheld smartphones for RFID readings – in the future - may aid this situation significantly.

The main areas of interest for prefabricated timber assemblies include:

- *Speeding information flows on the location of assemblies onsite i.e. tags on panels can potentially be linked to digital drawings or BIMs to know where panels go onsite or perhaps the order in which they should be placed*

- *Providing safety information on tags about safe handling processes.*

- *Make work ready planning possible and then potentially linking this with the contractor's planning and time scheduling software*

- *Providing real time information on the progress of installation including measuring the percentage of plan complete, and release of following deliveries onsite.*

- *Details on the types of materials used in a panel in terms of environmental certification, chain of custody and waste management requirements.*

In addition to the above, UHF technology was found to provide the best technology for RFID when used in prefabricated construction contexts, but care must be taken in the ability and accuracy of tag reading where tags/panels are exposed to excessive moisture or metal substances. Finally, use of the technology was found to be under-utilised where used purely as an isolated tool by workers for digitally cross checking tags against hard copy panel lists. Commitment needs to be placed in accessing and utilising the full strength of information held in the cloud database; the technology should also be used as a strategic tool for linking information flows between departments and for monitoring productivity and controlling processes – the technology can check process throughput in the factory and onsite by way of time and date stamping as well identifying bottlenecks, double handling and other process inefficiencies.

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