Applying New Timber Technologies to a Variety of Multi-Unit Residential Typologies

Studio Pacific Architecture Summer Scholar 2014 - 2015

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ABSTRACT

The outcome of this research will be used by Studio Pacific Architecture to choose relevant timber technology systems for multi-unit residential projects.

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1. Introduction

1.1. Title:

Applying new timber technologies to a variety of multi-unit residential building typologies.

For this project the words "new timber technologies" will be interchangeable with the word "prefabrication".

1.2. Questions:

- What systems have been used in New Zealand so far?
- What new or overseas systems are suited to a New Zealand application?
- How can adaptability, buildability and connections be considered?
- What is available and what is missing in the New Zealand supply chain?
- What changes is needed design wise?

1.3. Milestones:

- Early December - literature review and identification of categories of type of prefabrication system, plus an initial list of potential suppliers and their system types.
- Late January - completed a database of prefabrication methods classified according to a criteria matrix which permits the firm to access the information collated by design feature, cost or construction approach.
- End of summer - drafted a report and a conference paper length summary of the work and complete the presentation of an in-house Continuing Professional Development seminar for Studio Pacific Architecture.

1.4. Scope:

The outcome of this research will be used by Studio Pacific Architecture to choose relevant timber technology systems for multi-unit residential projects. This research identified the available modular timber technologies applicable to multi-unit residential buildings in New Zealand. The hybrid module-plus-panel method of modular building construction is a method that has been promoted by several researchers including Pamela Bell, the CEO of Prefab NZ. Bell identified a significant opportunity in the New Zealand market for prefabrication of buildings through this hybrid approach. This research has not found any reason to alter that view. The focus of this study was on modular, hybrid and panelised technologies as appropriate to the firm.

1.5. Proposition:

Using a combination of empirical, deductive and heuristic methods, a criteria matrix database will developed as a tool for understanding and comparing the range of available technologies in the market. The tool will cover an extensive range of prefabrication methods. The database can be split into sections according to broad construction typologies: module, hybrid and panel. Structure, typology and insulation will be the three main criteria selected for analysis. The tool will enable the user to identify across all criteria the highest scoring systems. A summary table will be created to allow a simple comparison.

The database will be used by Studio Pacific Architecture to select the most viable modular technologies for new multi-unit developments. Any gaps in the data will be accounted for as a zero score in the criteria matrix table.

1.6. Research Timeline:

1.6.1. Potential option one:

Summer Scholoarship Timeline 2014	17th Nov	24th Nov	1 Dec - first milestone/payment	8th Dec	15th Dec	Christmas Break 22/12-18/01	19th Jan - second milestone/ payment	26th Jan	2nd Feb	9th Feb	16th Feb - final milestone/payment
Key Dates	Week 1	Week 2	Week 3	Week 4	Week 5		Week 6	Week 7	Week 8	Week 9	Week 10
Introduction											
Literature review											
Prefabrifcation											
Substitution of stick frame											
Current NZ methods											
Potential overseas methods											
Supply chain NZ											
Environmental benefits											
Research Methodology											
Case Study analysis											
Recommendations											
Conclusion											

1.6.2. Potential option two:

Summer Scholoarship Timeline 2014	17th Nov	24th Nov	1 Dec - first milestone/payment	8th Dec	15th Dec	Christmas Break 22/12-11/01	12th Jan	19th Jan - second milestone/payment	26th Jan	2nd Feb	9th Feb - final milestone/payment
Key Dates	Week 1	Week 2	Week 3	Week 4	Week 5		Week 6	Week 7	Week 8	Week 9	Week 10
Introduction											
Literature review											
Prefabrifcation											
Substitution of stick frame											
Current NZ methods											
Potential overseas methods											
Supply chain NZ											
Environmental benefits											
Research Methodology											
Case Study analysis											
Recommendations											
Conclusion											

2. Literature Review

2.1. What is prefabrication

> *"Prefabrication, the assembly of buildings or their components at a location other than the building site. The method controls construction costs by economizing on time, wages, and materials. Prefabricated units may include doors, stairs, window, walls, wall panels, floor panels, roof trusses, room-sized components, and even entire buildings."* (Encyclopaedia Britannica, 2013).

The idea of prefabrication has been around for centuries although the modern form that many use dates from 1905. It wasn't until the invention of gasoline and the powered truck that prefabrication was widely used. The prefabrication of massive buildings was a result of construction during World War I in accordance with the fluctuation of building activity in the United States, the Soviet Union and Western Europe (Encyclopaedia Britannica, 2013).

2.1.1. Categorizations of prefabrication:

Component based prefabrication – this is the lowest level of prefabrication. Components are created out of materials to reduce the number of pieces, therefore reducing the waste, and increasing the speed of assembly (Encyclopaedia Britannica, 2013). Examples include roof trusses, pre-cut framing, built-up windows and kitset housing that is assembled like a jigsaw onsite (Burgess, Buckett, & Page, 2013).	
Panelised prefabrication – wall, floor and roof panels are main forms of this categorisation. The panels can be open (being only clad on one side, sometimes insulated) or closed (with plumbing, electricity, insulation, windows and clad on both sides) (Burgess, Buckett, & Page, 2013).	
Modular prefabrication – these are typically structural boxes or modules, which are constructed off-site and brought together onsite to form a complete building. This 3D assembly appears to be the fastest construction approach (Burgess, Buckett, & Page, 2013).	
Hybrid prefabrication – this is a method that can be used in combination with another prefabrication method or traditional construction. It involves onsite construction and assembly of prefabricated sections. The system typically uses “volumetric units” for the highly serviced areas such as kitchens and bathrooms, and constructs the remainder of the building using panels or by another means (Gorgolewski, 2005).	
Complete building prefabrication – whole buildings are constructed offsite and are transported to site; these are also known as transportable buildings (Burgess, Buckett, & Page, 2013).	

[1] Image sourced from http://www.swlaw.edu/campus/news/overview/newsr.7hRaq1Veyv accessed 17/11/2014.

[2] Image sourced from http://www.linwoodhomes.com/prefab-or-prefabulous-panelized-modular-or-package-home/ accessed 17/11/2014.

[3] Image sourced from http://inhabitat.com/one9-nine-story-prefab-apartment-tower-was-installed-in-just-five-days/ accessed 17/11/2014.

[4] Image sourced from http://inhabitat.com/prefab-construction-green-or-greenwashing/ accessed 17/11/2014.

[5] Image sourced from http://brandersonhomes.co.nz/waikato_pricelist.html accessed 17/11/2014.

2.1.2. Advantages of prefabrication

- Quality: this is the principle advantage of prefabrication. More quality can be offered for less time and money on site, this is done through the combination of professionals working on the project and through close monitoring of the design and construction within the factory.
- Technical:
    - Quality controls
    - Factory manufacture
    - Testing capability
    - Joint minimisation
    - Tighter tolerances
    - Elimination of defects
- Social:
    - Indoor protection
    - Material and tool security
    - Worker health and safety
    - Machinery training investment
    - Employment stability
    - Design variation
- Economic:
    - Time savings of 30%-60%
    - Cost savings
    - Reduced dependence on weather
    - Coordination of trades
    - Bulk ordering potential
    - Reduced transport to site
    - Reduced floor area
- Sustainability:
    - Reduced material waste of <75%
    - Increased energy efficiency
    - Less disruption at site

(Bell, 2009)

2.1.3. New Zealand historical overview

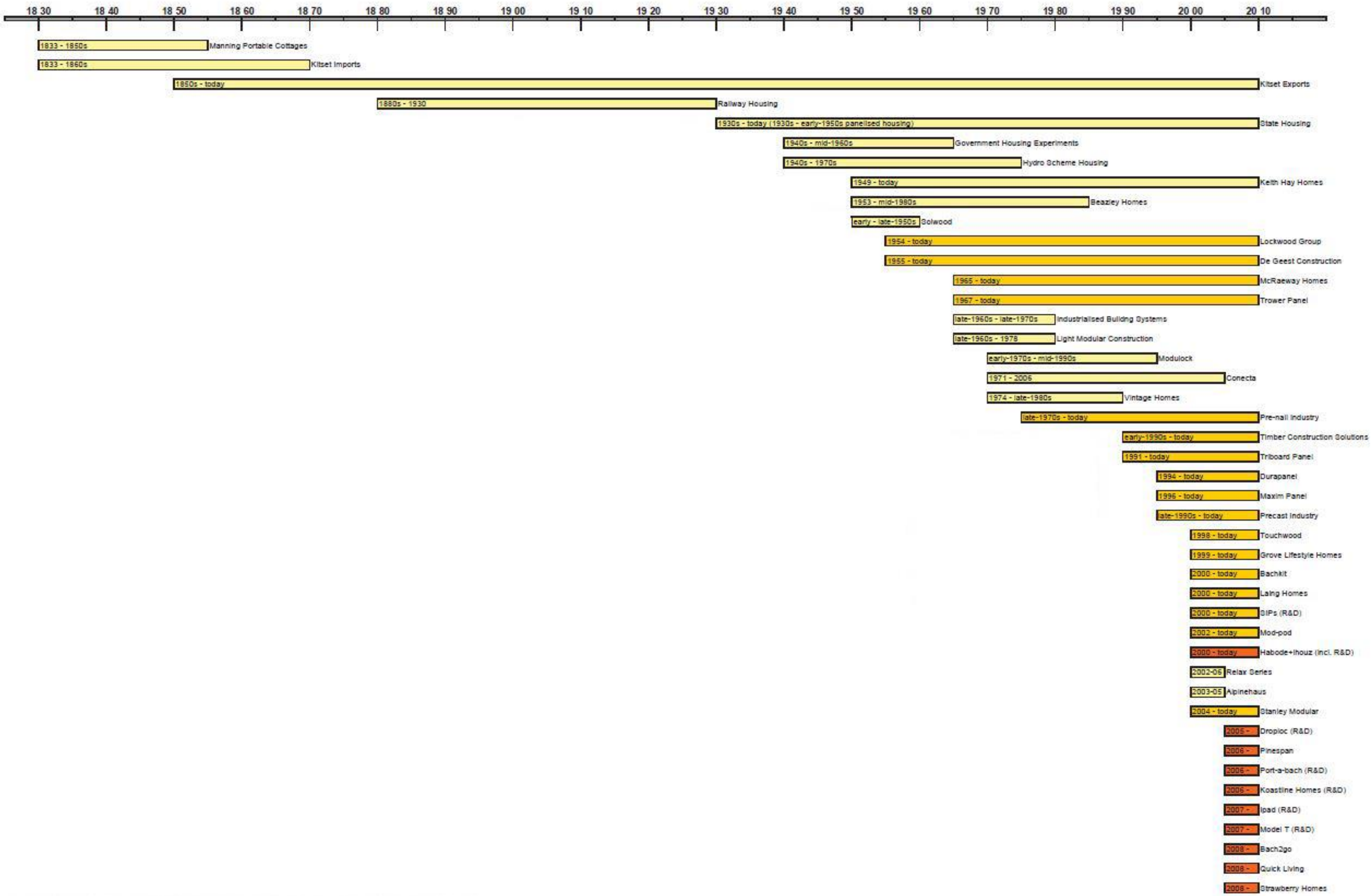


Figure 1: Historical overview of prefab in NZ amended from (Bell, 2009)

2.2. The international experience of prefabrication

Country	Characteristic
Australia	• Modular building sector supplying mass housing for mining camps • Architect and manufacturer collaborations for high-end custom houses • Peak prefab / offsite industry organisation being established 2012 / 2013 • Multi-unit student accommodation projects
Japan	• Housing viewed as a consumable or 20-30 year depreciable asset • 74% of homes 27 years old or less in 2008 6 • Prefabrication seen as a medium to high-end product • Up to 20% of domestic market is prefabricated homes 7 • Five major businesses supply 80% of the prefab home market • Investment in R&D since 1946 means a mature prefab market today • R&D centres offer customised choice of fittings, options, finishes material choices • Steel-frame, panel and modular systems dominate 8 • Highly mechanised, automated due to influence from manufacturing industries 9 • Most construction owner-initiated
USA	• Big firms build 66% of new houses • Most single-family homes • Similar materials • Established modular and factory-built, manufactured, home construction industry • Up to 1/3 all new single-family houses are modular or manufactured 10 • 10% of market is high-end architecture 'modern green prefab' 11 • Exhibition and book on prefab at Museum of Modern Art, New York, 2008 12
UK	• Similar industry set-up to New Zealand, but higher productivity • Barriers to innovation, including aversion to timber structure • Housing shortages • Wary of prefabrication / offsite construction due to post-WWII temporary 'prefabs' 13 • Prefab housing makes up less than 4% of new buildings (2005) • BRE Innovation Park showcases housing in Watford and Scotland • Government push for Modern Methods of Construction (MMC) target 25% for social housing (2007), 200,000 homes in 20 years using fast-track technologies (2004) 14
Scandinavia	• Pre-cut timber standalone houses and precast multi-unit affordable housing • Prefab makes up 90% of housing in Sweden 15 and more than 50% in Finland 16 • Ikea partnered with largest builder Skanska to provide affordable housing • Long acceptance of prefabrication / offsite construction • Quality focus for prefabrication / offsite construction • Drive for energy efficiency, environmental protection
Broader Europe	• Long history and acceptance of prefabrication / offsite construction – with prefab housing making up 5% in Spain and France, and 10% in Germany 17 • Prefab show-home parks in Germany and Austria – 50-100 houses each park • Focus on timber products, sustainability and family-owned small-scale operations • Drive for high-quality and cost efficiency through standards and certification

Figure 2: the international experience of prefab outlined in the Prefab NZ roadmap (Prefab NZ, 2013)

"It was found that the use of a perimeter-based structural system in the international market has been shown to enable open-plan configurations and non-load-bearing internal partitions for future adaptability. Off-the-shelf components have been encouraged in terms of affordability, flexibility, and continuity of supply. A flexible component-based system has enabled the variation in housing design that consumers demand, while a modular utility pod has captured factory efficiencies". (Bell, 2009).

2.3. Market size in New Zealand

The restricted market size in New Zealand for prefabrication is significantly problematic. It makes it difficult to achieve economies of scale particularly in the manufacturing sector. This is irrespective of the need to provide a significant amount of housing particularly in Auckland and Christchurch. In 2011, PrefabNZ surveyed 46 businesses and found that they collectively had the ability to supply 750 3-bedroom houses each year (Prefab NZ, 2013). The market is unpredictable overall and is limited by a lack of access to the project decision-makers at an early stage where the use of prefabrication can be considered. The market opportunities are further restricted by the boom: bust cycle of the design and construction industry. Companies that endure are the ones that offer a diverse range of options and products. The lack of incoming work only adds to the restricted uptake of prefabrication. Methods to potentially improve this problem are, to increase market penetration in New Zealand and to look overseas to grow export markets in the prefabrication sector (Prefab NZ, 2013). The companies that have endured are Lockwood Group, Keith Hay Homes and De Geest Construction (Bell & Southcombe, 2012).

2.4. Prefabrication and architecture

Historically there has been a separation of 'architecture' and 'building'. "*Architecture is associated with emotion, art and spirituality*" (Bell, 2009) whereas, building is just associated with construction (Jones qtd. In Nilsen). Commercially prefabricated buildings without architects have been successful whilst prefabricated architecture has not (Bell, 2009).

> *"It sometimes seems that commercial and industrial success is itself sufficient to disqualify a prefabricated house from the status of architecture"* (Davies, 2005).

Davies considers the reasons behind architecture's commercial failure to be closely connected to; the institution of architecture, projecting distaste for lightweight, a desire for authorship, a connection to the site, miscommunication with its public, and an overall misconception of prefabrication. He suggests the need for embracing 'pattern-books', working collaboratively, and learning from overseas markets is required to ensure success (Davies, 2005). Prefabricated housing is typically non-site-specific, lightweight, requires knowledge of business and challenges authorship. Additionally, the problem of architect-design aesthetics not being respected by non-architects shows that either everyone needs to be educated or architects need to respond to the market more closely (Davies, 2005).

In the past architects that focused on prefabricated housing have been focusing on design integrity as the bottom line, whereas commercially successful prefabs were driven by property developers and entrepreneurs (Ebong, 2005).

Davies also notes that the relationship between architecture and prefabrication has always been an issue. There are further historical misconceptions from the profession, that a potential for prefabrication will diminish the role of the architect. Yet it is argued that traditional construction has achieved this anyway (Davies, 2005).

There is an identified need to find a way to bridge the gap between the architecture profession and the construction industry and consecutively between architecture and prefabrication (Bell, 2009).

2.4.1. CAD package prefabrication programme

> *"After the client has selected a design, the structure is typically segmented into a number of panels (or modules) by specialised panelisation software*

(CAD packages). This step takes place on a screen, with the panelisation software helping to solve all construction details such as wall-to-wall joints, panel-to-panel joints and so on." (Betz, 2010).

A fully integrated panelisation package offers the generation of all building-related information in one model. This model can contain; thermal building performance, schedule of materials, CAD details and drawings, and the ability to communicate straight to the manufacturing machinery such as automated cutting equipment (Betz, 2010).

2.4.2. Building Information Modelling (BIM)

The use of BIM in the design process allows close collaboration of all design team members. This ensures effective early stage prefabrication design. The BIM model can form the basis for the design, development, fabrication and manufacture of the building. The use of this process is essential when using prefabrication methods, as extensive planning is required to deliver such a system. The model provides a high level of precision necessary for off-site fabrication and can be used to procure materials and plan assembly sequencing ahead of time. Schedules for the ordering of materials can come directly from the model and cost, weight etc. can be tracked through a development process. A BIM model can erase the need for the creation of shop drawings by a contractor; an architect can create these directly from the model thus saving time and money. The standard measurements of materials dictate the design as it ensures less effort cutting the materials to size. Due to the generation of the exact amount of materials there is a significantly lower amount of waste produced overall (AIA).

2.5. Recent issues with New Zealand Prefabrication

2.5.1. Economic recession

The economic recession that started in 2008 has significantly impacted the construction industry. It forced the market to withdraw and it is making it difficult for new businesses and sectors to start up. In the 1970's recession businesses such as IBS and LMC were forced to close (Alter, 2008). We have seen this happen with Mainzeal, one of the biggest contractors in New Zealand with big clients such as Victoria University. Prefabrication is understandably cheap but it is costs of overheads, transport and cranes that eradicate it (Alter, 2008).

2.5.2. Flexibility and responsiveness

This is an approach to fight tight economic times. Firms such as Pinecone have included feedback into the research and development division so that they can respond more appropriately (Bell, 2009).

2.5.3. Manufacture in China

A china based manufacture can be seen as threatening to New Zealand construction industry sub-contractors. There are perceptions that prefabrication is looking to replace traditional forms of construction; communication is needed to overcome this as prefabrication is intended to compliment the current New Zealand construction industry (Bell, 2009).

2.5.4. Protection of intellectual property

Protection is crucial; especially when sometimes over 2000 new different components are created. Although cost savings from offshore manufacture can offset intellectual property risks and quality control issues, this needs to be solved early in the whole process (Bell, 2009).

2.5.5. Industry relationships for research and development

Further development is needed particularly to achieve a higher level of innovation and to stay ahead of the market. There is a danger of repeating historical mistakes; this is why it is crucial to understand what went wrong nationally and overseas. The full range of options needs to be significantly explored as the market is unpredictable and supply is still a problem. Hybrid module-plus-panel systems offer flexibility but this needs to be researched as there is currently a gap in the market between component based and complete building systems. In the past, the New Zealand government recognised innovation through experimental housing projects and public works. This led to the development of several prefabrication companies and can continue to support growth in the future (Bell, 2009).

2.5.6. Marketing

Prototypes and show homes allow successful advertisement of prefabricated technology. Prototypes in the factory allow initial testing and design manipulation by the client at an early stage. Show homes provide the business with a means to allow potential customers to try the product before they buy. Show home events are also helpful at generating a higher level of interest in the product although it doesn't always result in sales (Bell, Kiwi Prefab: Prefabicated Housing in New Zealand, 2009). Further marketing and communication can change cultural perceptions of prefabrication and reduce misconceptions, which in turn will increase acceptance and uptake of the system (Pan, Gibb, & Dainty, 2005).

2.5.7. Designing out-of-the-box

This is an innovated response to the limitation of transport dimensions. Flexibility and adaptability beyond the standard 'shipping container' is now recognised. Smaller buildings are challenged by traditional house appraisals and price per square metre. This approach can only be improved through re-education (Bell, 2009).

2.5.8. Lack of innovation

The lack of innovation can be overcome through education in the construction industry and also through cross communication across multiple industries, for example, manufacturing. This can lead to collaborative ventures and inter-industry groups. Industry bodies and associations are the best options to overcome specific prefabrication challenges and opportunities (Bell, 2009).

2.6. Overwhelming challenges that may never be eliminated

- Wider economic recession
- Lack of prefabricated housing industry cooperation
- Construction industry resistance to innovation
- Few sustainable materials and systems incorporated in housing products
- Over-emphasis on historical typologies, with alternative typologies not well investigated or represented
- Restriction of the housing market to secondary dwellings (due to a smaller footprint of the complete building typology)

(Bell, 2009)

2.7. New Zealand's Public State Housing scheme

This scheme was developed in the 1930's; it used standard house parts such as construction details, window and door sizes and internal fittings such as cupboards, baths and washbasins. A single specification was created to cover 100 house plans (Firth, 1949). A schedule of colours was also formed to cover claddings, roof tiles and plasterwork. This ensured each neighbourhood was interesting and connected harmoniously (Ferguson, 1994). The State Housing programme generated the introduction of standard products through larger contractors, such as Fletchers, inevitably creating a more stable supply of prefabricated housing components throughout New Zealand (Smith J. , 2008). Over 400 housing designs were approved assuming a panelised system although were later decommissioned due to; lack of achieving low cost and time aims, difficult site requirements, limited plan options and the incorporation of expensive joinery (Smith J. , 2008). Despite this the State Housing scheme became one of the most successful public housing schemes in the world (Schrader, 2000). Public housing still continues in New Zealand today with Housing New Zealand running the government-funded housing development using traditional construction methods (Bell, 2009).

2.8. Prefabrication in multi-unit residential buildings

2.8.1. Current New Zealand methods

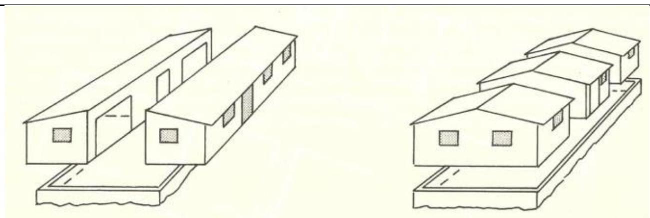
2.8.1.1. Panelised method

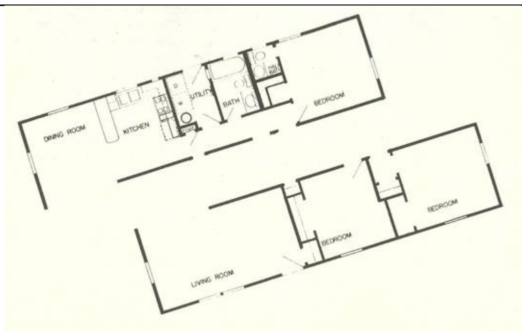
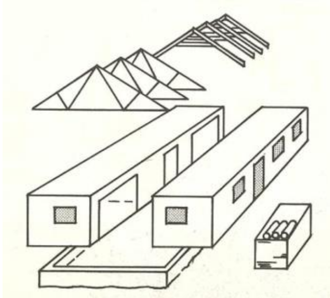
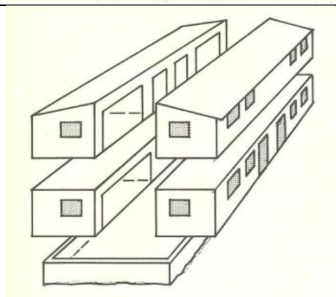
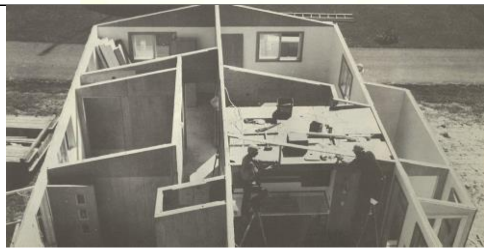
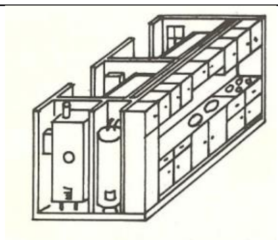
There are several forms of panels available in New Zealand. The differences between panel types stem from the way they are constructed or the level to which they are finished in the factory. Panels can be made up of compressed layers of timber particles and resin; an example of this is CLT panels. Panels can remain either open (clad one side and open for further work) or closed (fully finished and clad). Panels can also be used to create an insulated panel sandwich, these can be structural or non-structural, an example of this is SIP's panels (Bell, 2009).

2.8.1.2. Modular method

New Zealand's history of modular systems was in the early 1980's, i.e. bathroom modules. Recently bedroom modules became available specifically for state housing additions. Modular construction refers to a three-dimensional-unit that is built off-site and can be combined with other methods of prefabrication to form a complete structure. There are two main module types: structural, relating to rooms or large parts of the building or non-structural, referring to cores or pods (Eglinton, 2013). The decision to use this prefabrication method needs to occur very early in the design so that key elements can be aligned and integrated appropriately for the method to be successful. Typically 50-75% of the module is completed within a factory under controlled conditions. The installation of utilities, fixtures and fittings are also normally included in the factory installation. Just in time management is crucial to the delivery of the project whilst using this prefabrication method. It is important that the modules arrive on site at a time so that they can be lifted straight onto the structure and storage isn't a problem onsite (Eglinton, 2013).

Variation of module types:

Sectionals: Applies to a family of boxes or cubes when joined form a complete structural unit.	

Sectional House: Typically fabricated in half house sections it was the most popular type in 1970 USA. Average sizes are 12 feet (3.6 metres) in length. This housing method is usually produced in three to four units to form larger, more complex houses. Individual sections leaving the factory are completely finished.	
Sectional Box: This is simply a sectional house without the factory-installed roof system. This eliminates the low profile roof dominated by transport restrictions. The roof is typically component based, for example roof trusses, and is shipped with the section.	
Sectional Stack-on: With detailed design all sectional units can be stacked to form multi-storey apartment complexes. Typically a sectional box method is used for the bottom half and a unit similar to the sectional house is used for the top.	
Three Dimensional: This is used to describe a section that is neither sectional nor component. It is similar to sectionals but it is smaller. A greater number of these would be needed to form a complete building. Sizes range from room size wall panels to entire rooms.	
Mechanical Cores: These are modular units, which contain all mechanical, electrical and related systems. The units typically contain a kitchen and one or more bathrooms. All wiring, plumbing, heating, fixtures etc. are typically completed in the factory wherever possible.	

(Reidelbach, 1970)

Module constraints

- Amount of preplanning required
- Amount of project coordination
- Transportation
- Inflexibility
- Procurement
- Change in project risk

(Schoenborn, 2012)

2.8.1.3. Hybrid method

2.8.1.3.1. *Bell's conclusion*

> *"The investigation has revealed an opportunity for a fifth hybrid module- plus-panel typology. This is a significant finding as an area that has not been extensively documented and which holds considerable potential for a customisable, flexible, housing solution with substantial financial, quality and timeframe benefits"* (Bell, 2009).

Bell's work is particularly significant as it identifies the lack of documentation in the hybrid sector of the New Zealand market. This does not reflect the extensive documentation available internationally. Hybrid utility modules, pods, units or cores are methods promoted by several researchers in the last century, examples include Buckminster Fuller's Dymaxion bathroom and the autonomous living unit as cited by (Bell, 2009) and substantiated earlier by (Kelly, 1951), (Bahanmon, 2002), (Clark, 2008) (McShane, 2008) (Buchanan M. , Prefab Home, 2004) (Pawley, 1980). Kelly (1951) suggests that if the market cannot accept a highly standardised product, it is likely that there will still be a significant demand for parts of the full production line, such as simpler components like panels or utility pods.

Hybrid prefabrication systems are seen to combine benefits of two prefabricated construction systems, offering more flexibility and custom design (Wilson, 2009). Historical lessons from the company Industrialised Building Systems propose a hybrid approach that removes the highly serviced areas from the critical path of the project timeline, and potentially brings together the benefits of different construction systems (Gorgolewski, 2005).

Hybrid methods avoid the cost of shipping empty space according to Lloyd Alter (Alter, 2009). A semi hybrid system results in a complete building but is still determined by modules, which are restricted by the transport size. Therefore the semi-hybrid typology does not have the full advantages of flexibility that a hybrid module-plus-panel system could hypothetically have (Bell, 2009).

3. Significance of Research

As outlined above, there is an identifiable gap in the New Zealand hybrid market. Several researchers including Pamela Bell, the CEO of Prefab NZ, promote this technology method particularly for multi-unit residential typologies. Herein lies the significance of this research, to extend upon Bell's research and fill in the current gaps in the New Zealand residential multi-unit market with focus on module, hybrid and panelised timber technologies.

4. Prefabrication Database

Using a combination of empirical, deductive and heuristic methods, a criteria matrix database was developed as a tool for understanding and comparing the range of available technologies in the market. The tool covers over 50 different prefabrication methods. The database can be split into sections according to broad construction typologies: module, hybrid and panel. Structure, typology and insulation were the three main criteria selected for analysis. The tool enables the user to identify across all criteria the highest scoring systems. A summary table was created to allow a simple comparison.

4.1. Methodology

4.1.1. Background

"All organisms divide objects and events in the environment into separate classes or categories. If they did not, they would die and their species would become extinct. Therefore, categorization is among the most important decision tasks performed by organisms." (Ashby & Maddox, 2005)

Categorisation can be used as a method of data collection. An example of this is to use a randomised, shuffled pack of record cards, this will be given to the subject and he/she will be asked to sort the cards into as many or few groups as they wish. The subjects are usually asked to describe how and why they created these groups (Coxon, 1999). The purpose of this sorting method is to potentially develop the rule(s) in terms of which the allocation of cases is made (Romney, Weller, & Batchelder). The method of sorting is rightly referred to primarily as a method of discovery (Coxon, 1999).

The wording of general criteria, which aid to make other classifications include:

- How similar they seem
- The meanings are considered similar
- Belong together (or, belong in the same category together),
- Naturally go together
- Cluster together

(Coxon, 1999)

Evaluation is an assessment against a value measure. Four major items have to be present for this process to occur: a standard or set of standards, a unit of measure, actual measurements and judgement. There is no single method to ensure that they can be applied across all categories applicable to multiple subjections. Therefore measures are readily measured using standard units of measure, for example, metres or feet, but these cannot be compared unless they are altered to an appropriate common unit. Although some elements are not measureable at all, for instance, materiality (Gray & Baird, 1995).

4.1.2. Database

Using a combination of empirical, deductive and heuristic methods a database was developed. The empirical, deductive method used is based on observation and analysis of the gathered data. The heuristic method builds relationships between the data through the use of benchmarking to ensure models are comparable. The following criterion was developed through a literature review. An analysis was undertaken of the advantages of a prefabrication approach, as opposed to a traditional method, and developed to form benchmarks. The scaling system was established by a comparison of the obtained data. A low to high range was formed through analysis of the gathered data; this permitted the creation of a comparable and quantifiable benchmark (Laing & Anthony Craig, 2001).

4.1.3. Database user guide

The database is split into three main tabs; Criteria Matrix Table, Summary Table and Conclusion Table. The Criteria Matrix Table is sorted by alphabetical order with main row headings, New Zealand and Overseas method. Sub-headings include module, hybrid and panel systems. The developed criteria are listed in columns beside each system; a score is assigned where possible (see section 4.2), for comparability. The reference rows underneath each data cell provide the user with a method to find out more detail on the specific system. In some cases PDF files are listed; these and other relevant files are kept on the network (JOB 1715/Summer Scholar 2014 Prefabrication Tool/Files for reference). The second tab, Summary Table, displays a summary of the information on the first tab so comparisons between the different systems can be made. The data can be sorted in a variety of ways to allow the user to display top systems against sets of requirements. The third tab, Conclusion Table, provides the user with a final comparison of the available options of design in terms of structure, typology and insulation. Viability is measured by cost, time, connection, buildability and flexibility.

4.2. Scoring system

4.2.1. Materiality

- Definition: the material nature or quality (House, 1997)
- Scale: no scale as this is not measureable or quantifiable.

4.2.2. Cost

- Definition: per metre squared of total building using this prefabrication method. Material cost only as it is difficult to establish labour and site costs due to inconstancies.

5	<$1,000-$1,999
4	$2000-$2999
3	$3000-$3999
2	$4000-$4999
1	>$5000

4.2.3. Programme

- Definition: considers two main processes, time in factory and time on site. Scale up or down to average $78m^2$ of building (in days) so it is comparable. ($78m^2$ is the average case study requirement size).
    - Time on site (days):

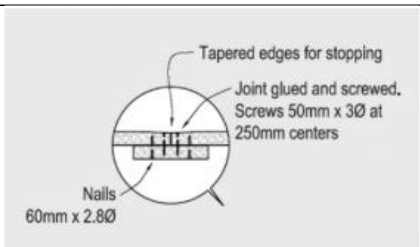
5	0-3
4	4-6
3	7-9
2	10-12
1	13+

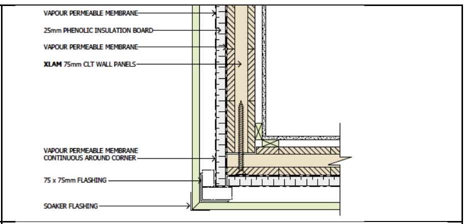
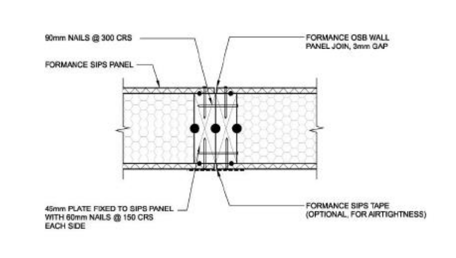
-
    - Time in factory (weeks):

5	1
4	2
3	3
2	4
5	5+

4.2.4. Ease of connection/complexity

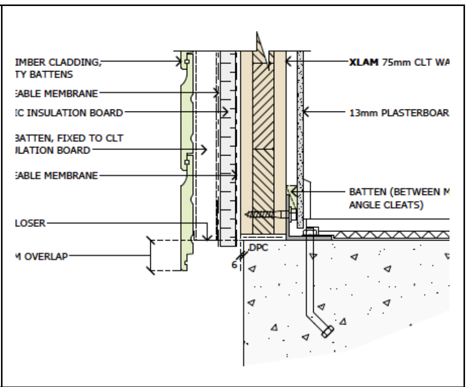
- Definition: detail construction drawings showing connection details. The more complex the drawing and the more work needed on site defines it as complex e.g. 1

5	

<table>
<tr><td>3</td><td>
</td></tr>
<tr><td>1</td><td>
</td></tr>
</table>

4.2.5. Buildability

- Definition: detail construction drawings showing section details, typically foundation/wall section. The more complex the drawing and the more work needed on site defines it as complex e.g. 1

<table>
<tr><td>5</td><td>
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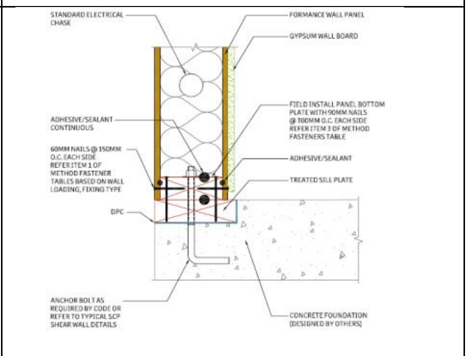
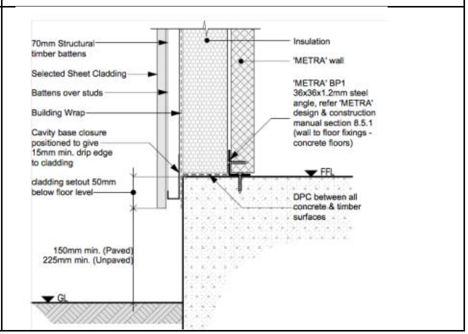
<tr><td>3</td><td>
</td></tr>
<tr><td>1</td><td>
</td></tr>
</table>

4.2.6. Services

- Definition: the nature of the services within the prefabrication system.

5	Single connection for everything
4	Empty cavity built onto design for services
3	Single connection for electricity only i.e. conduits
2	Some design work required for placement within the system
5	Traditional methods or design at a very early stage of the project

4.2.7. Adaptability/flexibility

- Definition: ability to change the design and form of construction (future proofing).

5	Cut and join new panel/module on site as required
4	Panels/modules slot able, similar size and forms for replacements
3	Variation of the panel forms and modules but off-shelf components
5	No flexibility at all

4.2.8. Ability to maintain

- Definition: accessibility for maintenance.

5	Removable smaller panels
4	Allows for small hole to be cut internally, quick replacement e.g. traditional methods
3	Remove cladding and access from external wall
2	Full replacement of whole panel
5	Extremely difficult to replace panel

4.2.9. Visual appearance/variability

- Definition: architect changeability to materiality of systems, finishes and forms available.

5	Allows for any finishes as required
3	Multiple varieties available, restricted changeability
5	Supplied ‘as is’, no changeability

4.2.10. Supply/availability

- Definition: how many typical 78m^2 units can be produced per year, a demand average taken from an in-house project.

5	500 units
4	400 units
3	300 units
2	200 units
1	100 units

5. Results

5.1. Criteria matrix table

The Criteria Matrix Table contains a column of systems sorted in alphabetical order. Main row headings are, New Zealand and Overseas methods. Sub-headings include module, hybrid and panel systems. The criteria are listed in columns beside each system; a score is assigned where possible from 0-5, 0 being no information and 5 being best. This allows for comparability. The reference rows underneath each data cell provide the user with a method to find out more detail on the specific system. In some cases PDF files are listed; these and other relevant files are kept on the network.

5.2. Summary table

A summary table was formed from the criteria matrix tool. It depicts the most viable 'timber technology systems' in terms of highest scoring across all measured criteria. The tool allows sorting, by each category, so multiple comparisons can be made according to different requirements. This tool can be used to select the 'most viable' 'new timber technologies' for residential multi-unit projects.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
System/Criteria	Location	Number of Storeys	Method	Structure	Insulation	Cost	Programme		Connections	Buildability	Flexibility	Maintenance	Services	Visual appearance	Supply	Total	
New Zealand						Scale	Scale factory	Scale on site	Scale	Scale	Scale	Scale	Scale	Scale	Scale		
Modular Method																	Key
Elam Hall Auckland	Matatmata	14	Modular	Exo-skeleton	Wool	0	1	5	3	2	4	4	4	4	5	32	5
First Light House	Wellington	1	Modular	Exo-skeleton	Wool	2	5	3	4	1	2	4	4	4	1	30	4
Qb Modular Commercial	Christchurch		Modular	Exo-skeleton	Rigid	4	2	4	1	0	3	4	3	4	3	28	3
De Geest Bathrooms	Oamaru		Modular	Self-supporting	Wool	2	1	0	3	3	1	4	3	5	4	26	2
Matrix Homes	Trentham		Modular	Self-supporting	Rigid	0	0	0	0	4	4	4	4	3	5	24	1
Getaway Homes	Auckland		Modular	Self-supporting	Wool	5	0	0	0	2	2	4	1	2	0	16	0
PLB Modules	Huntly		Modular	Self-supporting	Rigid	5	1	0	0	0	2	0	4	1	0	13	
Portacom Building Solutions	Auckland/Christchurch		Modular	Self-supporting	Rigid	0	0	0	0	0	3	4	1	0	0	8	
Space Moveable Rooms	Queenstown		Modular	Self-supporting	Any	0	4	2	0	0	0	0	0	0	0	6	
Ark Modular Structures	Christchurch		Modular	Exo-skeleton	Any	0	0	0	0	0	3	0	0	2	0	5	
PLB Bathrooms	Huntly		Modular	Self-supporting	Rigid	0	0	0	0	0	0	0	0	0	5	5	
Modular Accommodation Concept	Matatmata		Modular	Exo-skeleton	Any	0	0	0	0	0	0	0	0	0	0	0	
Hybrid Method																	
Classroom Hybrid System	Matatmata		Hybrid	Self-supporting	Any	0	0	2	0	3	3	4	1	3	0	16	
Transportable apartments Christchurch	Christchurch		Hybrid	Self-supporting	Rigid	1	0	0	0	0	4	2	2	0	0	9	
Iconbuildings	Auckland		Hybrid	Exo-skeleton	Rigid	0	0	0	1	2	3	0	0	1	0	7	
Welhaus	Christchurch		Hybrid	Exo-skeleton	Wool	0	0	0	0	0	2	4	1	0	0	7	
Formule 1 Hotel	Auckland	6	Hybrid	Exo-skeleton		0	0	1	3	0	0	0	0	0	0	4	
Quick Living Modular Housing	Christchurch		Hybrid	Exo-skeleton		0	0	0	0	0	1	0	0	2	0	3	
Panelised Method																	
Concision	Christchurch		Panelised	Self-supporting	Wool	4	4	0	1	3	4	4	3	5	5	33	
Metra Panel Construction - standard	Otaki/Levin		Panelised	Self-supporting	Rigid	0	4	5	5	1	5	3	3	4	3	33	
Structurally Insulated Panel (SIP) - TEK Panel timber - Knightbuild	Christchurch		Panelised	Self-supporting	Rigid	0	5	5	2	4	5	2	3	4	1	31	
Structurally Insulated Panel (SIP) - steel - Bondor	Auckland/Christchurch		Panelised	Self-supporting	Rigid	0	0	5	5	5	5	1	2	1	5	29	
Structurally Insulated Panels (SIP) - alternative timber - Metrapanel	Otaki/Levin		Panelised	Self-supporting	Rigid	0	4	5	4	1	5	3	2	4	1	29	
Structurally Insulated Panels (SIP) concrete - Magroc	Christchurch		Panelised	Self-supporting	Rigid	0	5	4	2	3	4	4	2	3	1	28	
Ehomes	Auckland		Panelised	Self-supporting	Any	0	0	0	4	5	5	4	1	3	0	22	
CLT - Xlam	Nelson		Panelised	Self-supporting	Any	0	0	0	3	5	5	0	1	5	0	19	
Ocean Shore Retirement Village	Matatmata		Panelised	Self-supporting	Any	0	0	0	4	0	5	4	1	5	0	19	
Triboard			Panelised	Self-supporting	Any	0	0	0	5	5	4	4	1	0	0	19	
Kingspan	Sydney		Panelised	Exo-skeleton	Rigid	0	1	0	3	4	3	3	3	1	0	18	
Click-Raft	Matatmata		Panelised	Self-supporting	Any	4	0	0	5	4	0	0	4	0	0	17	
Aridon			Panelised	Exo-skeleton	Rigid	0	0	5	3	1	0	0	3	4	0	16	
Structurally Insulated Panels (SIP) timber - Formance			Panelised	Self-supporting	Rigid	0	0	0	1	3	5	4	2	0	0	15	
Spanbild	Christchurch		Panelised	Self-supporting	Rigid	0	0	0	2	2	4	2	2	2	0	14	
Makers of Architecture			Panelised	Self-supporting	Rigid	0	0	0	1	4	2	0	1	5	0	13	
WoodlaNZ Panel			Panelised	Exo-skeleton	Any	0	0	0	0	0	3	4	1	3	0	11	
Expan	Levin		Panelised	Exo-skeleton	Any	0	0	0	3	0	5	0	0	0	0	8	
Lockwood Homes NZ	Rotorua		Panelised	Self-supporting	Rigid	0	0	0	3	0	0	0	2	0	0	5	
Overseas Methods																	
Modular and Hybrid Methods																	
Loblolly House		2	Modular	Exo-skeleton		0	0	2	4	4	4	5	4	3	0	26	
B2 Building	New York	10	Modular	Exo-skeleton		0	0	5	5	3	0	0	5	4	0	22	
T30 Hotel	China	30	Hybrid	Exo-skeleton		5	0	5	0	4	3	0	5	0	0	22	
Hickory Bathroom Pods	Australia		Modular	Exo-skeleton	Rigid	0	0	0	0	3	1	5	5	5	2	21	
Parkwood Homes	Australia		Modular	Exo-skeleton	Wool	0	0	0	2	1	3	4	2	4	5	21	
Hickory Unitised Building System	Australia		Hybrid	Exo-skeleton	Any	0	0	5	3	3	4	0	0	3	0	18	
Victoria Hall		28	Modular	Exo-skeleton		0	0	5	3	3	0	0	4	0	0	15	
Cellophane House		5	Modular	Exo-skeleton		0	1	1	5	2	3	0	0	0	0	12	
The Stack Building	New York	7	Modular	Exo-skeleton		0	3	5	3	0	0	0	0	0	0	11	
Wilmslow Park	UK	7	Modular	Exo-skeleton		0	0	5	1	4	0	0	0	0	0	10	
Zeta Design and Build	USA		Modular	Self-supporting		0	0	4	3	0	0	0	0	0	0	7	
Panelised Method																	
Solid Timber Panel - Novatop	Europe		Panelised	Self-supporting	Any	0	0	0	3	5	5	0	2	4	0	19	
Stadthaus, Murray Grove - UK first multistorey CLT	Austria	9	Panelised	Self-supporting	Wool	0	5	5	0	3	0	0	2	3	0	18	
Forte - World's Largest CLT Apartment	Austria	10	Hybrid	Self-supporting	Rigid	0	0	0	3	3	0	0	0	3	0	9	

6. Discussion

6.1. Conclusions table

After completion of the criteria matrix table three main categories were outlined for further analysis; structure, typology and insulation. These can be built up in several different clusters depending on the project. Pro's and con's of each are displayed in terms of cost, time, materiality, connection, buildability, flexibility and lifetime. Comparisons between and across categories can then be undertaken to understand the main available options for 'new timber multi-unit residential typologies'.

System/Criteria	Description	Size	Cost (wall or frame cost only)	Time (onsite only)		Material	Connection		Buildability		Flexibility of structure	
Structure					Score			Score		Score		Score
Self Supporting			(per m^2)									
Traditional	A traditional framed wall including insulation.	2.4m*1.2m.		12-16 weeks	1	Wood, steel or concrete	Traditional methods.	4	Site based, some components such as roof trusses used.	1	Quite flexible, traditional methods for extensions. Lots of rebuild required.	2
		Same as the panel size for comparability.		(Consumer Build)								
Panel	A compressed panel of different materials, normally includes insulation.	Typical size 2.4m*1.2m.		2-5 days.	4	Mixture	Screw, clip, locking system, male/female joint, jointing strip or box spline.	3	Low to high depending on the system, most systems require minimal site work using simple tools.	3	Can be flexible depending on the connection details, may have reliance on rest of structure.	3
	An average taken from wall rates, see criteria matrix tab.	An average taken from wall rates, see criteria matrix tab.		Average taken from wall rates, see criteria matrix tab.			Info gathered from criteria matrix tab.		Info gathered from criteria matrix tab.		Info gathered from criteria matrix tab.	
Exo-skeleton			(per m)									
Steel	A steel frame structure	Per metre.		An Average of 8 months.	1	Steel	Bolt connections or welding	1	Total onsite work or can manufacture modules offsite.	3	Quite flexible, extensions can be made fairly easily. No reliance on rest of building.	4
				Average taken from structure rates, see criteria matrix tab.					Info gathered from criteria matrix tab.		Info gathered from criteria matrix tab.	
Typology			(per m^2)									
Module	Typically steel or wood frame with infill or traditional wall methods.	Typical module 3m*9m.	$2,200.00	3 days.	3		Pins, simple bolt connections, interlocking/sealing system, tie, screw or fixing plates.	4	Typically modules are 70% complete offsite, requires connection to other modules and structure or forms structure.	4	Can be quite flexible depending on module connections and structure connections.	3
	An average taken from module rates, see criteria matrix tab.	An average taken from module rates, see criteria matrix tab.	An average taken from module rates, see criteria matrix tab. Supply rate only - contractor rate.	Average taken from module rates, see criteria matrix tab.			Info gathered from criteria matrix tab.		Info gathered from criteria matrix tab.		Info gathered from criteria matrix tab.	
Panel	A compressed panel of different materials, normally includes insulation.	Typical size 2.4m*1.2m.	$150.00	2-5 days.	4		Screw, clip, locking system, male/female joint, jointing strip or box spline.	3	Low to high depending on the system, most systems require minimal site work using simple tools.	3	Can be very flexible depending on the connection details, minimal site work required.	4
	An average taken from wall rates, see criteria matrix tab.	An average taken from wall rates, see criteria matrix tab.	An average taken from wall rates, see criteria matrix tab. Supply rate only - contractor rate.	Average taken from wall rates, see criteria matrix tab.			Info gathered from criteria matrix tab.		Info gathered from criteria matrix tab.		Info gathered from criteria matrix tab.	
Pod (typically service pods)	Tradtitonal stick frame walls, steel frame floor with villaboard lining. Includes fittings.	1.2m*1.6m.	$4,667	Several days.	4		The pods sit into a recess on site typically but can also become part of the structural slab.	3	Typically 100% completed in factory.	5	Near impossible for movement once placed.	1
	A typical De Geest bathroom pod.	A typical De Geest bathroom pod.	Obtained from De Geest bathroom pods. Supply rate only - contractor rate.	Obtained from De Geest bathroom pods.			Obtained from De Geest bathroom pods.		Obtained from De Geest bathroom pods.		Due to the connection to structure.	
Insulation			(Assume Wellington location, supply only, m^2)									
Wool (fibreglass)	Pink Batts R2.2 90mm fitted between studs	Per metres squared.	$13.21			Fibreglass	Inside framing					
	(Rawlinsons, 2011)		(Reserve Bank of New Zealand) (Rawlinsons, 2011)									
EPS (expanded polystyrene sheet)	40mm R1.052-1.765 fixed to framing	Per metres squared.	$18.75			Polystyrene	Inside framing or attached to					
	(Bondor)		(Reserve Bank of New Zealand) (Rawlinsons, 2011)									
PIR (polyisocyanurate)		Per metres squared.				Polyisocyanurate	Inside framing or attached to					
PUR (rigid polyurethane)		Per metres squared.				Polyurethane	Inside framing or attached to					
XPS (extruded polystyrene sheet)	40mm R1.4	Per metres squared.	$37.78			Polystyrene	Inside framing or attached to					
	(Eco Insulation, 2014)		(Reserve Bank of New Zealand) (Rawlinsons, 2011)									
Low Density Wood Fibre - N/A in NZ												

7. Conclusion

The hybrid module-plus-panel method of modular building construction is a method that has been promoted by several researchers including Pamela Bell, the CEO of Prefab NZ. Bell identified a significant opportunity in the New Zealand market for prefabrication of buildings through this hybrid approach. This research has not found any reason to alter that view.

Using a combination of empirical, deductive and heuristic methods, a criteria matrix database was developed as a tool for understanding and comparing the range of available technologies in the market. The tool covers over 50 different prefabrication methods. The database can be split into sections according to broad construction typologies: module, hybrid and panel. Structure, typology and insulation were the three main criteria selected for analysis. The tool enables the user to identify across all criteria the highest scoring systems. A summary table was created to allow a simple comparison.

The database will be used by Studio Pacific Architecture to select the most viable modular technologies for new multi-unit developments. It proved impossible to find detailed information to fully populate the database with relevant cost and construction detail information. These gaps in the data are accounted for as a zero score in the criteria matrix table. With more time a complete table could be produced which includes more local and international manufacturers' systems. However, the current database has a sufficient range of typologies, structural systems and insulation approaches for the tool to be used on an everyday basis. Potential future development of this tool would be to add other (non-timber) material groups and typologies, to enable, for example, selection of appropriate modular concrete typologies for use in commercial buildings.

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