STUDY REPORT

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Prefabrication Impacts in the New Zealand Construction Industry

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EXECUTIVE SUMMARY

This report assesses the impact of prefabricated building systems in the New Zealand construction industry, in particular determining whether there are discernible differences in economic and environmental outcomes between prefabricated building approaches and traditional construction.

A tool to monitor the market penetration of prefabricated building systems is presented, (the “monitoring tool”) which allows changes in the uptake of prefabrication to be tracked.

The report also presents a tool designed for the housing sector, to recommend different prefabrication approaches to clients (the “PrefabNZ toolkit”). This tool informs decisions about appropriate prefabricated construction types, based upon site-specific parameters and client preferences.

A case study of a prefabricated house is undertaken where the economic and environmental impacts of using the prefabricated approaches of:

- Transportable housing
- Panelised housing, and
- Hybrid modular housing

… are compared against a traditional onsite build.

International findings, and consultation with PrefabNZ industry members and affiliates in seminars, workshops and discussions has also informed this work.

This study has concluded that:

Prefabrication of buildings and building elements in New Zealand provides:

- **Greater security in economic outcomes**
- **Potential for further improvement in economic outcomes, and**
- **Greater opportunity for enhanced environmental sustainability than traditional construction.**

The research finds that improved economic outcomes can result from prefabricated building approaches as the necessary focus on project management provides higher levels of budget accuracy, which are not inherent in traditional onsite construction.

The most significant restriction on achieving better economic outcomes appears to be the limited size of the New Zealand market. This is because economies of scale are an important requirement of efficient prefabricated construction. The small New Zealand market size and limited export opportunities may constrain the market’s ability to take advantage of the benefits of large-scale prefabricated manufacturing.

Reduced waste, transport, time, energy and greenhouse gas emissions during construction are more readily achievable through the application of prefabricated construction approaches than with traditional onsite construction.

Key Messages

- Prefabricated construction approaches increase security in economic outcomes.
- Prefabrication provides greater opportunity for enhanced environmental outcomes than traditional onsite construction, as the energy and greenhouse gas emissions of construction are more readily reduced.
- The most common prefabricated elements in non-residential construction are concrete wall panels (50 percent of all prefab walls) and floor beams (100 percent of all prefab floors).
- The most common prefabricated elements in residential construction are pre-cut wall frames (91 percent of all walls) and roof trusses (95 percent).
- By value, 17 percent of all building work in New Zealand is prefabricated.
- The small market size in New Zealand may be restricting the uptake of prefabrication.
- Half the time elapsed on traditional building sites is lost to wasteful activities.
- Prefabrication reduces the waste generated at construction sites.
- Building prefabricated systems is safer, with 75 percent fewer fatalities in factory-based construction than using site-based processes.
- Prefabrication reduces the rate of human error – which is a primary cause of defects in construction.
- A rise in quality expectations coupled with a declining skill base makes greater use of prefabrication almost inevitable.
- One of the key barriers to the uptake of prefabrication in New Zealand is the low level of innovation in the industry.
- Caution is required when using statistics on prefab uptake, as prefabrication can be classified as a manufacturing activity, rather than an activity of the building and construction industry.
- The greatest benefits of prefabrication can be gained when there are multiple units to construct.
- Exposed sites with adverse weather conditions have high costs for onsite construction, which increases the value delivered by prefabrication.
- Compliance requirements are less onerous once processes and relationships are established between authorities and prefabricators.
- Prefabrication provides a reduced likelihood of timber treatment chemicals leaching into the environment through more controlled waste management processes.

Learnings

The learnings from this study are encapsulated in Table 1, where the benefits of prefabrication on the New Zealand building industry are evaluated under a set of "impact" headings. The ticks indicate where the impact has been recognised: either in the international literature; in New Zealand practice; in the case study undertaken in this work; or where there is **potential** for the outcome in the New Zealand construction industry. The dashes indicate where this impact has not been evaluated (or the outcome is marginal) and the crosses indicate where the impact is not present.

Prefab impact summary				
Impact	**International**	**New Zealand**	**Case Study**	**Potential for New Zealand**
Lower initial cost	✓	-	X	✓
Reduced environmental Impact	✓	-	✓	✓
Reduced time	✓	✓	✓	✓
Improved Health and Safety	✓	✓	-	✓
Reduced defects and improved quality	✓	-	-	✓
Reduced GHG emissions	✓	✓	✓	✓
Improved economic security	✓	✓	✓	✓
Reduced waste	✓	-	✓	✓
Reduced operational emissions	✓	-	-	✓

Table 1: Source of findings in regard to the impacts of prefabrication on the New Zealand construction industry

The summarised results in Table 1 indicate that while not all economic and environmental prefabrication benefits noted have been shown in New Zealand, they are all potentially available and bear further investigation.

Preface

BRANZ has been engaged to research various forms of prefabricated building systems since this organisation's inception in 1969, although systems such as built-up windows and pre-manufactured stairwells were often not thought of as "prefabricated".

With the initiation of a construction sector group (PrefabNZ), to specifically focus on prefabrication in 2010, the subject has come into clearer focus and more effort has been applied to differentiate prefabrication from other more traditional types of construction.

There are many facets to prefabricated building elements, some of which are explained in the thesis of Pamela Bell (the current CEO of PrefabNZ). However, this report concerns the impact of prefabricated building systems on the New Zealand construction environment.

This report addresses the hypothesis that 'Prefabricated systems for construction have discernibly different economic and environmental sustainability outcomes than site-constructed systems'.

Figure 1: A hybrid prefabricated dwelling under construction, utilising shipping containers

Acknowledgments

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Thanks also to Andrew Alcorn, (Alcorn & Associates) and James McDevitt (Scion) who reviewed Appendix A regarding the case study of GHG emissions from construction in New Zealand, and offered significant comment.

Industry practitioners have also commented on the data and report wherever possible. However, any inadvertent errors remain the responsibility of the authors.

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1. GLOSSARY

Anthropogenic – of, or related to human activity.

BIM – see Building information modelling.

Building information modelling – digital representation of physical and functional characteristics of a building to allow ready access to information by all relevant parties

CNC – computer numerical control.

Construction GHG emissions – the total of the GHG emissions that are released in the process of integrating the product/material/system into the construction – e.g. the GHG emissions from the diesel burnt by a forklift operating on a construction site and electricity consumed.

Cradle-to-gate – life cycle stages from the extraction or acquisition of raw materials to the point at which the product leaves the organisation making the product – in this case it is the factory – i.e. factory gate.

Cradle-to-site – life cycle stages from the extraction or acquisition of raw materials to the point at which the product is embedded in a house.

Craneage – utilisation of a crane.

Embodied emissions – is the sum of all the GHG emissions required to produce the materials that are used in the construction of the reference building (which is referred to as the “functional unit” in the LCA world), considered as if the GHG emissions were incorporated or “embodied” in the product itself.

End-of-life emissions – the GHG emissions released at the end of the useful life of a product including removal and disposal – e.g. the GHG emissions from the diesel used by a crane dismantling a structure and the truck transporting construction debris to a landfill.

GHG – see greenhouse gas

Global warming potential – a measure of the amount that a certain GHG contributes to the greenhouse effect, normalised to the impact of the same weight of carbon dioxide.

Greenhouse gas (GHG) – any of the atmospheric gases that contribute to the greenhouse effect by absorbing solar infrared radiation, warming the Earth’s surface. Other than naturally occurring water vapour, the anthropogenic gases of importance in New Zealand are: carbon dioxide; methane; and nitrous oxide.

Group builders – companies that use a franchise model to construct housing throughout New Zealand, using different builders in different locations working under the same branding for a group of house builders – e.g. GJ Gardner, Jennian Homes, Stonewood Homes, David Reid, Signature Homes etc.

GWP – see global warming potential.

Heavy goods vehicle (HGV) – a vehicle designed to transport loads by road with a tare (unladen weight) over 3.5 tonnes.

Harvested wood products (HWPs) – any timber-based products that are sourced from milled forestry timber.

HGV – see heavy goods vehicle.

HWPs – see harvested wood products.

Keith Hay Homes Limited (KHH Ltd) – a transportable house manufacturer in New Zealand.

KHH Ltd – see Keith Hay Homes Limited

LCA – See Life Cycle Assessment

LGV – see light goods vehicle

Life Cycle Assessment – a technique to assess environmental impacts associated with all the stages of a product's life cycle from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, to disposal or recycling).

Light goods vehicle (LGV) – a vehicle designed to transport loads by road with a tare under 3.5 tonnes. This can include vans, light trucks and utility vehicles.

Module – a construction unit with three distinct dimensions, typically encompassing a single room or service area, which is readily transported and craned onto sites. While a whole house can be termed a “module”, usage in this work regards a module as a section of a construction, with several modules used to assemble a complete house.

Offsite – European term for construction that utilises prefabrication of systems undertaken away from the final building location site to improve logistics, improve the cost benefit equation and reduce the impact of operations on the construction site.

Operational emissions – the GHG emissions that are released during the operation of the building – e.g. the GHG emissions due to space heating and cooling. GHG emissions related to materials and processes used in the maintenance of the building may also be included, as are the GHG emissions from replacement materials.

Panelised construction – a two-dimensional construction form that can be open (framing with one or no sides closed in) or closed (both sides clad or covered in lining) ready for incorporation into a house. Panels can form walls, floors or ceiling panels.

Stick-built – American term for construction that is assembled onsite from random lengths of materials. The analogous British term is “onsite” construction or traditional construction, where most construction processes are performed onsite.

VBA – see Visual Basic for Applications

Visual Basic for Applications – Software package for implementing event-driven programming in Microsoft’s products.

2. INTRODUCTION

The construction, use and demolition of New Zealand’s buildings are responsible for:

- 40 percent of New Zealand’s energy consumption
- 40 percent of the waste generated in New Zealand
- 35 percent of carbon dioxide (CO_2) emissions in New Zealand, and
- 40 percent of the raw materials used in New Zealand (Bell, 2009).
- This means that the construction industry in New Zealand has a significant opportunity to contribute to the reduction in this country’s energy consumption, waste generation, carbon dioxide emissions and use of raw materials.

Offsite prefabrication of building systems provides an opportunity to address these issues and is investigated in this report.

2.1 The situation

Internationally, prefabricated construction is being used to improve the efficiency of construction and to reduce the energy use in the construction of residential and commercial buildings. The New Zealand market is applying similar methodologies. However, there is little information available about how prefabricated construction performs against traditional construction in regard to economics and environmental outcomes. This report addresses this area.

Offsite construction and prefabrication are not new to New Zealand. Early settlers brought small prefabricated cottages with them to New Zealand in the mid-1800s. In the 1920s, the New Zealand Railways set up and ran a factory in Frankton manufacturing cottages for railway workers, many of which still stand (Bell, 2009). In the 1950s, prefabricated state houses were imported from Austria and located in Titahi Bay, Porirua (Porirua City Council, 2013), and transportable homes became popular for low-cost housing and vacation homes. In the 1970s with the “Think Big” Government infrastructure building scheme, transportable homes were used to house workers (De Geest Bathrooms, 2013).

However, the success of prefabricated construction and prefabrication in New Zealand has been hampered by the growth of negative perceptions, largely through the historic use of prefabricated building systems. School “prefab” classrooms and temporary worker housing aimed at the low-cost market, have led to a widespread perception of prefabrication representing cheap, flimsy and temporary structures. This is being addressed in New Zealand through the efforts of the PrefabNZ industry group, with the application of international knowledge, engagement with the architectural sector and a push for improved performance for prefabrication within the construction industry.

The purpose of this report is to assess the hypothesis that the “prefabrication of buildings has discernibly different economic and sustainability outcomes than traditional onsite construction methods”.

This allows the impact, use and uptake of prefabricated construction in New Zealand to be assessed.

3. APPROACH

This report compiles information on the impact of prefabrication in the New Zealand construction industry, drawing on the following sources:

1) International literature on the prefabrication of building and building components in the residential and commercial construction industries of principally Western countries.
2) An examination (undertaken as a case study) of the economic and environmental costs of prefabricating a transportable 120 m² house in three different ways, and compared these to traditional onsite construction (see Appendix A).
3) Seminars, site visits, workshops, interviews and discussions with industry members and groups associated with the industry group, PrefabNZ.

The report also presents other outputs developed as part of this work:

4) A "Monitoring tool", developed by BRANZ as an instrument to measure the uptake of prefabrication in the New Zealand construction industry (Section 4), and
5) The "PrefabNZ toolkit", presenting results to support data on the PrefabNZ website (http://www.prefabnz.com/Community/Wiki/) in Appendix D.
6) Content for a presentation made at the inaugural PrefabNZ conference, held at the Copthorne Hotel in New Plymouth, March 13-15, 2013, including the country's first national prefabrication exhibition 'Kiwi Prefab: Cottage to Cutting Edge' at Puke Ariki Museum.

An explanation of offsite construction and the prefabrication of buildings is presented in Section 3.1, the monitoring tool is presented in Section 4, while Section 5 contains a discussion of the economic outcomes of prefabrication of building systems and elements. Section 6 presents an assessment of the environmental sustainability outcomes of prefabrication, while Section 7 presents the conclusions of this work and includes the outcomes from the case study investigated in Appendix A.

The economic analysis in Section 5 considers:

- Economic cost factors,
- The cost of time and lending,
- Productivity,
- Health and safety,
- Quality,
- Material durability,
- Innovation and automation,
- Case studies of prefabrication in New Zealand.

The environmental sustainability analysis considers:

- Energy,
- GHG emissions,
- Waste,

- Transport,
- Indoor environment quality (IEQ),
- Materials use, and
- Water resource management issues.

3.1 Definition: What is prefabrication?

Prefabrication encompasses the practices, systems and structures which facilitate the construction of buildings and parts of buildings away from their final location. These buildings or parts of buildings are then brought onto site at the appropriate time and assembled and completed as necessary.

The location where prefabrication is undertaken may be a factory, yard or any appropriate space that can be utilised to improve the cost, logistics, convenience, access or environmental outcomes of the construction of buildings or parts of buildings. The completed constructions are then transported to site and installed as part of a permanent building, see Figure 2. On occasion, elements such as roofs (that can be difficult to work on at height), may be prefabricated on the ground at the construction site and craned to their location. (See Figure 2). The term “offsite construction” is often used interchangeably with prefabrication (or “prefab”), which is defined to be “any component constructed away from the site” (Bell, 2009, p. 25).

There are several different types of prefabrication in construction, reflecting the degree of completion in an offsite setting. While these definitions differ slightly throughout the literature, this report adopts Bell’s definitions, as in Figure 3.

The types of prefabrication in Figure 3 represent different amounts of value added during construction. Component-based prefabrication typically represents the lowest value added offsite and the highest amount of value that is added onsite. At the other end of the spectrum, transportable homes represent the highest value added offsite and the lowest amount of value added onsite, where typically just foundations and the connection of services is completed onsite.

Figure 2: A modularised home being assembled onsite by crane

Component-based prefabrication – the lowest level of prefabrication, creating components out of materials to reduce the number of pieces and increase speed of assembly – e.g. pre-cut framing, built-up windows and kitset housing that is assembled onsite like a jigsaw.	 [1]
Panelised prefabrication – wall, floor and roof panels. Panels can be open (being framed, clad on one side and sometimes insulated) or closed (with plumbing and electricity conduits, insulation installed, clad on both sides and windows in place). This is essentially an assembly of two-dimensional “area” elements.	 [2]
Modular prefabrication – structural boxes or modules erected offsite and brought together onsite to form a complete building. This is an assembly of three-dimensional “volume” units and appears to be the fastest construction approach, although typically only the onsite activities are seen by the public.	 [3]
Hybrid prefabrication – a method of prefabrication used in combination with another or with traditional construction – e.g. modules interspersed with panels. Will typically involve some onsite construction as well as assembly of prefabricated sections.	 [4]
Complete building prefabrication – whole buildings constructed offsite and carried to site – also known as transportable buildings.	 [5]

Figure 3: The types of prefabricated building systems used in this report

[1] Image sourced from http://www.tractorbynet.com/forums/attachments/projects/146507d1258942349-started-new-house-new-house-framing.jpg, accessed 12/2/2013.
[2] Image sourced from: http://www.oshrc.ictas.vt.edu/Projects/PROJECT/DSS-ErgoConstruction.html, accessed 8/2/2013.
[3] Image sourced from: http://www.advancedmodularservices.com/Modular-Home-Services.html, accessed 12/2/2013.
[4] Image sourced from: http://www.ecocontainerhome.com/adam-kalkin-maine-container-house/, accessed 19/2/2013.
[5] Image sourced from: http://www.bigriverhomes.co.nz/WhyTransportable, accessed 12/2/2013.

4. PREFABRICATION MONITORING TOOL

To measure the uptake of prefabrication and the change in the uptake of prefabrication in the New Zealand building industry, BRANZ has developed a prefabrication monitoring tool.

The tool asks builders questions on the amount of prefabrication in specific buildings identified from building consent data. These questions have become part of the regular surveys BRANZ carries out on the use of materials in housing and commercial buildings. The generic survey form for non-residential buildings is shown in Appendix E.

There are different ways to interpret the application of this tool. The simplest is shown in Figure 4 where "Yes" or "No" responses to the prefabrication question are analysed.

In this figure, the percent value on the ordinate (y axis) refers to the total floor area from the positive answers. So 88 percent of those erecting motels/hotels and who responded to the prefabrication question are using some prefabrication. To ascertain the average for all buildings, the percentage from each type was weighted by the total value of work (from consents) for that type, giving the 70 percent average noted on the chart, i.e. 70 percent of all non-residential buildings work have some prefabrication.

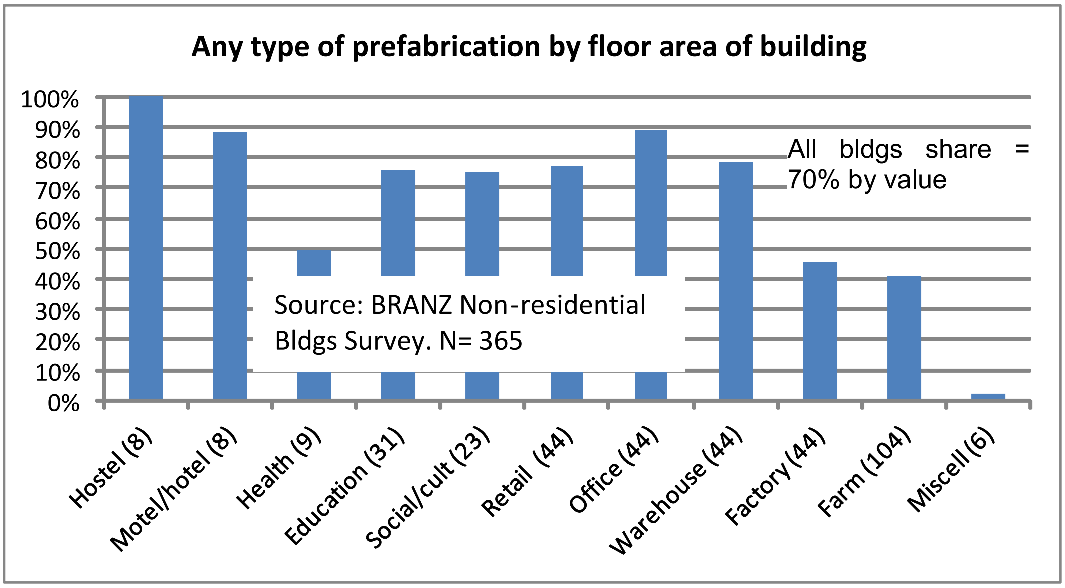


Figure 4: Prefabrication in new non-residential buildings 2012 – percent of buildings with some prefabrication

A limitation of the above method is that a "Yes" response conveys no information about the extent of the prefabrication Therefore the survey was modified to identify the components being prefabricated, namely the frame, walls, floor and other (mainly roof). Respondents are asked to specify one or more of these categories. To allow for the varying extent of prefabrication we used the definitions from Rawlinson's Handbook (Rawlinsons, 2012) to find the component cost share for each building type. This showed that on average, structural frames account for 12 percent of the total cost of a building, walls 11 percent, floor 3 percent and roof structure 4 percent. So if a respondent ticked all four boxes relevant to these four elements, the maximum amount of prefabrication expected would be about 30 percent. In fact, the range is a minimum of 20 percent for health buildings up to a maximum of 42 percent for warehouses. The low percentage for health buildings reflects their large services content (HVAC, lifts, wet areas etc) which is not counted as prefabrication but is a large part of the total building cost. Conversely, warehouses are basic structures with little in the way of services or fitting-out, so their potential prefabrication content is quite high.

The results from using this approach are in Figure 5 and Figure 6, and show much lower percentages than the previous chart (because they are limited to 30 percent). For all non-residential buildings it is estimated the prefabrication content amounts to only 8 percent of the total cost in 2012, up from 5 percent in 2011.

The various building types show some variation in prefabrication share between the two years. It will probably be necessary in the future to use rolling three-year averages for prefabrication shares by building type to better see the trends. Monitoring will provide a measure of innovation progress for the non-residential sector.

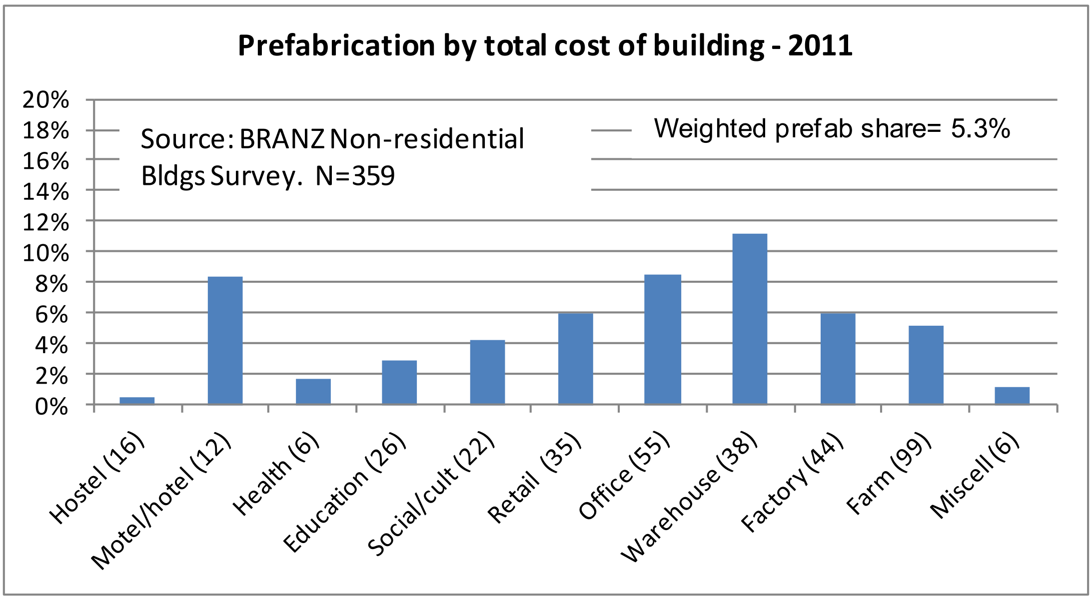


Figure 5: Prefabrication in new non-residential buildings as percent of total costs 2011

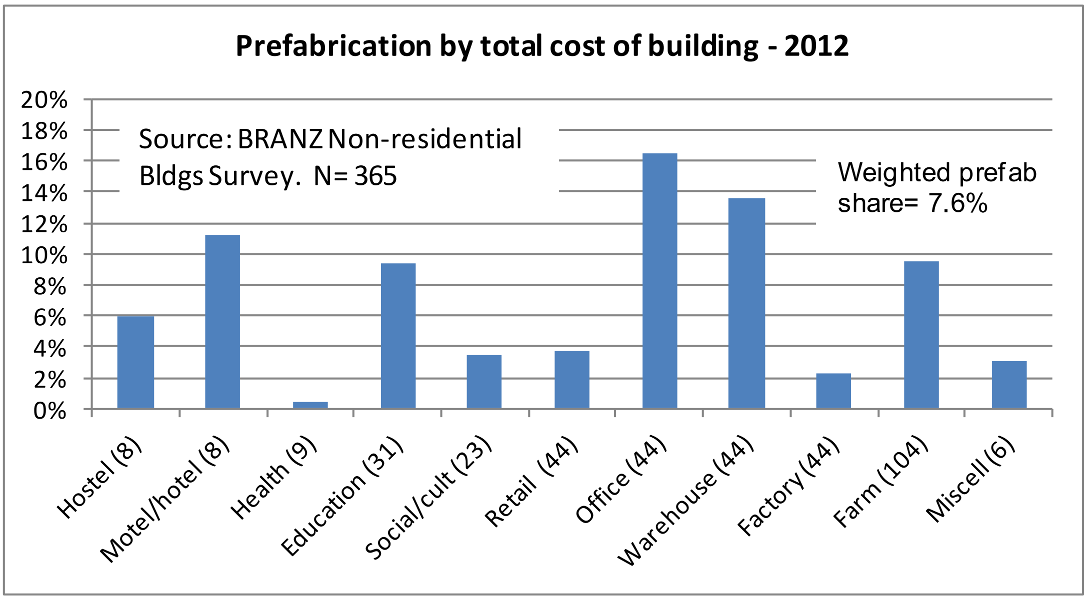


Figure 6: Prefabrication in new non-residential buildings as percent of total costs 2012

The material types used in the prefabrication of non-residential buildings are shown in Figure 7. The most common are concrete wall panels and floor beams. Prefabricated steel frames and roof trusses are also common.

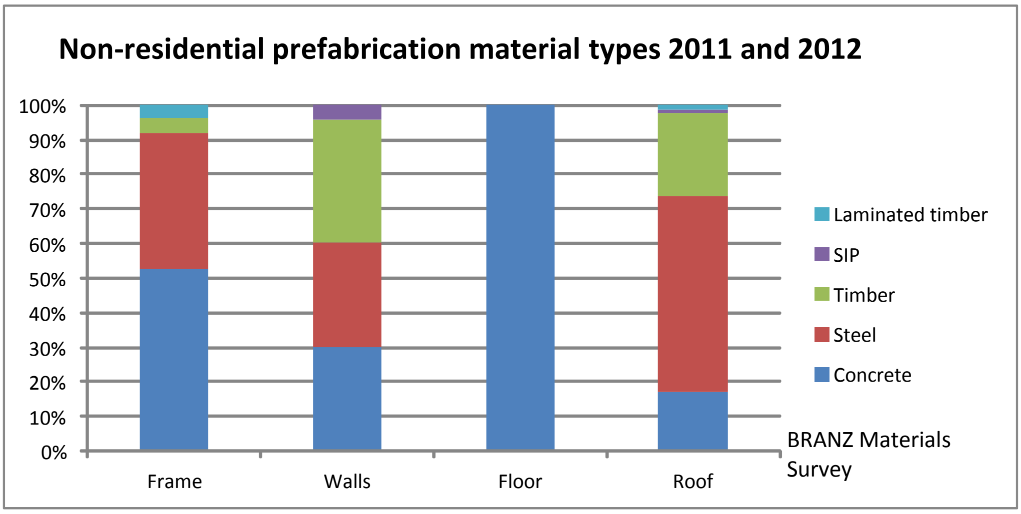


Figure 7: Prefabrication materials by component 2011 and 2012 combined

For detached housing the main use of prefabrication is pre-cut wall frames and roof trusses. Some cladding types have a prefabricated component, e.g. solid-timber houses, AAC panels, tilt slab cladding and reconstituted wood-based panels. Transportable houses and light steel-framed houses are also included.

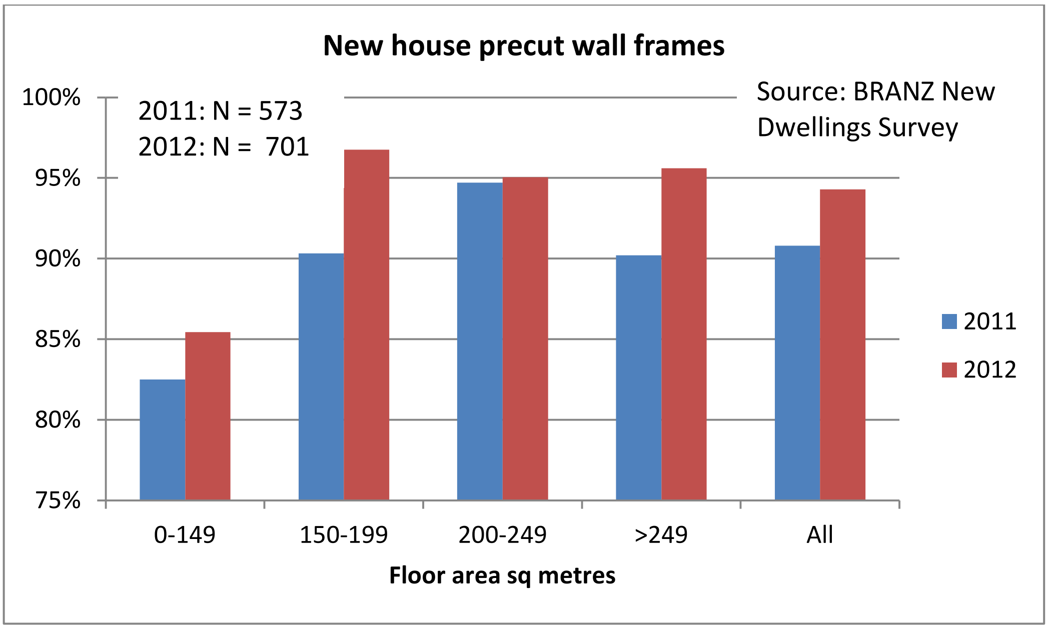


Figure 8: Pre-cut wall frames in new housing 2011 and 2012

Almost all new houses have ceiling trusses (Page & Curtis, 2011). Prefabricated wall frames are in approximately 91 percent of all new housing consented in 2011 and about 94 percent in 2012, as shown in Figure 8. This includes steel-framed houses, which currently (September 2012) form about 5 percent of the detached new housing market. Anecdotal evidence suggests the pre-cut percentage increases as workloads increase and this chart tends to support this view with new dwelling starts up about 15 percent in 2012 on 2011.

Data for housing and non-residential buildings can be combined to arrive at a single number for prefabrication uptake. Applying the above survey results for percentage share to the value of each building type and component, provides the summary result in Figure 9. The process for obtaining these figures is shown in Table 9, Appendix C.

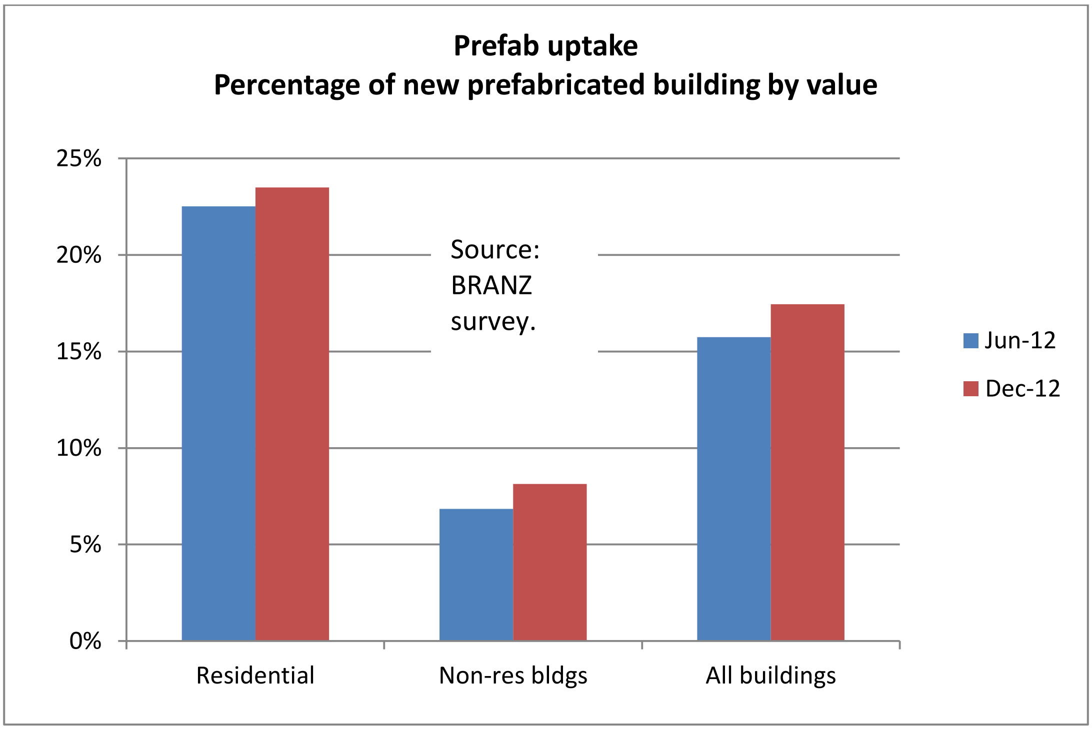


Figure 9: Prefabrication proportions in all construction – 2012

Figure 9 shows that prefabrication formed 17 percent by value of all building types in late 2012, increasing from 16 percent in mid-2012.

4.1 Economic definition of productivity

Productivity is defined as "the rate at which a company produces goods or services, in relation to the amount of materials and number of employees needed" (Encarta Dictionary, UK). The formula used to calculate productivity (Page, 2010) is:

$$\text{productivity} = \frac{\text{profits} + \text{wages} + \text{expenses}}{\text{time}}$$

Prefabrication offers a vehicle for the increase in productivity. However, one of the difficulties here is that surveys of productivity of New Zealand industry undertaken by others (such as the Department of Statistics) could misclassify prefabrication as manufacturing.

The Australia and New Zealand Standard Industrial Classifications 2006 (ANZSIC) incorporate prefabricated wooden building manufacturing (C149100) under wood product manufacturing (C14) and prefabricated steel building manufacturing (C222200) under fabricated metal product manufacturing (C22) (Statistics New Zealand, 2007). Construction (Sector E) includes onsite-centric trades and services, including land development, site preparation, structural and installation services, and completion (finishing) services (Statistics New Zealand, 2007).

According to the ANZSIC 2006 definitions, factory-built housing is manufactured rather than constructed. Therefore, when ANZSIC 2006 data is used in productivity analyses, it is entirely possible for construction sector productivity to appear to stagnate or even fall, while the cost of new houses falls and quality rises due to the move toward manufacturing.

The monitoring tool will be used by BRANZ to track the use of prefabrication in New Zealand and to provide robust data to recognise the increased value that is added to the sector at earlier stages in the process.

There are limitations with the tool – not least that it is only able to address a certain range of prefabricated elements and systems, and is reliant upon the input of valid data which continues to be obtained through quarterly BRANZ material surveys.

Results from the tool can be compared with the results from other analyses such as that from the Department of Statistics (Statistics New Zealand, 2007). Provided that appropriate application of the definition of prefabrication is made, advances obtained through investment in the prefabrication sector will not be lost in poor categorisation, or the processes of data analysis.

Figure 10: A panelised home under construction in the USA

5. ECONOMIC OUTCOMES OF PREFABRICATION

International results from larger markets such as Europe and the USA show that prefabricated building systems have better economic outcomes than traditional construction. Experience in New Zealand indicates that this is not usually the case, where this finding appears to be dependent upon market size.

5.1 Definition: what are better economic outcomes?

The economic outcomes throughout the construction value chain are defined differently for the different actors, as shown in Table 2.

Better economic outcomes		
Consumer	**Consenting authority**	**Construction industry**
Lower purchase prices	Reduced time spent processing consenting documentation	Lower construction overheads
Fewer administrative costs	Clear consent expectations	Lower design fees
Reduced maintenance requirements	Fewer consent alterations	Reduced regulatory and compliance costs
Higher resale value	Reduced time spent on construction sites assessing compliance and travelling to site	Lower material, labour, sourcing, handling and mechanisation prices
Improved quality of the completed construction		Reduced logistical and time requirements
Better understanding of system performance		Higher profit margins

Table 2: Definition of "Better economic outcomes" in the construction industry

It is unlikely that all of these outcomes can be achieved concurrently on all projects: some will be mutually exclusive; some unachievable; and some attained only under certain conditions. Many of these outcomes have relevance beyond the prefabrication industry, however, their specific opportunity is discussed below.

5.2 Cost of building – onsite versus offsite

International literature shows that prefabricated construction is often considered to be more cost-effective than onsite construction, but this is not necessarily the case in New Zealand. Although capital costs will not necessarily be lower, budgets are more predictable and outcomes more secure.

In countries with more established prefabricated construction industries than New Zealand, savings have been found when compared with onsite construction. This is particularly the case where demand allows purpose-built facilities to efficiently construct large quantities of similar products. For example, in Germany, prefabrication savings on house construction have been found to be around 22 percent (Craig, et al., 2002; Hargreaves, et al., 2003). In a USA case study, architect Michelle Kaufmann built one design twice, once using traditional construction methods and the second using modular construction. The modular house was found to cost 25 percent less than onsite construction (Winter, et al., 2006). Some of these savings came from a reduced timeline and the ability to reuse materials in the factory environment.

Certainly there is potential to save costs through the use of prefabrication in New Zealand (Fawcett & Allison, 2005; Bell, 2009; Koones, 2010; Shahzad, 2011), however costs are often similar, and are not necessarily reduced by using prefabricated systems. In the UK, constructing a building with a high percentage of prefabricated elements (typically a hybrid or modular construction) produces a product with higher performance (Davies, 2005, p. 81) than if it was not prefabricated. The economic benefits of higher quality are:

- Better value for the consumer
- A higher performing product
- A potentially longer-lasting product
- A marketing benefit, and
- Fewer call-backs.

As many of the benefits of prefabrication increase with scale and repetition, the full benefits of prefabrication can only be gained when there are multiple units to construct, which needs careful planning (Davies, 2005; Fawcett & Allison, 2005; Lessing, 2006).

... the full benefits of prefabrication can only be gained when there are multiple units to construct ...

In the UK, with its similar building industry structure to New Zealand, only 49 percent of projects are delivered to budget (Yorkon, 2012). In comparison, 40 percent of sample projects in the New Zealand Centre for Advanced Engineering (CAE) 2006 National Key Performance Indicator (KPI) survey were delivered to budget (Caldwell, 2007).

The enhanced cost control of prefabrication, paired with the predictability of the final bill (Kaufmann & Remick, 2009) is attractive for investors and construction clients from across the purchasing spectrum. Greater control over schedule and budget leads to reduced risk of over-investment or under-financing, less uncertainty, better ability to allocate capital into investments, shorter borrowing periods and resulting reduced cost.

Prefabricated construction is subject to risk from insolvency (Fawcett & Allison, 2005) of subcontractor suppliers, due to the delivered item being a product rather than a set of raw materials. The materials and final product are tied up with the manufacturer's assets while it remains property of the company. Liquidators may opt to retain incomplete product as part of the company's assets, potentially leading to delays for the client or in a worst-case scenario, loss of payments made to the point of liquidation. In the case of onsite construction, the client could be left with an incomplete house and lost progress payments; it is extremely unlikely the house would be removed from their land, so they would at least be able to employ trades to finish the job. The plethora of recent construction and renovation programmes on national television (2013) typically reflect the fact that time and budget over-runs are commonplace, and threaten the completion of projects.

A UK study (Goodier & Pan, 2010) notes that "it has been widely documented that both prefabricated and MMC (Modern Methods of Construction) technologies offer potential for reductions in cost, time, defects, health and safety risks, labour requirements and environmental impact and a corresponding increase in quality, build times, predictability, whole life performance and profits".

There are other examples of cost-benefits that have resulted from the prefabrication of buildings and parts of buildings, such as the prefabrication of the Knoll Ridge Cafe at the Whakapapa Skifield on Mt Ruapehu, and the modular prefabrication of student accommodation units for Elam Hall (now called University Hall) at Auckland University by Stanley Modular, based in Matamata. In both projects, prefabrication under factory conditions meant delays due to inclement weather were significantly reduced. Weather delays are a real challenge when working on tall, exposed or high-altitude construction sites. The size of these projects, and repeatability of the units was sufficient that systems could be developed in the factory to accelerate the speed of construction. Further analysis of the construction of Elam Hall and a case study of Cottages New Zealand is provided in Section 5.9.

5.2.1 Case Study - Economics

A case study assessment of a prefabricated construction approach was undertaken, with the details presented in Appendix A. For the cost analysis, the case study assumed:

- that the sale price of a prefabricated house is the same ($1000/m²) for three different approaches to prefabrication as for a house built in the traditional manner
- capital investment is required to develop capacity to deliver the prefabricated elements, and the return on investment forms part of the construction overheads
- that an acceptable profit margin is dictated by the rate of return on investment required.

Figure 11 shows the results for builders and manufacturers, with the bands showing the typical modelled profit ranges. For the panelised approach, the average profit margin needed to service the investment in manufacturing plant, and deliver the product at 1000/m² is 27%. If a panelised system manufacturer can accept a slower return or lower profit (e.g. 20% at the bottom of the band for panelised construction) then they may be able to reduce their market price below $1000/m², and be more competitive. Conversely, if a quick return on investment, and a higher profit margin is required (e.g. 34% at the top of the band) then the sale price may need to be increased above $1000/m². The gross profit margin must cover the costs of overheads, and thus the bottom of the margin increases as the required capital increases. These figures were arrived at through analysis of materials and labour costs, waste and time savings (see Section A.6).

It was found in this case study that hybrid construction provides the greatest efficiencies, and therefore allowed the highest profit margin. This provided the greatest opportunity to recoup the overheads of investment in the production facilities, followed distantly by panelised construction, then transportable homes, and lastly – onsite construction. This assessment assumes that there is sufficient throughput to maintain high utilisation of plant capacity, and is from assessment of construction of a single 120 m² house. It was found in this case study, that transportable buildings have around the same overhead/margin range as onsite and panelised construction. However, the increased overheads, (such as maintaining premises or a yard in which to build) require higher profit margins.

> ... exposed sites with frequent adverse weather conditions increase the costs of site construction through delays and reduced productivity of workers...

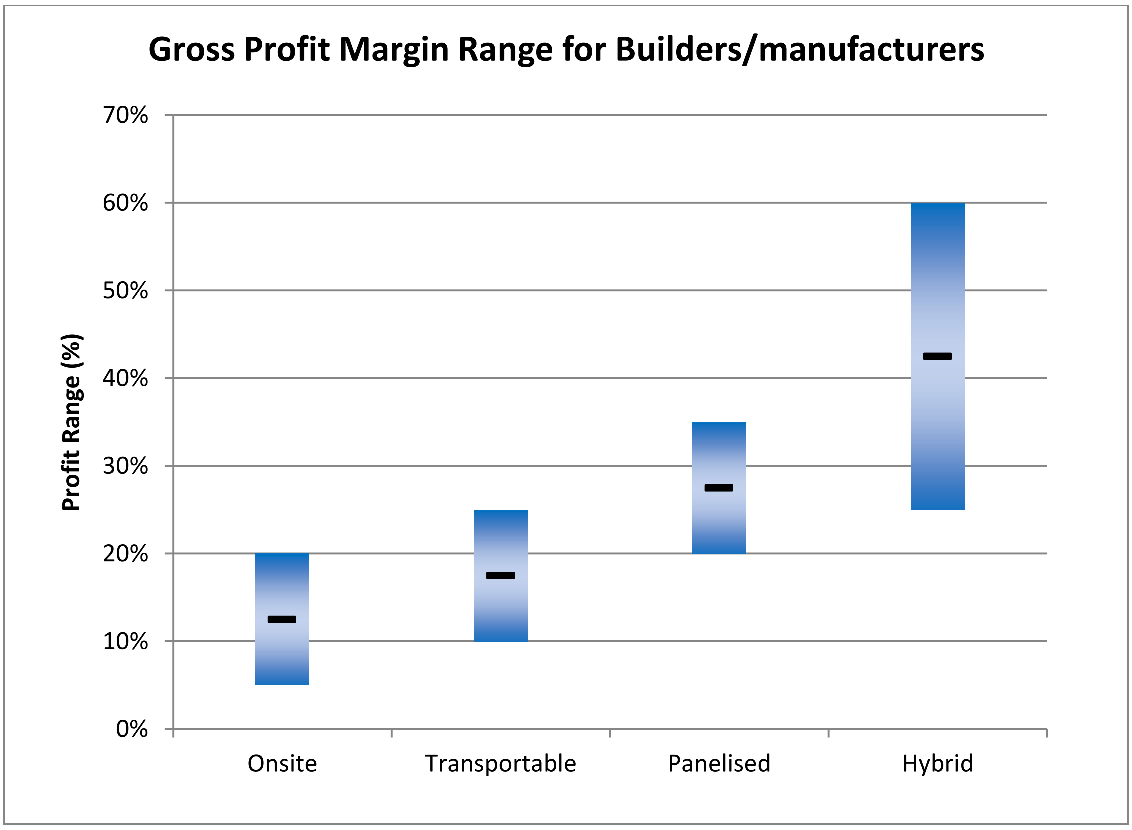


Figure 11: Profit margin range available for prefabricated construction at equal sale price

5.2.2 Cost of building – Discussion

The information available has shown that the cost of building with prefabricated systems is sensitive to a number of factors including:

- Economies of scale – the more projects that are undertaken, the higher the ability to bulk procure, the higher the potential for recycling and reallocating materials, and the wider the distribution of overheads. However, it is recognised that international data is sourced from larger domestic markets with larger export markets such as Europe. There are opportunities for the exporting of flat-pack construction systems to the South Pacific, particularly for temporary shelter or disaster relief. However, while economies of scale should result in cost efficiencies in New Zealand, our limited market size and extra costs incurred in exporting to distant markets may jeopardise this as an option.
- Site access – tight urban sites can make the use of large cranes necessary and may favour the use of modular construction methods. This means that craneage cost must be carefully factored into the build equation. Similarly, exposed sites with frequent adverse weather conditions increase the costs of site construction through delays and reduced productivity of workers.

The New Zealand domestic market contrasts to Europe, Japan and the USA where the larger market sizes, volume demand and acceptance of mass-produced housing give prefabricated construction a clear economic advantage (Page, 2010). Given the bespoke nature of the bulk of New Zealand housing and the comparatively small market, prefabricated construction has limited ability to provide an economic advantage over traditional onsite construction. However, it does provide higher levels of budget security and the opportunity for earlier habitation.

5.3 Time and lending costs

The New Zealand Productivity Commission has found that the fastest way to reduce building cost is by reducing the time taken in production, not by focussing on costs themselves (May, 2013). Shorter time also entails shorter lending periods for capital and in turn, reduced lending costs.

In New Zealand, only one-quarter of the CAE's National KPI survey construction projects were completed on time (Caldwell, 2007). In comparison, the UK's industry delivers 63 percent of site-based construction projects on time (Yorkon, 2012).

(Davies, 2005, p. 65) suggests that nearly half of the time spent by the labour force in traditional construction projects is spent on "wasteful activities". This arises from subcontractor delays, supplier delays, weather delays, rework, injury and unscheduled break times. Lessing (2006, p. 44) also found that "when processes are studied concerning waste, it is a common finding that less than 5 percent of all activities actually add value, while about 35 percent are necessary but do not add value and the rest, 60 percent is waste". Waste is often regarded as a tangible item; however, as Lessing (2006, p. 44) points out, a large amount of the value of waste in construction projects surrounds the inefficient use of time. Consequently, there is a huge potential for productivity improvement simply by reducing the wasted time.

Reduced timelines and more certainty of completion dates are a major benefit of prefabricated production. With weather removed as a factor and a concentrated pool of skilled workers with all the necessary tools and materials onsite, factory production is far faster than onsite production. The range of suggested time savings for prefabricated construction for residential applications internationally is between 30 percent and 60 percent compared to onsite construction (Kaufmann & Remick, 2009; Atkin & Wing, 1999; Bell, 2009).

> ... nearly half of the time spent by labour on construction sites is devoted to wasteful activities ...

The time duration for onsite construction compared to prefabricated construction methods were estimated for a case study house and are shown in Figure 12. This data for a 120 m² transportable house is detailed in Appendix A. Here, onsite construction is expected to take 14 weeks, compared to hybrid construction which is expected to take just five weeks when replicating multiple modules. Transportable housing is expected to take ten weeks, and panelised construction seven weeks.

Faster turnaround means less interest on borrowing for both builders and clients, and less time means room for more jobs and profit for builders. For clients, the amount of time paying for interim accommodation is reduced as are lending costs on progress payments. However, as Davies (2005, p. 83) points out "the inclusion of the cost of labour in prefabricated product can require larger payments earlier in the construction process than for traditional construction".

These figures vary widely across the industry and depend upon a variety of factors, including replication and demand.

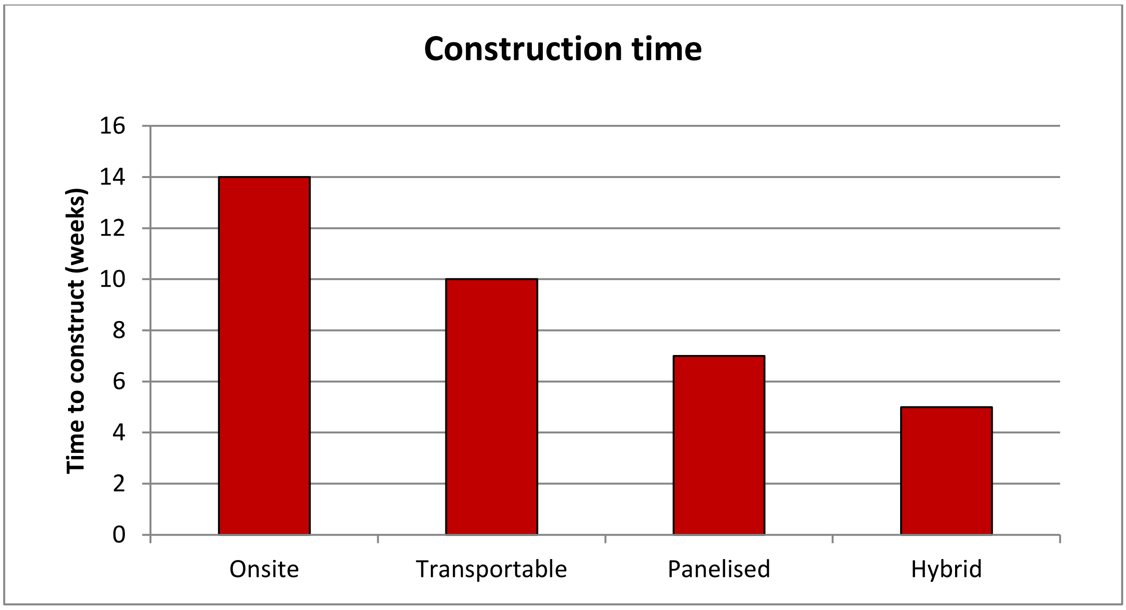


Figure 12: Time to prefabricate a 120 m² case study house compared to traditional onsite construction

5.4 Other building costs

Because of the reduced amount of time taken for prefabricating the case study house, the total cost of labour was lower than undertaking the same activity with onsite construction (see Figure 13). In actual job sites, this is likely to come about due to better scheduling, enhanced quality control, improved access to tools and facilities, a single site for trades, less travel time and easy site access.

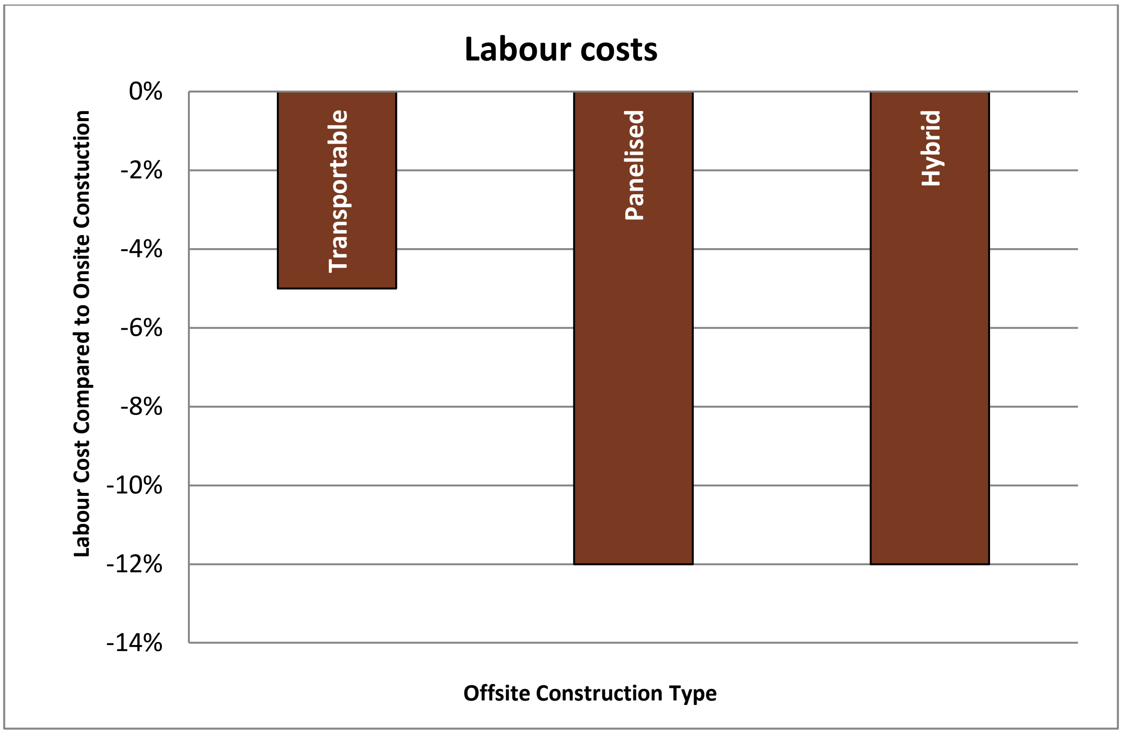


Figure 13: Labour costs for the 120 m² case study house when compared to onsite construction

Prefabricated construction allows companies to take advantage of bulk procurement discounts, as more jobs are put through the one site in a shorter length of time. As Figure 14 shows for the case study house, panelised and hybrid construction (which in this case is 60% modular, 20% panelised, and 20% conventional) have the greatest capability to reduce material costs due to the faster turnover of products, the ability to use warehousing to enable bulk ordering and to reduce waste through material reuse.

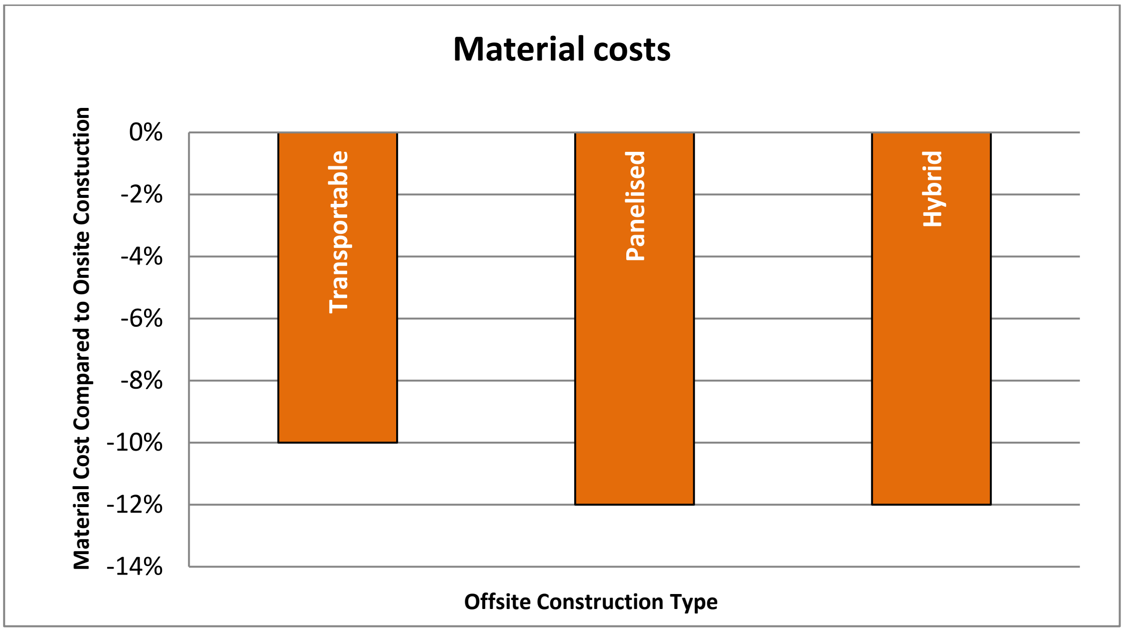


Figure 14: Material costs for the 120 m² case study house when compared to onsite construction

The BRANZ Study Report *"Value of Time Savings in New Housing"* (Page, 2012) has a detailed analysis of time saving effects on cash flow and profits. The main findings are summarised in the following sections.

5.4.1 Contractual arrangements and cash flow

The benefits to the builder of shorter lapsed time are influenced by the type of contract. There are different cost implications to the builder with a progress payment contract compared to a spec-built house ready to occupy.

Progress payment contracts usually entail a deposit and four or five progress payments. The aim is for the builder to be cash flow-positive so that outgoings are at least covered by progress payments. (Page, 2012) shows that the effects of quicker construction on cash flow are small, typically less than $100 per house (Page, 2012). Perversely, in some cases where the initial deposit is large, the builder can be better off with delayed construction because interest received on the deposit more than covers the delayed outgoings.

For spec-built houses the situation is different. The builder is typically paying interest on the land costs as well as the completed house. So any savings in elapsed time enables a quicker sale and reduced interest charges on the borrowings. These savings are more than $2000 per week on a typical new house (Page, 2012).

From the client's perspective, the advantage of quicker construction is they have the satisfaction of taking early ownership with an improved lifestyle and may reap the benefit of less rental payments on their existing accommodation.

5.4.2 Greater profits and reduced overheads per house

Quicker construction allows builders to earn more profit in a year. For example, if a builder can save one week in a "normal" construction period of 18 weeks this is a 6 percent time saving and hence 6 percent more houses can be erected per year. For a small builder this translates into several thousand dollars profit per year, and more for a large-scale builder.

(Page, 2012) finds that for medium-sized builders the above savings are $1600 per week and for small builders about $1000 per week. The latter saving has been used in this work.

The other advantage for larger-scale builders of producing more houses per year is their fixed costs per house are reduced, effectively increasing their profit margins. These costs include a sales team, show home and advertising, which collectively amount to over $20,000 per house sold (based on data for group home builders erecting approximately 90 homes per year).

5.4.3 Planning, regulatory and compliance costs

Established prefabricated manufacturing companies are able to reduce the cost of the planning process compared to onsite construction. However, this is often as much due to simple design as it is to repeated design and consistency of quality.

Multiproof can make consents for similar designs faster, easier and cheaper.

Within the New Zealand prefabrication industry there is a general consensus that the consent and compliance processes are easier for offsite construction once relationships with territorial authorities (TAs) are established. The consistency of the team, product and materials, plus the refinement of submissions for consent approvals, mean that TAs are able to process the requests more quickly. Established relationships through consecutive consent submissions create a feedback loop enabling companies to perfect their documentation according to the TAs' needs. The more work is done offsite, the less onsite building inspections need to be done (Fawcett & Allison, 2005, p. 14).

Where multiple TAs are used due to the building being constructed in another's jurisdiction, communication and coordination between all three parties concerned becomes vital, as interpretations of the Building Code vary between jurisdictions.

In the case of repeating the construction of a single design, the former Department of Building and Housing (now the Building and Housing Information Group within the Ministry of Business, Innovation and Employment [MBIE]) developed Multiproof consents. A Multiproof consent allows an approved house plan to be built multiple times without having to go through the entire consent process each time (MBIE, 2013). Building Consent Authorities (BCAs) must accept the consent as evidence of conformance with the New Zealand Building Code providing it fits within approval conditions. It is only the foundations and site-specific details that still need to be approved by the local BCA.

Multiproof can make consents for similar designs faster, easier and cheaper (MBIE, 2013), as a list of acceptable customisations can be incorporated in the consent to allow a wider range of designs to be approved. This allows considerable benefit when multiple units are to be constructed, based upon a core design.

The New Zealand Government's move toward centralised online consenting is intended to promote greater consistency of interpretation of building regulations across the country. Local authorities will retain the role of performing inspections, but will have less direct client interaction. This may have unintended consequences, as reducing the feedback loops between the BCA and the builder limits the ability for the transfer of local experience with climate and land conditions.

5.4.4 Other building costs summary

Time and usually lending costs are a factor in all construction projects and the more time is spent on a project, the higher the costs become. Prefabricated construction offers financial advantages relating to both time and lending for construction projects for both clients and builders.

For clients, shorter timeframes can reduce alternative accommodation costs and the lending period, speed up turnaround on investment and provide higher convenience. For builders, shorter timeframes lead to faster turnaround of jobs and shorter interest-bearing periods on overdrafts, thus providing higher profits.

Bulk procurement and higher efficiency of time which must be part of a prefabricated building solution reduces the costs of both materials and labour. The ability to reallocate waste streams also reduces costs to each project for both client and builder. In addition, the security of fixed costs and timelines allow both clients and labourers to plan their investment of capital more precisely.

In short, the money invested can work harder for both clients and builders in a shorter amount of time. However, sound processes and planning are required to maximise the benefits of prefabricated solutions.

5.5 Health and safety

By taking work from the site to the factory, the ability to control working conditions increases, (although the ANZIC code for the activity changes from "construction" to "manufacturing"). Workers are no longer exposed to adverse weather conditions (Bell, 2009; Fawcett & Allison, 2005), and health and safety is more easily and effectively monitored.

The environment of a factory not only protects workers from extremes in temperature, wind, solar radiation, glare and rain/snow/hail (Fawcett & Allison, 2005), but also creates a healthier environment and improves productivity (Scofield, et al., 2009). However, the increased focus on health and safety has interestingly led to increased reports of injury and illness (Nahmens & Ikuma, 2009), most likely due to the under-reporting of injuries and illness on the traditional construction site. This may occur because for sole-traders or those on casual contracts (a large proportion of the workforce) a sick day or compulsory time off work for injury means no pay – which highlights a potential unintended consequence of a regulatory improvement.

Manufacturing has 75 percent fewer fatalities in New Zealand than the construction industry.

It is broadly recognised that prefabricated construction reduces health and safety risks for workers (Scofield, et al., 2009; Shahzad, 2011). Bell (2009) argues that “more emphasis is needed on factory conditions, rather than outdoor yards, to achieve potential benefits from prefabricated processes in terms of safety, efficiency and productivity”.

As prefabricated construction is classified as manufacturing in New Zealand, this has the impact of attributing any improvements in health and safety from prefabricated operations to manufacturing operations. Manufacturing has 75 percent fewer fatalities in New Zealand than the construction industry, as shown in Figure 15 (MBIE, 2013). The impacts of lower health and safety risks are felt throughout society. Fewer accidents mean workplaces have fewer issues with understaffing, less sick pay and potentially higher morale. Fewer families lose loved ones or have to cope with reduced incomes and/or disablement through injury. Government spends less on medical treatment and ACC cover for construction workers, and less money is spent on taking firms to court for preventable accidents. While taking construction offsite is not enough on its own to provide these benefits, more highly-controlled environments make injuries easier to prevent (McDevitt, 2012).

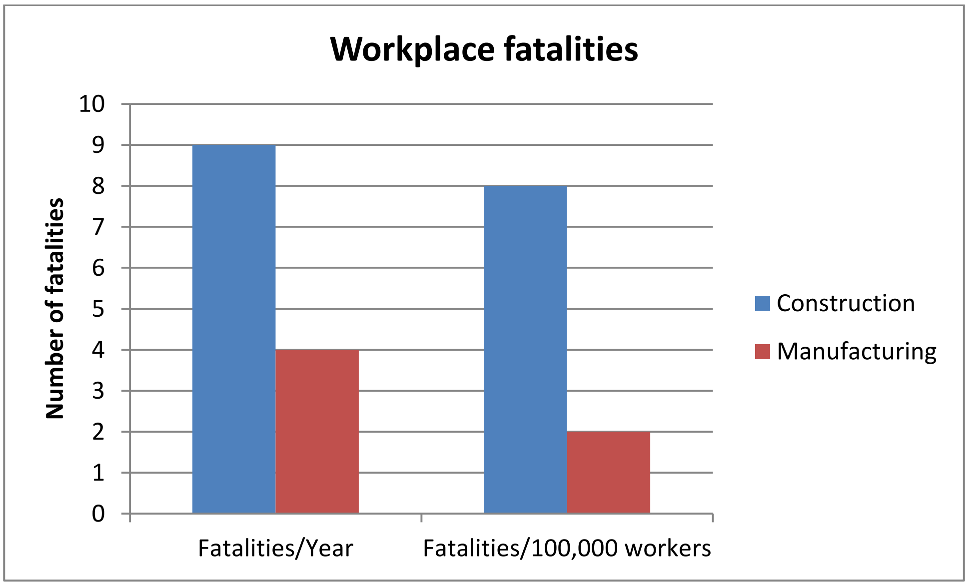


Figure 15: Workplace Fatalities in the New Zealand Construction and Manufacturing Industries

5.5.1 Skills and skill shortages

In order to function well, factory environments require constant workflow, access to tools and machinery, and appropriately-trained staff. The consistency of the workflow improves the ability to employ permanent staff and investment in training is retained (Bell, 2009).

The more mechanised the factory, the higher the skill level of workers required and the fewer the staff numbers. This is because workers are no longer there for just labour purposes – the more automation in place, the higher the need for engineers to control the equipment and the lower the need for physical labour. According to analysis of case studies of building sites in the UK, Germany and The Netherlands, higher levels of skill and mechanisation promote greater speed and labour productivity (Clarke & Wall, 2000), albeit with a lower number of labourers.

Conversely, where offsite construction is used, the overall level of skill onsite may be reduced due to more highly-skilled technical workers being moved into the factory setting, increasing the risk of defects occurring onsite (Stirling, 2003).

During times of skill shortages, mechanisation is able to increase the capacity of the construction sector, reduce the need for labourers and thus increase the skill base of firms, and provide a consistent, quality product to clients.

This is currently an opportunity for the Christchurch rebuild. However, there is a danger that the necessity of a rapid response has reduced the need for full investigation of prefabricated construction advantages.

5.6 Quality

5.6.1 Defects and rework

One of the key aspects of improving quality is to reduce the amount of rework to fix defects that need not have occurred. Costs for redressing defects have been estimated to account for around 6 percent of the cost of construction (Johnsson-Meiling & Henrik, 2009).

The ability to control the quality of the product going through the factory means that defects in the materials being used or the system being produced are adressed on the production line and usually before the product leaves the factory (Fawcett & Allison, 2005; Bell, 2009). There is less opportunity in the factory environment for a product to acquire defects (Stirling, 2003). This reduces the company's defect liability post-delivery (Bell, 2009; The New Zealand Productivity Commission, 2012) which includes interruption to following jobs and the resulting reduction in profit margins.

Human error is a primary cause of defects in construction ...

Human error is a primary cause of defects in construction (Johnsson-Meiling & Henrik, 2009). This can be reduced with increased levels of skills and training, and/or increased levels of automation. Both options lower the opportunity for human error, while automation increases precision (Robichaud, et al., 2005).

With CNC (computer numerical control) cutting and routing – providing the BIM (building information modelling) data input files are correct – the chances of error are virtually eliminated. A single incorrect cut can lead to either costly rework or discarding of an entire wall frame if it puts the framing off-square – consequently the demand for accuracy moves back up through the planning process.

Offsite construction also removes the potential for weather-related defects because construction work and storage is undercover. Site damage of vulnerable materials from water, wind, humidity or sun is virtually eliminated (Stirling, 2003) – e.g. undercover stocks of treated timber are not rain-washed to the point they need replacement due to the treatment being rendered ineffective.

Defects and rework are a costly part of construction. However, they can be minimised with a focus on quality through the use of a controlled environment, skilled staff, strong processes and precision technology.

5.6.2 Quality in construction

"Standards lead to perfection" (Le Corbusier & Benton, 1924).

Prefabricated construction has the potential to be of higher quality in comparison to onsite construction. As Davies (2005) points out "it is not that onsite construction cannot be high quality, rather, high quality is achievable at a lower cost with offsite prefabrication than otherwise".

The notion of prefabricated construction leading to high quality outcomes is well documented in the literature from both New Zealand and around the world and perceived to be the "principle advantage" of prefabricated construction (Bell, 2009).

... high quality is achievable at a lower cost with offsite prefabrication than otherwise ...

There are numerous reasons for this, including:

- Controlled climate environment (Bell, 2009; Fawcett & Allison, 2005; Huang, 2008).
- Quality control (Fawcett & Allison, 2005; Robichaud, et al., 2005; Kaufmann & Remick, 2009).
- Automation (Robichaud, et al., 2005).
- Precision (Robichaud, et al., 2005; Kaufmann & Remick, 2009).
- Consistency (Johnsson-Meiling & Henrik, 2009; The New Zealand Productivity Commission, 2012; Kell, 2012).
- Defect reduction/prevention (The New Zealand Productivity Commission, 2012) – see Section 5.6.
- Coordination (Bell, 2009).
- Continuous improvement processes (Gray & Davies, 2007).

5.6.3 Material maintenance and lifetime

Rather than being attributable to whether construction occurs onsite or in a factory, the maintenance and lifetime of materials is mainly determined by the choice of materials (Fawcett & Allison, 2005). Prefabricated manufacture does not necessarily improve the lifetime or durability of products; however, quality control processes may offer a chance to capture faulty materials early. The manufacturing procedures and warranties may also lead to "recalls", where materials determined to be of a faulty batch can be traced and replaced.

The nature of prefabricated construction also leads to more careful consideration of materials used and the methods of construction in offsite settings. Modules and panels are expected to be transported with minimal damage to the item when it reaches its final destination. This increases the level of structural rigidity required of the transported item and may influence the types of materials used, for example bracing lining, and the amount and placement of structure, fixings and the like[6].

Craig et al (2002, p. 49) suggested that "the theoretical benefits of prefabrication for quality of construction could manifest themselves in aesthetics, maintenance requirement or even running costs".

The durability and lifetime differences between onsite and prefabricated construction of homes are mainly attributable to reduced defects, material choices and structural requirements for transportation. These may increase the resilience of the home and/or reduce the maintenance requirements. A well-built home constructed onsite from the same materials with the same structure could be expected to have the same durability and maintenance requirements. So while increased resilience and reduced maintenance factors are perhaps more prevalent in prefabricated construction, the benefits are not exclusive to prefabricated construction.

5.6.4 Quality – discussion

Quality is impacted upon by a wide variety of variables, some of which are direct, but most of which are buried inside the primary factors – profit, wages, expenses and time.

Controlled environment

The factory environment improves the ability of the workers to deliver a quality product compared to onsite construction. Labour operating in an indoor controlled environment are much less sensitive to variations in weather. This allows factory production lines to be designed for maximum efficiency and precision with controlled quality.

Quality control

> ... a growing group of architects have utilised offsite construction to obtain "exceptional construction quality" ...

This close control of quality means that prefabricated homes should be of higher quality than conventional, onsite-built homes. Indeed as Bell (2009) points out, there are a growing group of architects – mostly in the USA – who have utilised prefabricated construction in order to tighten quality controls and obtain "exceptional construction quality". Likewise, a well-controlled factory environment could potentially lead to better finishing quality; conversely, if the factory environment has particles that have become airborne from processes, this could also detract from the level of finish.

Automation

Automation is a key area which is used to increase speed, precision and quality as the more automation is used, the less human error occurs. Provided that the plans are

[6] Discussed at the PrefabNZ Hive Event in Christchurch, 23 March 2012.

correct, automated systems and CNC are able to produce a far more consistent, precise product than one built with human hands.

Precision

The hybrid home industry in New Zealand is as yet far less developed than overseas. The USA's modular home industry is able to deliver a house of virtually any size and design for clients in a short time – and of higher quality than site-built. A similar response is expected in New Zealand, where a rise in quality standards coupled with a declining skill base means that a move towards factory-produced homes is almost inevitable.

Consistency

The speed and scheduling of prefabricated construction methods leads to tighter coordination of trades, sub-trades, materials and equipment (Bell, 2009). In order to meet project objectives in a timely manner, each stage of the project must be complete before subsequent stages can begin. This encourages prefabricated production facilities to employ their own tradespeople in order to ensure expertise is onsite at the right time in order to keep the production line moving.

Coordination

Prefabricated construction requires changes to the way construction is traditionally undertaken in order to improve the quality of builds. However, the ability to operate undercover with prefabricated construction, paired with use of tighter quality controls and employment of both precision manufacturing and automation, could go a long way towards improving the quality of completed buildings in New Zealand. This in turn has implications for the performance of the buildings, as discussed in Section 6 (environmental sustainability).

> ... one of the key barriers to productivity growth in the New Zealand construction industry is the low level of innovation ...

Continuous improvement

Closer coordination also assists with continuous improvement processes, as the feedback loop is improved. The notion of continuous improvement "implies that there is a continuous process to look for improvements in the whole of the activities of the firm" (Gray & Davies, 2007). All participants in the firm are encouraged to look out for and report areas where a change or adaptation could improve the system and of course its outputs. The corporate environment in this case can either encourage or hinder this process, depending on whether the person reporting is rewarded or punished for their observation.

5.7 Innovation and automation

Although not solely the domain of prefabrication, the topics of innovation and automation, and lean production are discussed here, as they have a potentially significant impact upon prefabrication operations.

Innovation is defined as "a new invention or way of doing something" (Encarta Dictionary, UK). Innovation is a constant process in construction (and affiliated manufacturing), as industry seeks to make and produce better products in less time, and costing less money. For the purposes of this section, prefabrication itself is not regarded as innovative, as it is not new, nor is the concept particularly unusual – although the extent of prefabrication in New Zealand low (17 percent – see Section 4), in comparison to overseas markets.

A report from the New Zealand Productivity Commission states that one of the "key barriers to productivity growth, is the [New Zealand construction] industry's ... low levels of innovation".

There are two main areas of innovation which remain largely unrepresented in the New Zealand prefabrication industry; partnering or alliancing (group procurement and cooperative operations) and automation.

Partnering or alliancing is where companies, often including designers, clients and/or members of the supply chain (Pitts, 2000), collaborate (Barrett, et al., 2007). Partnering circumvents the fragmented supply chain of traditional construction. It allows companies to come together as a large group to negotiate lower materials and labour rates, perform cooperative problem solving, improve access to suppliers and manufacturers, as well as share risks and research and development costs (Blayse & Manley, 2004). Opportunities for this to happen in New Zealand have been taken up through operators such as group builders in the Canterbury rebuild and have potential through public-private partnerships (PPP) which have facilitated improved efficiencies. However, they are not specific to prefabrication. Partnering on disparate projects is not seen as an innovation in itself; however, a change in relationships, for example between the contractor and the supplier, is an innovation (Barrett, et al., 2007).

Automation is defined as "a system in which a workplace or process has been converted to one that replaces or minimises human labour with mechanical or electronic equipment" (Encarta Dictionary, UK). Much prefabrication in Australasia is traditional construction taking place at a centralised site. In New Zealand, the extent of automated construction typically ends with the CNC cutting of timber for prefabricated framing and trusses – power tools need people to operate them and are therefore not automation. However, automation provides the opportunity to improve quality, precision, speed and cost-effectiveness, plus reduce waste, human error and downtime due to injury (Bell, 2009; Robichaud, et al., 2005). Automation does not replace the need for the worker; it is merely a tool at a firm's disposal. This is in recognition of one of Toyota's key production principles, Jidoka: "Machines only do what has been perfected – humans do what can be done better, or whatever handcraft has a value. A machine should never replace a worker, but work alongside according to Toyota. Jidoka is used to increase precision and quality and reduce waste." (Davies, 2005, p. 64).

Improvements in quality rely upon precision, which can be achieved in part through the use of automation (Robichaud, et al., 2005). Automation in industrialised house building requires the coupling of process thinking and advanced information and communication technology (ICT) (Lessing, 2006, pp. 72-73).

The use of ICT enables the consolidation of the information required to complete a building and full automation of construction processes. Two examples of advanced ICT are product data model systems and enterprise resource planning systems. Product data models include the information required in the construction process, such as three-dimensional computer aided design (CAD) models, engineering calculations, materials schedules and costing information (Lessing, 2006, pp. 72-73).

The implication of the combination of automation and ICT is an innovation that allows mass-customisation to become economical. Mass-customisation is where a standardised format is used to produce a customised plan – for example, each house is made up of a series of ultimately repeatable components.

Computer aided manufacturing (CAM) allows the design's CAD data to be fed into the computers controlling the automated construction line and the specified product is made. Repetition holds no particular advantage over individual design with automation, aside from the need for the design-specific data. Thereby the actual product of the New Zealand construction industry would not need to change in character due to the introduction of highly-mechanised prefabricated house building.

While automation is an innovation which provides the New Zealand residential construction industry with a method to address current issues, including skill shortages, quality, cost, waste and defects, its application may be restricted due to the size of the market available.

A successful model has been provided in the frame and truss industry, where 95 percent of residential timber wall frames and roof trusses (Page & Curtis, 2011) are completed in factory conditions and sent out to the job site. If this could be extended into the factory-production of wall and roof panels, then additional value could be added in the factory setting, which would mean many of the other benefits of factory production would accrue to a larger portion of the construction industry.

The opportunity to implement mechanised replacement of human labour is noted as being most effective when the process has been perfected by manual methods and can be repeated with machinery. This pre-supposes that multiple replicates of prefabricated production elements are required to support the investment in automation – and, as for other drivers of prefabrication, a significant market size is necessary.

5.8 Lean production

Lean production is the concept of minimising input (e.g. materials, labour) and waste, while maximising outcome for both the company (e.g. profit, output) and the client (e.g. quality, value, timeliness and achieved objectives).

Lean production systems lead to "time, cost, quality and productivity benefits ... derived through the minimisation of onsite operations and duration" (Lefaix-Durand, et al., 2005) Prefabricated housing manufacturers can utilise lean production techniques to reduce waste, production space, damage, labour and rework (Nahmens & Ikuma, 2009, pp. 2-3).

By combining components into modular and panelised units, offsite construction moves work into the factory, where worker productivity is increased, quality is higher, costs are lower and the overall need for labour is reduced (Huang, 2008).

The terms "lean" and "agile" construction are often used interchangeably. Agile production focuses more on customisation and effectiveness than lean construction, which focuses on technical efficiency of production processes (Bergstrom & Stehn, 2005).

“Leagile” (a combination of lean and agile) production “achieve[s] both the minimisation of resource requirements through the elimination of waste in the supply chain and the maximisation of customer service at an acceptable cost” (Pan & Dainty, 2007).

Issues have been raised surrounding the unintended consequences of lean production, one of which is the potential for a psychological toll of its introduction on workers. Research shows that this particularly affects staff in assembly lines, as lean groupings have resulted in a loss of worker autonomy, lower skill utilisation and “work design changes and outcomes” (Parker, 2003). The nature of constant pressure on the human psyche is to stimulate a stress response (Meier, 2013) and this may lead to reduced workplace performance, attendance and innovation (Parker, 2003). However, where lean production is introduced with the intention of improving workplace satisfaction and performance, positive outcomes can be achieved (Parker, 2003).

As for the area of innovation and automation, aspects of lean production have been implemented in the New Zealand prefabrication sector. However, they deliver greatest benefit in large markets where there is a consistent demand for similar products, high levels of mechanisation and good production control systems.

The construction industry beyond the prefabrication sector can learn from the examples of lean production provided by Toyota (among others).

5.9 Case studies

Numerous overseas studies have illustrated benefits of prefabricated construction (or manufacture) over onsite construction. One such study – (Wilson, 2006) notes advantages of offsite manufacturing (OSM) over conventional in the UK include:

- An average increase of productivity value by nearly 2.5 times.
- Improvement of onsite productivity by 12 percent on UK sites and 2 percent above overseas sites.
- Lost time and delays halved on UK sites.
- Better planning, sequencing and therefore time savings.
- Improved facilities, materials grouping, sequencing and organisation in OSM factories.

Reduced time waste through the use of IT-based materials ordering and tracking is another benefit. However, it is difficult to evaluate, as there are also higher setup costs (Shahzad, 2011; Wilson, 2006).

A Hong Kong case study (Jaillon & Poon, 2009) demonstrated improved quality, a 20 percent reduction in construction time and a 56 percent reduction in waste, resulting in “considerable cost benefits for developers” (Shahzad, 2011).

A 1996 Wood Truss Council of America (WTCA) study of the differences between panelisation and onsite framing of walls showed that panelisation reduced assembly time by 60 percent (O'Brien, et al., 2000). A 2006 case study of identical houses built onsite (traditional construction) and offsite (panelised construction) demonstrated significant time and resource savings. While the amount of framing timber used was comparable, the panelised house construction saved a total of 253 man-hours and 1600 metres of lumber compared to the traditionally-built house. Waste was reduced from 13 m³ to 3 m³ for the prefabricated-built house, diverting 10 m³ of waste from landfill (O'Brien, et al., 2000). The result was a combined cost saving of $4000 (1996) for materials, labour and waste disposal fees (O'Brien, et al., 2000, p. 53).

5.9.1 Elam Hall – A New Zealand case study

Auckland University's Elam Hall of Residence was constructed between August 2010 and August 2011. Elam Hall was intended to increase the number of spaces of student accommodation provided by the university. Acknowledging the increasing expectations of quality (Honey, 2012), the university's architects, Warren and Mahoney (WAM), employed the use of prefabricated modules.

The modules were built in a quality-controlled factory environment by Stanley Modular, while the base structure to house the modules was built onsite by Hawkins Construction (PrefabNZ, 2010). The 468 modular units were divided into 14 module variants (Stanley Group, 2013). Minimising the number of variants allowed for a higher degree of repeatability for the factory and for higher efficiency through familiarity for the workers. Stanley Modular built up to six modules per day over a six-month period (Stanley Group, 2013).

The modules were finished in the Matamata factory, shrink-wrapped and delivered 161 km to site (UoA, 2011) using just-in-time delivery methods (Stanley Group, 2013). This enabled traffic conditions around the Central Auckland site to be taken into account and also minimised the number of onsite workers required (UoA, 2011). A maximum of 16 modules were installed on a single day. The modules were stacked three-high, with structural inter-floors between.

The end result was the building went up far faster than it would have using conventional construction methods. Vehicle movements were minimised through the creation of modules offsite and staged deliveries. The costs were lower, fewer workers were required onsite and the site was safer than if traditional construction had been used (UoA, 2011). The differences in productivity between a factory and a construction site were also clear, with such issues as the distance that workers traverse to access ablution facilities impacting upon the workflow.

Economy, convenience, minimised disruption, speed and quality were all benefits from choosing to prefabricate the Elam Hall project. This case study reflects the benefits of prefabrication for large-scale projects with a high degree of repetition, as well as the reduced disruption from prefabricated construction offsite.

5.9.2 Cottages New Zealand – case study

Initially a builder of baches, secondary dwellings and basic cottage-type buildings, Cottages New Zealand has diversified into commercial buildings, including police stations and classrooms (Cottages New Zealand, 2013), after recognising a gap in the market (Roil, 2011).

Cottages New Zealand uses the Hastings District Council's "PlanSmart" system, where applications are pre-checked for completion before being lodged for assessment. Under PlanSmart, applicants who provide six complete applications with all required information in a row, receive priority in the processing line (DBH, 2009).

In addition to fast processing through the PlanSmart system, Cottages New Zealand's own standard operating procedures (SOPs) have allowed it to negotiate reduced onsite visits by building inspectors. The number of site visits by building inspectors before the issue of code compliance certificates for Cottages New Zealand has been reduced from around five (depending on the type of construction (HDC, 2013) to two because of its undertaking to complete work to the specified standard. The result of this is faster, cheaper consenting, the savings of which can be passed on to the client.

Cottages New Zealand employees perform the bulk of construction work undercover, virtually eliminating weather delays (in the case of the Hawke's Bay being rain, frost, solar radiation intensity or heat). The construction timeframe is typically six to eight weeks to guaranteed completion onsite (Cottages New Zealand, 2013), which provides significant certainty for investors, clients and procurement officers. The price of the build is also fixed in order to give the client higher financial security.

Cottages New Zealand has demonstrated the benefits of using prefabricated construction to reduce cost and improve quality. Collaboration and open communication with the local BCA has enabled a reduction in consenting costs and inspections, in turn enabling the company to operate under tight time schedules.

5.9.3 Retirement villages

Although the efficiencies in the construction of a specific retirement village have not been assessed in this work as a case study[7], there are a number of observations that can be made about this building sector that are relevant to prefabrication.

A retirement village is a purpose-built complex of residential units with access to a range of ancillary facilities planned specifically for the comfort and convenience of the

[7] No assessments specific to the construction of retirement villages were found.

residents (Bates & Kane, 2006). Most retirement villages in New Zealand have between 40 and 170 homes although two-thirds have less than 80 homes (Grant, 2006). In 2004 it was estimated that approximately 5 percent (23,500 people) of the 65-years-plus population were living in nearly 20,000 units in retirement villages. (Statistics New Zealand, 2013)

Since 2004, the number of units in retirement villages has continued to increase (Statistics New Zealand, 2013). With nearly 1000 new units consented in each of 2011 and 2012, this was 6 and 7 percent of the total residential consents. Ryman[8] has increased its build rate from 550 units per annum in 2011 to 700 per annum, and Summerset8 has increased its target build rate for 2016 to 300 units per annum from 250 units per annum (Milford Asset Management, 2012). In February 2012, all of the apartments consented were in retirement complexes (Statistics New Zealand, 2013).

This sector provides one of the key requirements for pr efabricated dwellings – a consistent demand for similar constructions, although it appears that most construction of these homes is still undertaken onsite. While many of the benefits of group home construction are captured (bulk purchasing, consistent workflow, reuse of materials), the construction is still exposed to the weather and the full benefits of factory-based construction is not captured.

Outside of this niche area, there appears to be a market reluctance to accept large numbers of clustered similar homes that are a feature of retirement villages. In construction sectors where mass production of similar construction units is acceptable (such as hotel bathroom modules or student accommodation units), there are major cost savings possible. There appear to be opportunities to exploit the advantages of prefabrication in these sectors and suggests that work should be targeted to this area.

[8] Ryman and Summerset are two of the major providers of retirement village capacity in New Zealand.

5.10 Economic conclusions

Findings in the literature that prefabrication of buildings is a better economic choice than onsite construction were not borne out in the case study house investigated in this work, nor in the experience of the PrefabNZ industry membership (PrefabNZ, 2013), albeit with a few exceptions. This is largely because of the small size of the New Zealand market and its inability to exploit the efficiencies inherent in mechanised bulk production of similar products.

However, this section (Section 5) has shown that there are a wide range of economic benefits from utilising prefabrication in construction, both residential and non-residential. While prefabrication is often used for high and medium-density residential projects, there are a set of learnings that can be applied regardless of the type of building. These are:

- Repeatability = consistency = speed increases (for non-automated construction).
- Quality is built into the process.
- Project staging is more effective = time reduces = forward planning is improved.
- Fixed prices = greater security for the investor.
- Fixed timelines = ability to plan capital investments in rapid succession.
- Less onsite work = higher safety, less site traffic, fewer delays.
- Formalised internal procedures can lead to reduced compliance costs.

It is expected that greater levels of capital investment are required to derive the greatest benefit from prefabrication. In this case prefabricated construction has economic benefits, provided that economies of scale can occur. Time savings equate to cost savings and fixed prices enable investors to plan and invest their money with more certainty. Overseas studies are demonstrating the economic benefits of using prefabricated construction for housing. However, there are yet to be firm economic benefits established for one-off, independently-commissioned dwellings in the New Zealand context, scale and current time, other than greater certainty in budgets and timeframes.

Consequently, the primary economic advantage of prefabricated construction in New Zealand is enhanced budgetary security.

It is suggested that the New Zealand prefabrication market requires additional drivers to maximise the economic benefits that are available.

Natural opportunities for next steps in the adoption of prefabrication include:

- Mass construction approaches like the development of social housing, new suburbs or quantities of homes in response to disasters such as the Canterbury earthquakes.
- Recognition of the benefits of prefabricating larger sections of buildings – i.e. the extension of the successful model of prenailed wall frames and roof trusses into wall and roof panels.
- Integration of prefabricated modules such as bedrooms into group homes.

Irrespective of the drivers for the future uptake of prefabrication, this work has discovered that prefabricated construction provides greater economic security in meeting budgets and timelines, given the higher level of planning and processes that surround the prefabricated construction sector.

6. ENVIRONMENTAL SUSTAINABILITY OUTCOMES OF PREFABRICATION

Prefabricated manufacturing has been shown internationally to have better sustainability outcomes in comparison to onsite manufacturing. These findings are replicated in this work, where it is concluded that more opportunities for stronger sustainability outcomes exist with prefabrication, as opposed to onsite construction.

6.1 Definition: What are better sustainability outcomes?

Better sustainability outcomes are a more difficult issue to evaluate than the economic outcomes which typically have metrics in terms of dollars. This report takes the view that sustainability is focused on environmental good, rather than just economic good.

Environmental sustainability can be defined as "The maintenance of the factors and practices that contribute to the quality of environment on a long-term basis". This draws from the oft-quoted report "*Our common future*" published in 1987 by the United Nations World Commission for the Environment and Development (Brundtland, 1987) as providing "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

For the purposes of this report, we define better sustainability outcomes as involving:

- Less energy and GHG emissions.
- Less material and waste production.
- An improved indoor environment.
- Less use of water.
- Better management of hazardous materials.

6.2 Building energy and emissions

The generation and use of energy creates emissions[9], including greenhouse gas (GHG) emissions. Each gas has a global warming potential (GWP) based on the degree to which it contributes to radiative forcing in the atmosphere and the consequent greenhouse effect (Verbruggen, 2012). Emissions of GHGs are important for the ongoing health of the environment, which is likely to have a significant effect on the way we live (Brundtland, 1987). Details of the issues involved with the release of GHGs are discussed in Section A.6.

[9] While the generation of renewable energy *per se* does not create emissions, the hardware and infrastructure development is responsible for GHG emissions.

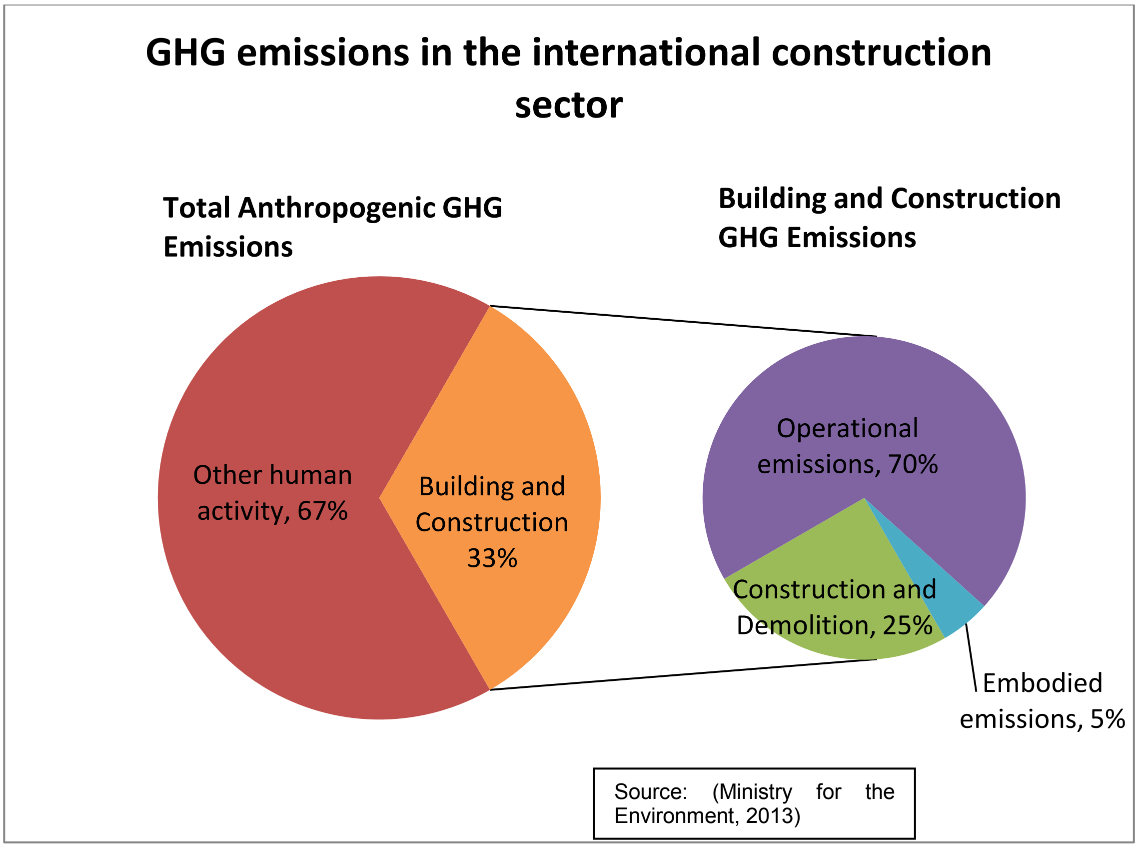


Figure 16: Anthropogenic GHG emissions and the proportion that are attributed to building and construction activity from international data

Although New Zealand has not signed up to Stage 2 of the Kyoto Protocol, anthropogenic GHG emissions continue to be released and still need to be managed. In 2011, New Zealand's total greenhouse gas emissions were 72.8 million tonnes of carbon dioxide-equivalent (Mt CO_2-e) (Ministry for the Environment, 2013).

The building and construction sector is responsible for energy use and GHG emissions through the:

- Emissions embodied in materials.
- Construction of buildings.
- Operation of buildings.
- End-of-life management of buildings (demolition, reuse, recycling and landfill).

The proportions of GHG emissions that are attributed to each of these parameters internationally are shown in Figure 16. This illustrates that building and construction activities are responsible for a third of the world's anthropogenic GHG emissions and of this third, 70 percent are from the emissions used for space-conditioning the buildings, 25 percent for constructing and demolishing buildings, and 5 percent for the emissions embodied in the construction materials.

This data is relevant to all buildings internationally. However, the amount and proportions vary based on construction material and use.

This section recognises that while the use of buildings contributes significantly to the GHG emissions from a building over its life, this has been considered by others in the New Zealand context (Alcorn, 2010; Buchanan, 2007; Collins & Blackmore, 2010).

This work focuses on the GHG emissions from the other parameters of construction/demolition activities, and of the emissions embodied in construction materials, which make up the other 30 percent of emissions shown in Figure 16.

6.2.1 Embodied emissions

Embodied emissions are the quantity of carbon dioxide-equivalent (CO_2-e) emissions that are attributed to materials due to the emissions evolved through their manufacture. These stages are:

- Extraction/milling of natural resources.
- Processing of resources into materials.
- Transportation of resources, materials, products and systems.
- Installation of materials, products and systems.

These are pictured in Figure 17.

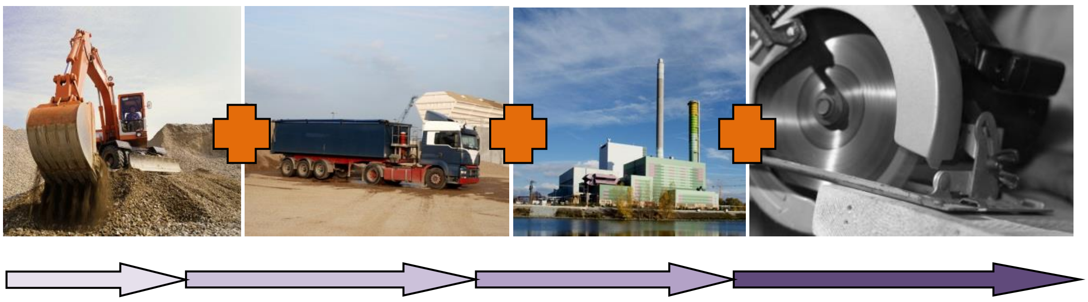


Figure 17: Process flow of extraction, transport, processing and manufacture to indicate the contributors to the emissions embodied in materials during the creation of a building product

There can be significant GHG emissions embodied in construction materials, particularly in those such as concrete and metals which require significant processing. Figure 16 shows that, on average, emissions embodied in the materials used in the building and construction industry total 5 percent of the total emissions from the sector, being a third (1.5%) of the total anthropogenic emissions.

(Buchanan, 2007) suggests that the emissions embodied in a timber house in New Zealand are 5-10 percent of the total form the sector, but this does not account for biogenic carbon that is stored in timber, which effectively reduces the total emissions. (See section A.6.10).

In this work we principally examine the GHG emissions from construction activities, transportation of building material and construction waste management processes, and make reference to a case study of three different prefabricated processes used to construct the same house, compared to the traditional onsite process, as described in Appendix A.

6.3 Construction phase emissions

The construction of a building results in the emission of GHGs because:

- Materials must be transported (using fuels),
- Fuels are burnt in the operation of machinery (diggers, forklifts, cranes, post-hole borers and other onsite machinery) in site preparation activities,
- Energy must be used to assemble materials into structures (electricity, powder-actuated fasteners etc)
- Waste streams must be managed (energy used in separation of co-mingled wastes, transport to management facilities and emissions from processing or final disposal).

While the emissions released during the construction of a timber building have been found to be only 1 percent of the total emissions from cradle-to-end-of-use (Buchanan, 2007), prefabricated construction has been found to outperform traditional construction in terms of reduced greenhouse gas emissions in the construction phase (Shahzad, 2011).

Australian author Grant Daly (2009) also notes that "prefabricated housing materials are presently enjoying a renaissance on account of the well-publicised need to reduce the carbon-footprint associated with building and construction activity, and the idea of erecting housing which is environmentally friendly, mostly for energy cost savings."

The amount of GHG emissions resulting from construction energy use "var[ies] by country due to: the energy mix; transformation processes; the efficiency of the industrial and economic system of that country", and also varies over time as factors change (Monahan & Powell, 2011).

The same result has been replicated in the case study house described in Section A.6 with the results in Figure 18[10]. This case study undertook a detailed assessment of the GHG emissions from the construction of a 120 m² transportable home, modelling the results of constructing the home with three different approaches to prefabrication and comparing this to conventional construction.

The modelled options were as follows:

- "**Onsite**" – With conventional onsite construction.
- "**Panelised**" – with 60% factory prefabricated, and 40% site constructed.
- "**Hybrid**" – with 60% modular, 20% panelised and 20% site built.
- "**Transportable**" – with 95% factory construction and 5% sitework.

[10] Note that the source of this data is Figure 31, although the embodied emissions from the construction materials are not included in this graph.

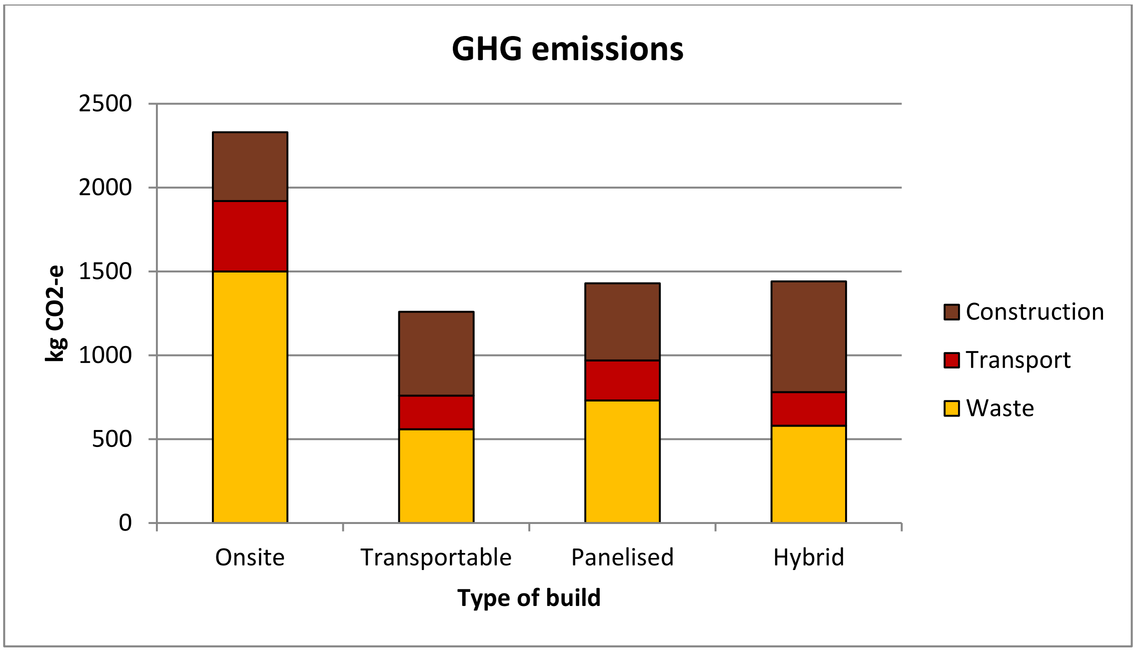


Figure 18: GHG emissions resulting from the construction of the 120 m² case study house with the four different construction approaches

The method of construction was found to have an effect on the amount of greenhouse gas emissions.

Onsite construction of a single house by a non-group builder in the case study was found to have the highest GHG emissions (Figure 18), due to the higher waste and the significant contribution from transport[11]. The high waste figure in onsite construction (1500 kg CO_2-e) is nearly three-times the figure for transportable homes due to the reduced ability to store or recycle waste materials, as extra material must be ordered to account for site errors and all surplus materials must be disposed. The higher transport figure for onsite construction (420 kg CO_2-e) is twice the value of transportable and hybrid homes, as all materials for onsite construction are sourced from the supplier, there is poorer utilisation of trucks and there is no opportunity to bulk purchase for multiple constructions as can be undertaken by manufacturers of prefabricated systems.

The three offsite prefabrication methods in Figure 18 represent less GHG emissions than the onsite build, but the differences between the three approaches should not be viewed as significant. The hybrid option's higher construction emissions are due to the need for a mobile crane rather than a hiab to allow access to difficult sites. The transportable house does not need a crane[12] and the panelised approach uses a hiab on the delivery truck. The variation in waste is largely due to the proportion of construction for the panelised and hybrid approaches that must be undertaken onsite – which inherits the low material utilisation figures from the onsite waste management practices. Further detail is provided in Section A.6.

[11] A comparison of transport and waste emissions from the construction of a single house by a group builder was not included, as significant assumptions about the movement of materials and waste between the various group builder sites were not available.
[12] The transportable house is jacked off the truck in this case.

6.4 Transportation emissions

Prefabricated construction can reduce the transportation of materials, components and labour, and thereby the emissions resulting from vehicle movements in construction activities.

By moving construction offsite into a factory, workers are able to live closer to where they work, without frequent changes to their commute. This sentiment is echoed by Michelle Kaufmann, a USA architect who until recently owned a prefabricated architectural housing firm:

" ... People who work in the prefab factory typically live closer to work than the average contractor or subcontractor who drives to a remote job site. In addition, the shorter time frame for building prefab results in less gas used to get to work.” (Kaufmann & Remick, 2009).

Reinforcing Kaufmann & Remick’s findings, another USA study found that the transportation energy use by employees in a modular home factory was 6 percent that of employees in onsite construction (Kim, 2008). This was not a major issue though, since in this study (USA), suppliers were often hundreds of miles away, and so employee transportation formed less than 1 percent of material transportation emissions.

To minimise material transportation distances, prefabricated construction holds the advantage of being able to site factories close to suppliers. Reduced distance from suppliers reduces cost due to reduced delivery time and fuel use:

“Not only does a prefab home require putting fewer trucks on the road (due to larger loads supplying multiple homes), but also as deliveries become more consistent, the trucking company dispatcher can arrange return loads so that trucks don’t come back empty. This level of coordination and fuel savings would be almost impossible to accomplish with a stick-built jobsite, where deliveries are more unpredictable." (Kaufmann & Remick, 2009, p. 71).

Results from the case study house (Figure 19) show differences in transportation GHG emissions depending on the method of construction. Emissions due to commuting of the workers are excluded in accordance with PAS 2050 (BSI, 2011) and distances of material deliveries vary depending on the location of the construction site. The number of material supply trips is also shown on the right hand axis, which has a significant effect on the results.

Onsite construction leads to the highest amount of GHG emissions for transportation due to a higher number of material deliveries, with 29 trips generating around 420 kg CO_2-e in this case study. Transportable and hybrid construction emissions were more than halved compared to onsite construction, with both calculated to be ~200 kg CO_2-e. Panelised construction’s transportation emissions were just over half that of onsite construction, at 240 kg CO_2-e.

The main reason for the reductions in GHG emissions from transportation with prefabricated solutions is the benefits of bulk purchasing, better economics in the loading of delivery trucks and ability to store goods for later projects. In the case study example, the materials for one house were aggregated into supplier-lots and the transport distances (from supplier to site) and weights (of the materials) used to calculate the GHG emissions where trucks of various sizes carried part loads. In the case of the prefabricated construction, the most efficient sized truck (usually an articulated truck and trailer unit) is able to be fully loaded and make a single delivery of materials sufficient for multiple houses. This reduces the emissions (and costs) attributed to the construction of each panel/module/complete house.

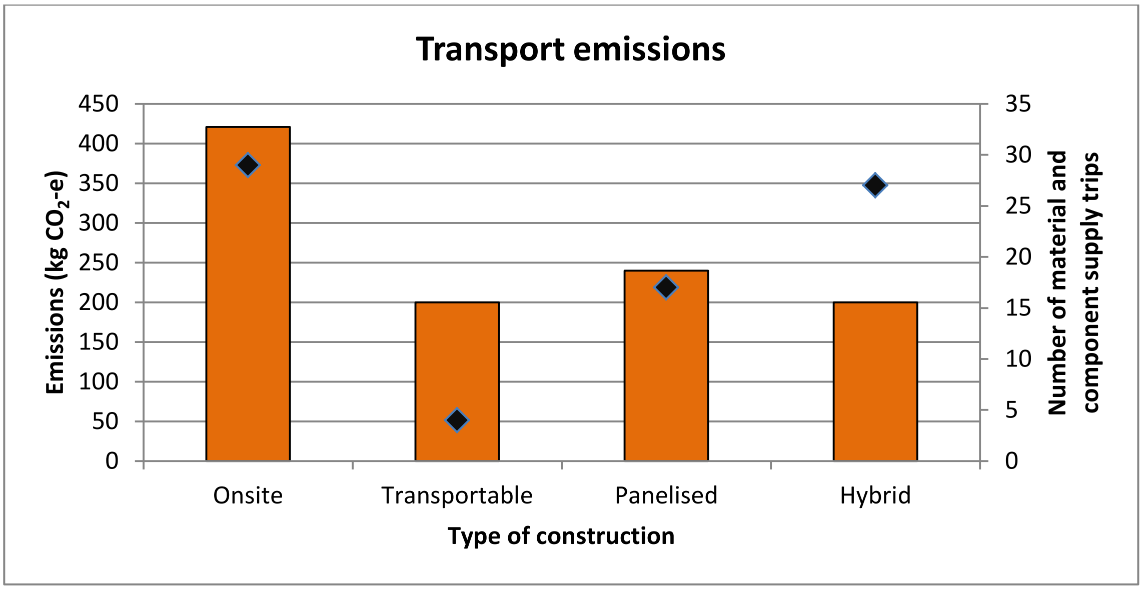


Figure 19: Calculated construction transport emissions of the case study house construction type scenarios, excluding labour transport emissions

Industry feedback[13] suggests that the aggregation of transport from multiple suppliers cannot always be exploited. However, other solutions have been found, such as the operation of warehousing for multiple projects and selected use of building supply companies to supply only in efficient batches of product. Significant differences were found in the provincial areas, where material volumes were typically smaller than in the larger urban areas, and batching was not often possible.

6.4.1 Transportation conclusions

International experience and information from large urban areas in New Zealand shows that prefabricated construction of buildings reduces the energy and GHG emissions from transportation.

Although transportation emissions typically do not provide a significant contribution to the overall GHG emissions from construction, (being between 14 and 18 percent of the GHG emissions in the case study), other benefits such as reduced vehicle movements[14] and reduced transport cost make them worth achieving.

Capturing the benefits of transport reductions relies upon the following:

- Good logistics control.
- Larger companies with multiple projects.

[13] This was sourced from anecdotal discussions at PrefabNZ workshops and meetings.

[14] Reduced vehicle movements have the co-benefits of reduced traffic congestion, reduced road damage and reduced impacts on human health from the release of particulates and gases from the operation of vehicles.

- High demand for construction.
- Dense population clusters.

In New Zealand, it is expected that these benefits will generally be restricted to the seven main urban centres of Auckland, Wellington, Christchurch, Hamilton, Napier/Hastings, Tauranga and Dunedin, or areas where significant development is occurring concurrently.

There are other transportation reduction options that are available more widely outside of the prefabrication industry that are the subject of other research projects at BRANZ, such as the establishment of regional materials distribution centres across building material sectors. These are being assessed at BRANZ in the Auckland Construction Lifelines project (Ying & Roberti, 2013).

6.5 Waste

This section explores physical construction waste (the construction by-product which needs to be removed from site and disposed) from traditional construction as compared to waste streams emanating from prefabricated construction offsite.

Around 40 percent of New Zealand's landfilled waste comes from construction (Bell, 2009, p. 47), which is similar to that of the European Union (Huovila & Koskela, 1998, p. 2) and slightly higher than the USA at 29 percent and Australia at 20-30 percent (Oxley III, 2006).

The modular home industry in the USA achieves waste levels of around 2 percent, as compared to the traditional onsite industry's waste levels of up to 40 percent. This translates into prefabrication saving 50-75 percent of the waste compared to traditional construction methods (Kaufmann & Remick, 2009; Koones, 2010). This is despite some prefabricated framing systems using around 9 percent more material for framing, e.g. as the edges of abutting prenailed wall frames each use a structural stud – one of which becomes redundant when the frames are connected together.

Similar savings have been cited for the UK, where it has been observed that the amount of waste decreases the more prefabrication is employed (Monahan & Powell, 2011, p. 180).

A non-residential productivity survey from the USA (McGraw-Hill Construction Ltd, 2011) found that:

- 76 percent of respondents indicated prefabrication/hybrid modularisation construction reduced site waste.
- 62 percent of respondents believe that these processes reduced the amount of materials used.

In the ideal prefabricated construction operation, the high-precision, low-error working platform available in a factory/yard-based environment (also see Section 5.6) means that traditional rough estimates of material quantities can be replaced with detailed calculations of precise material quantities. Over-ordering to create a contingency in case of mistakes is greatly reduced (Bell, 2009) and warehousing/stockpiling allows bulk ordering benefits. As a case in point, the UK's construction industry typically overorders by around 10 percent as a design measure, with around 10-15 percent of the ordered materials exported from site as waste (Monahan & Powell, 2011).

The controlled environment of a factory also works to reduce waste by ensuring the preservation of materials used. Protection from the weather keeps materials dry, preventing water damage to materials, and timber twisting and warping (Stirling, 2003).

This is of particular importance with treated timber, where there are human health, and environmental toxicity issues with the management of offcuts, together with sawdust and shavings from working with treated timber. Controlled prefabricated construction areas, and particularly undercover factories, give better opportunity to capture, store, and dispose of fine waste than onsite, which reduces the release of hazardous materials into the environment. This also reduces the propensity for rain to leach treatment chemicals into the environment from offcuts and sawdust.

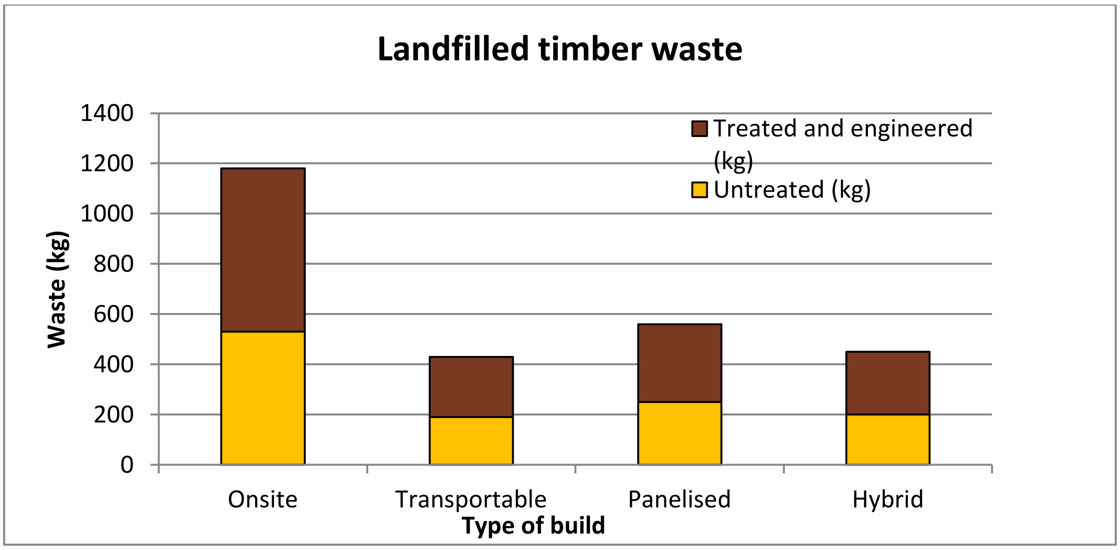


Figure 20: Waste calculated for the case study example for each type of construction

Recycling becomes more economical and feasible when multiple jobs occur in rapid succession at one site, and the control of the flow of materials is improved. What would be relegated to the skip on a construction site can instead be tagged for use in an upcoming job (Koones, 2010; Stirling, 2003; Bell, 2009). For example, material offcuts can be fed into CNC systems where they can be used for short elements, returned to suppliers or used in later projects.

The case study (Section A.6) showed that using prefabricated construction reduced the amount of waste generated at a construction site. The specific example of timber waste is shown in Figure 20. This was largely because factory/yard-based locations allow stockpiling and warehousing to supply the timber needs. While the volumes of waste from the three prefabricated construction processes are different, sensitivity analysis suggests that there is no measurable difference between these cases, although the difference between the onsite and prefabricated practices (50 percent) are significant.

6.5.1 Waste conclusions

International experience and information from New Zealand shows that the prefabricated construction of buildings reduces both the volume of waste created and the proportion of waste that is diverted to landfill. This reduces the GHG emissions from the management of waste, and the likelihood of hazardous wastes from treated timber being released into the environment.

6.6 Water

Internationally, it is suggested that prefabricated construction uses less water in construction, although this is not well supported.

Phillipson (2001) identified a scheme with European Commission (EC) funding which anticipated saving 50 percent of the amount of water used to construct a typical house when using prefabrication techniques.

The main construction use of water is for the making, placing and curing of concrete. Most of this water becomes incorporated in the material, so it is just the management of the water volumes and avoidance of excess water use that becomes important. While it is expected that factory conditions will allow better control of concrete manufacture, placement and curing, this is not always possible, so provides little opportunity for prefabricated construction practices to use less water.

On the other hand, the provision of sanitary facilities and for the provision of hot water, as required under Section 6 of the Health and Safety in Employment Act (New Zealand Government, 1992), can have a large impact on the use of water on construction sites.

Site-based construction often entails the use of chemical toilets, whereas purpose-built prefabricated construction facilities will more than likely have flushing toilets. The presence of a kitchen onsite and perhaps showers may also add to the water loading for factory-based construction.

Due to bulk water metering onsite, the lack of sufficient data for analysis has meant that it could not be established at this time whether there is a difference in water use between traditional onsite construction and offsite prefabrication in New Zealand.

6.7 Prefabricated versus onsite – environmental sustainability outcomes

This study has found that prefabricated construction has greater opportunity for improved environmental sustainability when compared to onsite construction.

In particular, international experience and information relevant to large urban areas in New Zealand shows that prefabricated construction of buildings is able to reduce the environmental impact of construction through:

- Reducing the waste created during construction by maximising the potential for reuse of materials and minimising the proportion of waste that is diverted to landfill.
- Reducing the GHG emissions from the transportation of buildings, modules, panels and materials, by reducing transportation distances and the number of trips.
- Reducing the likelihood of timber treatment chemicals leaching into the environment through more controlled waste management processes.

The key messages from this research are contained in Table 3.

Key messages
Prefabricated construction approaches increase security in economic outcomes.
Prefabrication provides greater opportunity for enhanced environmental sustainability than with traditional construction.
The most common prefabricated elements in non-residential construction are concrete wall panels (50 percent of all prefab walls) and floor beams (100 percent of all prefab floors).
The most common prefabricated elements in residential construction are pre-cut wall frames (91 percent of all walls) and roof trusses (95 percent).
By value, 17 percent of all building work in New Zealand is prefabricated.
The small market size in New Zealand may be restricting the uptake of prefabrication, since prefabrication is less efficient with lower demand.
Half the time elapsed on traditional building sites is devoted to wasteful activities.
Prefabrication reduces the waste material generated at construction sites.
Prefabrication benefits from factory-based processes having 75 percent fewer fatalities than site-based processes.
Prefabrication reduces the rate of human error – which is a primary cause of defects in construction.
A rise in quality expectations coupled with a declining skill base makes greater use of prefabrication an inviting option for the future.
One of the key barriers to the uptake of prefabrication in New Zealand is the low level of innovation in the industry.
Caution is required when using statistics on prefab uptake, as prefabrication can be classified as a manufacturing activity, rather than a building and construction activity.
The greatest benefits of prefabrication are gained when there are multiple units to construct.
Exposed sites with adverse weather conditions have high costs for site construction, which increases the comparative value delivered by prefabrication.
Compliance requirements are less onerous once processes and relationships are established between authorities and prefabricators.
Prefabrication provides a reduced likelihood of timber treatment chemicals leaching into the environment through more controlled waste management processes.

Table 3: Key messages found in research into the impact of prefabrication on the economic and environmental outcomes of the New Zealand building and construction industry

7. CONCLUSIONS

This work has found that:

- **Prefabricated construction provides more security in economic outcomes than onsite construction.**
- **Prefabricated construction has greater opportunity for better environmental outcomes than onsite construction.**

Improved economic outcomes are not inherent in prefabricated construction. However, better outcomes are more likely than with traditional construction.

Prefabricated construction has been shown both overseas and in large-scale New Zealand contexts to have improved economic outcomes through:

- Reduced initial capital cost
- Shorter construction periods, and
- Reduced site access requirements.

However, the single-storey case study house examined as part of this project did not indicate reduced total costs over traditional onsite construction. Rather, the costs were similar to onsite construction as the associated higher levels of process control, project management and return on investment typically allayed the reduced production costs.

Prefabricated construction has significantly better opportunity to provide a number of other benefits in construction, including:

- Higher-quality construction with fewer defects, reducing the need for rework.
- Better regulatory control, reducing compliance time and hurdles.
- Higher levels of health and safety, reducing time and production lost to injury[15].

Enhanced environmental sustainability is a key reason to use prefabricated construction.

Reduced waste, hazardous waste, transport needs and GHG emissions during construction can readily be achieved through the application of prefabricated construction approaches.

[15] The energy provided by manual labour is not considered because the PAS 2050 assessment metric (BSI, 2011) does not consider commuting of construction personnel nor the energy content of manual labour, but only considers the use of electricity, gas or petroleum-based fuels for energy. The effect of this is a natural bias towards traditional construction, as much of the travel involved in traditional construction is not accounted for and the energy used by factory machinery cannot be balanced against human labour.

APPENDIX A CASE STUDY ASSESSMENT OF PREFABRICATION COSTS AND GHG EMISSIONS IN A TIMBER HOUSE

This Appendix has been prepared based on research into the variation in greenhouse gas (GHG) emissions and construction costs that accrue from the construction of a single building form, using three different prefabricated approaches in the New Zealand construction environment.

This work provides technical background and content to support the body of the report and the decision tool (http://www.prefabnz.com/Community/Wiki/).

A.1 Abstract – Case study

Prefabricated building elements and systems have been entering the production cycle of the built environment internationally at different rates and with divergent approaches. Much of this prefabrication has been pursued due to the logistics of construction, economic factors and the availability of appropriate skills. However, there has not been any work undertaken globally on the comparison of the various prefabrication approaches in regard to their environmental impact.

The work reported here takes a case study of a transportable house and compares the economic and environmental costs of constructing this building in four different prefabricated forms, using GHG emissions as the environmental metric. The work shows that the prefabricated options have similar capital costs, but up to 15 percent lower GHG emissions when compared to traditional house construction on a cradle-to-site basis.

Given the importance of embodied emissions in the construction industry, it is suggested that attention should be turned towards the reduction of GHG emissions in construction, by:

- Reducing the use of construction materials with high levels of embodied GHG emissions – for example by encouraging the use of materials with low embodied emissions and disclosing the GHG emissions in a completed construction,
- Reducing the amount of GHG emissions embodied in necessary construction materials – for example by continuing to investigate lower-energy processing or manufacturing methods for existing materials,
- Reducing the environmental impact of embodied emissions – for example by identifying means of increasing the recycling and repurposing of materials in existing construction to displace the need for the production of virgin materials.

A.2 Summary of findings – Case study

This Appendix assesses the economic and environmental costs of the construction of a transportable 120 m² house from KHH Ltd in New Zealand with two other prefabrication approaches and compares this to a traditional onsite build of the same house with the same materials. The environmental assessment uses GHG emissions and has been carried out on a cradle-to-site basis informed by PAS 2050 (BSI, 2011) – a UK product carbon footprint standard that is finding application globally. The economic assessment has been undertaken using the actual economic costs incurred to put in place the completed houses, with no allowance for inflation.

The study found that:

- There is no significant cost difference between the prefabrication construction approaches.
- Prefabrication construction approaches provide a 15 percent reduction in the GHG emissions released, in comparison to traditional construction.
- The economic cost of prefabricated houses is the same as the cost of houses built with traditional methods, although this result is sensitive to:
  - Volume demand (where it is expected that higher volumes and cost efficiencies will reduce the unit price of prefabricated housing), and
  - Profit margins, where the return on investment may alter the outcomes.
- GHG emissions from the prefabricated options are 15 percent less than the traditional construction approach. This result is insensitive to the distance from the prefabrication factory to the site, except where access for prefabricated systems is very difficult and extensive craneage is required.
- About 50 percent of the GHG emissions from materials used in this lightweight house are located in the claddings.
- Embodied GHG emissions are a significant portion of the emissions required to put a house in place.
- The average distance from a KHH Ltd yard to a site is 30 km.

Given the importance of embodied emissions in the construction industry, it is suggested that attention should be turned towards the reduction of GHG emissions in construction, by:

- Reducing the use of construction materials with high levels of embodied GHG emissions – for example by encouraging the use of materials with low embodied emissions and disclosing the GHG emissions in a completed construction
- Reducing the amount of GHG emissions embodied in necessary construction materials – for example by continuing to investigate lower-energy processing or manufacturing methods for existing materials, or
- Reducing the environmental impact of embodied emissions – for example by identifying means of increasing the recycling and repurposing of materials in existing construction to displace the need for the production of virgin materials.

A.3 Introduction – Case study

A.3.1 Background

The use of prefabricated building systems has been increasing in construction operations worldwide and offers potential benefits over traditional construction techniques. Given that many transportation limitations have been overcome due to the development of major road and rail infrastructure, alternative construction materials, systems and approaches can more readily be employed – if the local industry is prepared to embrace them, costs are competitive and the logistics can be organised.

Globally, prefabrication is one area that has benefited significantly from technological advancement, through such utilities as computer aided design and computer aided manufacture (CAD and CAM), although uptake in New Zealand is low (Page & Curtis, 2011). Together with improvement in transportation infrastructure, the benefits of precise, repeatable cutting and assembly systems, and rapid transport has allowed greater integration of prefabrication into the built environment.

In New Zealand, prefabrication in residential construction encompasses manufacture and assembly of systems from windows, to walls and right up to whole houses. The purpose of this work is to better understand differences between the various prefabricated building system approaches in terms of GHG emissions and economic costs, and how they compare to traditional construction in a specific case.

A.3.2 Approach

This document presents and discusses the GHG emissions and economic costs from the construction of a transportable, prefabricated, 120 m², three-bedroom house.

While a house of 120 m² is significantly smaller than the average sized house of 165 m² – being 205 m² minus a double garage of 40 m² (Page & Curtis, 2011) – the modular nature of the home assumes the size can be scaled up, provides for easy transport by road and ready comparison to the panelised and hybrid options.

The same house design was used to compare the economic and environmental costs of the three prefabricated approaches and the traditional build. The house is a simple rectangular shape provided by group builders. The reasons for choosing this house include that:

- There is readily-available cost information[16].
- The house can be easily segmented into modules and panels, so that a comparison can be made for traditional and yard-built housing with no changes in layout.
- The exact schedule of materials and suppliers is available, so that the transport implications and GHG emissions implications can be readily assessed.

Construction approaches assessed in this report are onsite, transportable, panelised and hybrid/modular.

[16] Provided by KHH Ltd.

A.4 Construction Options – Case study

A.4.1 Onsite construction

Construction is performed as a traditional method. This is not assessed as a group-builder house and does not gain from the bulk-buying and other efficiencies inherent in the group-builder construction model. All materials are delivered directly to the site from the supplier, with timber framing and trusses built onsite[17]. Windows and roof cladding are made or cut to size and delivered to site when needed, but all other materials are stored onsite until they are needed.

A.4.2 Transportable construction

Construction is similar to the onsite method, although there are significant benefits of a well-managed yard or factory including process control, immediate availability of materials, health and safety advantages, and access to forklifts and hoists. There are labour and material economies compared to site construction arising from staged construction of several very similar (if not identical) houses being built at one time in the same location, with dedicated labour for all houses. Only the foundations (piles and bearers) are constructed onsite.

This is constructed as a transportable house built offsite (except for foundations) and relocated to the final site. An artist's rendering of the transportable house is shown in Figure 21. This construction makes use of:

- Bulk purchasing directly from manufacturers.
- Warehousing and distribution of job-lots.
- Prenailed frame and truss manufacture.
- Prebuilt kitchen manufacture.
- Other economies of scale that minimise cost and time inputs.

Figure 21: Artist's rendering of the transportable house located onsite

[17] This is actually now uncommon, as (Page and Curtis, 2011) report that 95 percent of New Zealand house construction uses prenailed frames or trusses.

A.4.3 Panelised construction

This is a house constructed from panels in a factory, which are later assembled onsite. This option assumes that 60 percent of the home (by value) is prefabricated at a yard or factory, with 40 percent of the house assembled in the traditional manner onsite, and attracting the same economic and environmental costs as the onsite build. The panelisation of this option is shown in Figure 22. The panel construction has the efficiency benefits of being at a central site, whereas the site construction portion suffers from the disadvantages of being located at disparate locations throughout the country, potentially at considerable distances from suppliers.

There is some extra use of timber when prefabricated panels are used, as each panel must be self-contained and have vertical elements which are affixed to the vertical elements of the next panel. This and all other prefabricated construction approaches have the same potential structural redundancy. This slightly increases the amount of timber which is used in the construction of prefabricated construction, which increases the embodied emissions. However, this is offset by the reduced amount of waste compared to traditional construction.

The walls consist of 16 open or closed wall panels, as shown in Figure 22. The flooring is five panels of Strandboard glued and screw-fixed to LVL joists, with three rows of bearers and timber piles installed onsite. With a panel house construction there are some minor walls built onsite, but most are prefabricated.

Wall panels use 90 x 45 mm and 70 x 45 mm studs and plate construction for external and internal walls respectively, with plasterboard linings (exterior walls only), ply sheathing, insulation, plumbing piping and wingbacks, wiring and switch and outlet mount plates. The wiring lengths allowed for junctions into adjacent panel switches and to the ceiling lights. Draw cables through conduits are used where needed for wiring[18]. The sheathing on exterior walls is 7 mm plywood and is extended to the joists for nail-fixing of panels to the joists. On the top of the plates a 140 x 45 mm second plate is used to connect panels. Nail plates are used at mid-height on the sheathing at panel junctions. The cavity battens (as required), cladding and windows/exterior doors are fixed onsite.

For internal walls only one side is lined; fixing to the floor and adjacent panels is done by nailing. The other side of these internal walls are lined onsite. The roof is truss construction and is as per traditional method. This means that 60 percent of the construction is panelised and 40 percent constructed in the traditional manner.

A.4.4 Hybrid/Module construction

This is a house constructed in a factory using a hybrid approach including modules, panels and infill construction. In this case it was assumed that 50 percent of the house (by value) was modularised, 25 percent was panelised and 25 percent was constructed in the traditional manner. See Figure 22. As for the panelised option, construction of the panels and modules benefit from being constructed at a factory/yard, with only 25 percent of the construction being undertaken onsite, including assembly and foundations.

There are three modules as shown in Figure 22. The modules include wall and ceiling linings and fittings, but not cladding or windows. Also the flooring, and floor and ceiling joists are included in the modules. The walls in the modules have sheathing on the exterior, and cladding and windows are site-fixed, as described for the wall panels.

[18] While the economic costs of electrical and plumbing work is included, the resultant GHG emissions from these utilities are not included.

Only the bedrooms and services room were considered suitable for modular units. The living, dining, and family and kitchen area were “too open-plan” to modularise and transport, and instead are built using panels.

The remainder of the flooring are the panels described above – i.e. floor Panels 3 and 4, and part floor Panel 2. Away from the modules the walls are panel construction. The modules have ceiling joists but the roof over the modules is onsite rafter and ridge board construction, while the remainder of the roof is truss construction.

Of the construction value, 50 percent is in modules, 25 percent in panels and 25 percent in traditional construction.

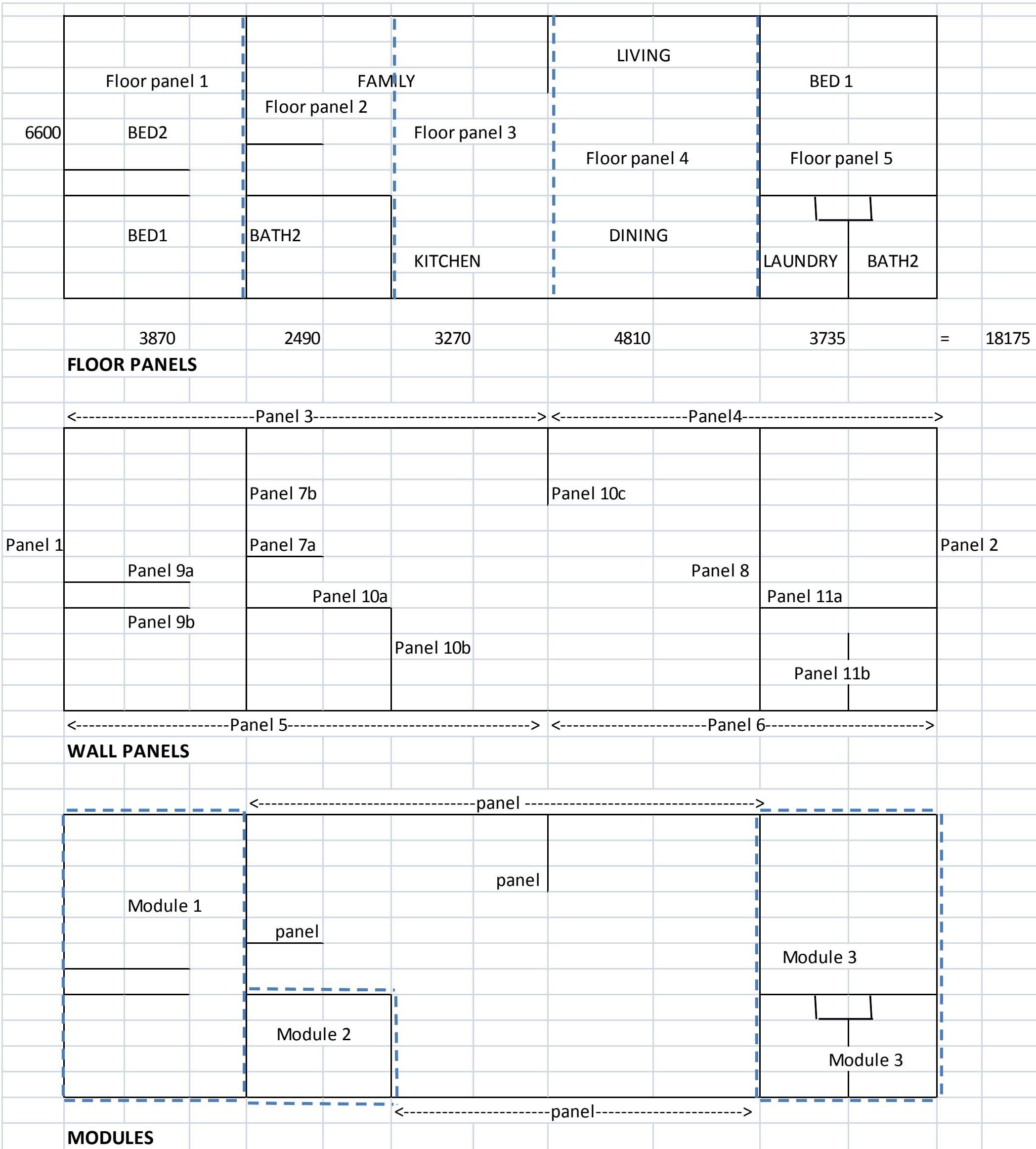


Figure 22: Panel and module layouts

This approach to an examination of prefabrication has limitations (both economic and environmental) which are presented in Section A.4.

Section A.5 examines the economic costs and Section A.6 focuses on GHG emissions from the prefabrication and onsite construction of the 120 m² house.

A.5 Prefabrication economic costs – case study

The capital cost of a construction is often the only cost that is used to affect purchasing decisions of construction systems in the built environment. It is therefore useful to better understand the economic variability of prefabricated systems.

This section examines the economic costs of construction of the house using traditional onsite (stick-built) construction methods and the three prefabrication techniques presented in Section A.3.2, which are expected to impart the same performance levels.

The cost-based performance of each option was assessed, with the floor plan shown in Figure 22.

A.5.1 Results summary – prefabrication economics

The results indicate that there are no significant differences between the lowest costs in the price ranges for all of the options (a 3.5 percent range), so Figure 23 is used to present the price ranges dependent upon the profit margins that are applied (as driven by the return on investment required) assuming that higher profit margins are required where higher capital investment is needed, as addressed in Section A.5.2.

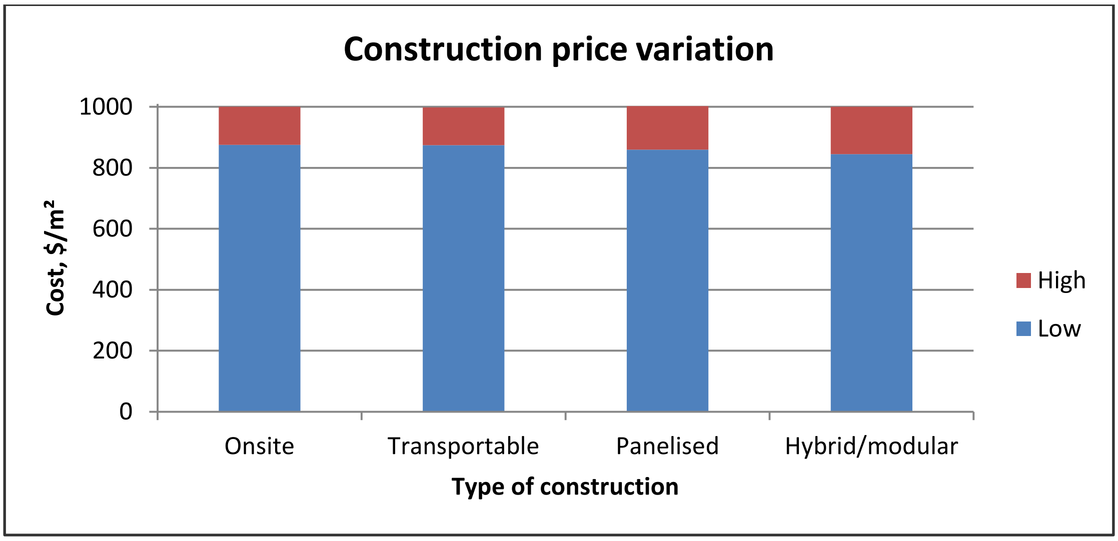


Figure 23: Typical house cost and prices by type of construction

If the yard or prefabrication sites are at or near the final delivery point, the costs for these options reduce. However, the actual transport distance[19] is not highly significant as the major cost is due to the time spent in the pick-up and set-down operations of the building, hybrid/modules or panels.

The main assumptions made in deriving the results are:

- A reasonable volume of throughput (see Section A.5.2) so that the costs of setting up for panel and modular construction can be recovered.

[19] Section 7.A.6.15 deals in some detail with transport distances and the variation in emissions due to these factors.

- That panels and hybrid/modules require higher profit margins (see Section A.5.2) than site-built and yard-built houses because factory setup costs and operations need to be recovered.
- The cost advantages of quicker construction (i.e. reduced overheads per house) are passed on to the owner.

A.5.2 Method – prefabrication economics

Whole house and component cost per square metre rates were obtained for traditional and yard-built construction from Rawlinson's handbook (Rawlinsons, 2012) and discussions with industry members. For the panelised and hybrid components the percentage cost difference compared to traditional construction was estimated for each component, based on discussions with New Zealand manufacturers. This assumes an ongoing demand for prefabrication, at levels exceeding 80 percent of existing capacity utilisation, and allowing for recovery of setup and manufacturing costs over five or ten years. These production costs are lower than if the same component was built onsite. The reasons for the cost savings in prefabricated construction approaches are:

- Repetition of work on fabrication tables and frames speeds up the construction process.
- Computer-controlled semi-automation reduces waste and allows for customisation.
- Lost time due to weather is avoided with factory prefabrication.
- Potentially large volumes can be put through a factory enabling lower prices for the raw materials.
- Less skilled labour is needed in factory fabrication than with onsite construction.

Labour and material costs for prefabrication are lower than onsite construction due to larger volumes, lower skill costs and the efficiencies associated with factory construction.

Prefabricated house price summary				
120 m² rectangular basic house				
Assumptions	**Onsite**	**Transportable**	**Panelised**	**Hybrid/ modular**
Price $/m² (excl GST)	875-1000	874-998	860-1003	845-1001
Material costs compared to onsite-built	-	-10%	-12%	-12%
Labour costs compared to onsite-built	-	-5%	-12%	-12%
Profit margins	5-20%	10-25%	20-35%	25-60%
Construction time weeks	14	10	7	5
Price allows for $1000 per week construction time savings to the builder, which is passed on to the owner				

Table 4: Modelling assumptions for prefabricated house costings

Margins are typically up to 20 percent for small-scale onsite-built housing while larger margins are used for factory construction to recover setup costs. These profit margins are net of materials and labour, are per build not per business, and will range with market conditions. They need to cover overheads associated with the business such as management, insurance, business services, finance etc. They also allow for a "normal" profit after all expenses. The margins cover both the builder and prefabricator, with most of the margin going to the prefabricator to cover setup costs. The modelling allows for the cost savings associated with quicker construction and assumes these savings are passed on to the owner. These savings are based on earlier work (Page, 2012).

A range of results are shown in Table 4. The dollar per square meter ranges correspond to the upper and lower profit margins in the table. The upper margin for each option was chosen so that the cost of the house was the same in all four options. The lower margins are believed to be a bare minimum to cover most overheads, but only for a short time in the expectation of a recovery in demand.

A.5.3 Results and discussion – prefabrication economics

The results of this part of the work indicate that the four options have similar costs at the two extremes used for the margins. At the lower profit margins the hybrid/module option is slightly cheaper than the others. Insufficient data is available to say what the margins need to be to recover costs in the prefabrication options, so we cannot give a definite answer as to which option is cheaper. Readers could look at the upper margins and ask themselves if they can make a business work at lower margins, in which case they may have a cost advantage over other options.

These higher profit margins are necessary to cover the increased investment in plant required for the bulk construction of prefabricated construction systems. The implication of the larger volume throughput possible in prefabricated construction is that profit margins could be reduced and that these savings could then be passed on to the customer, provided that demand was sufficient to sustain higher production levels.

A.6 Greenhouse gas emissions – Case study

This section assesses GHG emissions as a result of the construction of prefabricated and traditional site-built variants of the same 120 m² house, as set out in Section A.3.2.

A.6.1 Results summary – GHG emissions

Cradle-to-site GHG emissions attributed to the 120 m² house are based on the four different construction approaches as in Figure 24.

These results show that the GHG emissions due to the construction of the sample house with the three prefabricated approaches are lower (up to 15 percent) than the site-built option, although the uncertainty in data used for this study means that this difference is only marginally significant.

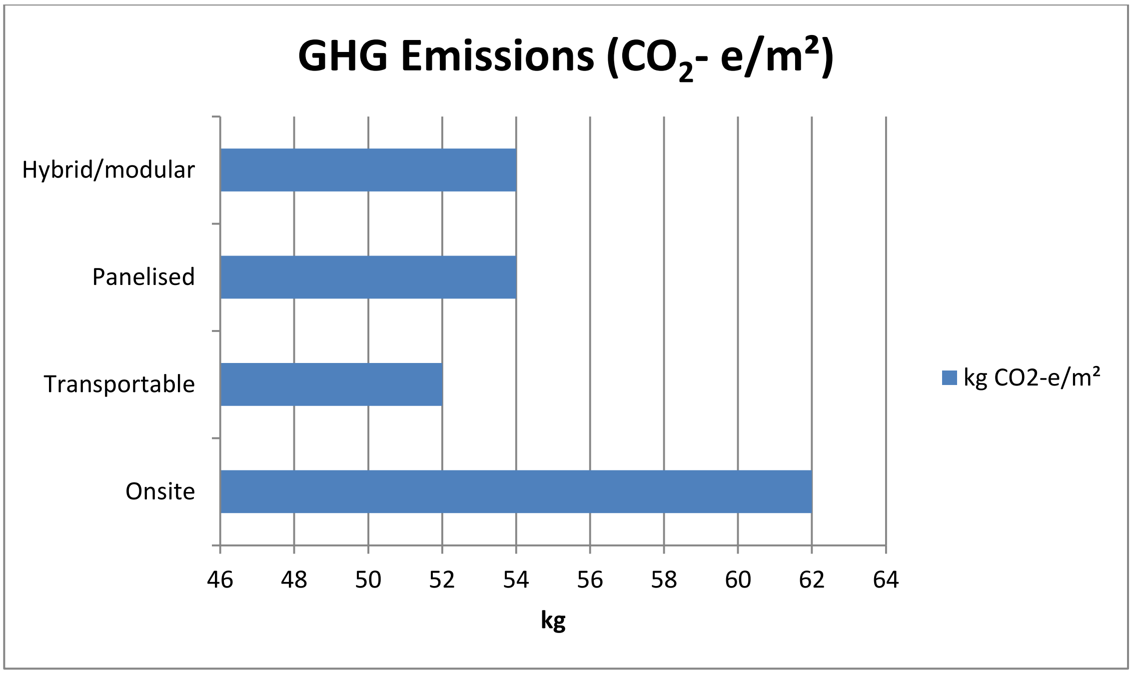


Figure 24: GHG emissions from the construction of the 120 m² case study house

A.6.2 Method – Prefabrication GHG emissions

There are numerous national and international standards that have application to GHG emissions from products and systems. However, the PAS 2050 (BSI, 2011) was chosen as being the most applicable. This is because it specifies system boundaries and a functional unit, which fit the scope of this study.

The standard ISO/WD 16745 (ISO, 2012) uses the metric of carbon as a yardstick for the GHG emissions of building and construction activities, and would have been more applicable. However, this is still in draft, so is not used.

A.6.3 System boundaries

PAS 2050 (BSI, 2011) requires the establishment of system boundaries, which are defined in EN 15643-2:2011 (EN 15643, 2011) as the "Interface in the assessment between a building and the environment or other product systems, which defines what is and what is not included in the assessment".

The boundaries used in this study are set as cradle-to-site, which (as per those highlighted in Figure 25) includes:

- The product stage (raw materials and the manufacturing of product), and
- The construction process stage (distribution and the building site installation processes).

The use (operation) phases and end-of-life deconstruction or recycling is not included in this work. The choice to locate the system boundaries as in Figure 4 and to truncate the assessment at the site presents a particular view of the GHG emissions, which disallows direct comparison of these results with other studies that include a larger proportion of the life cycle – i.e. operational and end-of-life processes. This means that the proportions of GHG emissions from such unit processes as manufacture and transport are higher than if the system boundaries had incorporated use, maintenance and end-of-life processes. This approach serves to highlight smaller differences between these processes than would otherwise be evident – which has the danger of magnifying differences that are potentially insignificant. Recognising this danger, the boundaries are applied carefully.

> ... the boundary of the study is set at the completion of the building ... which highlights the differences between the construction emissions from each approach ...

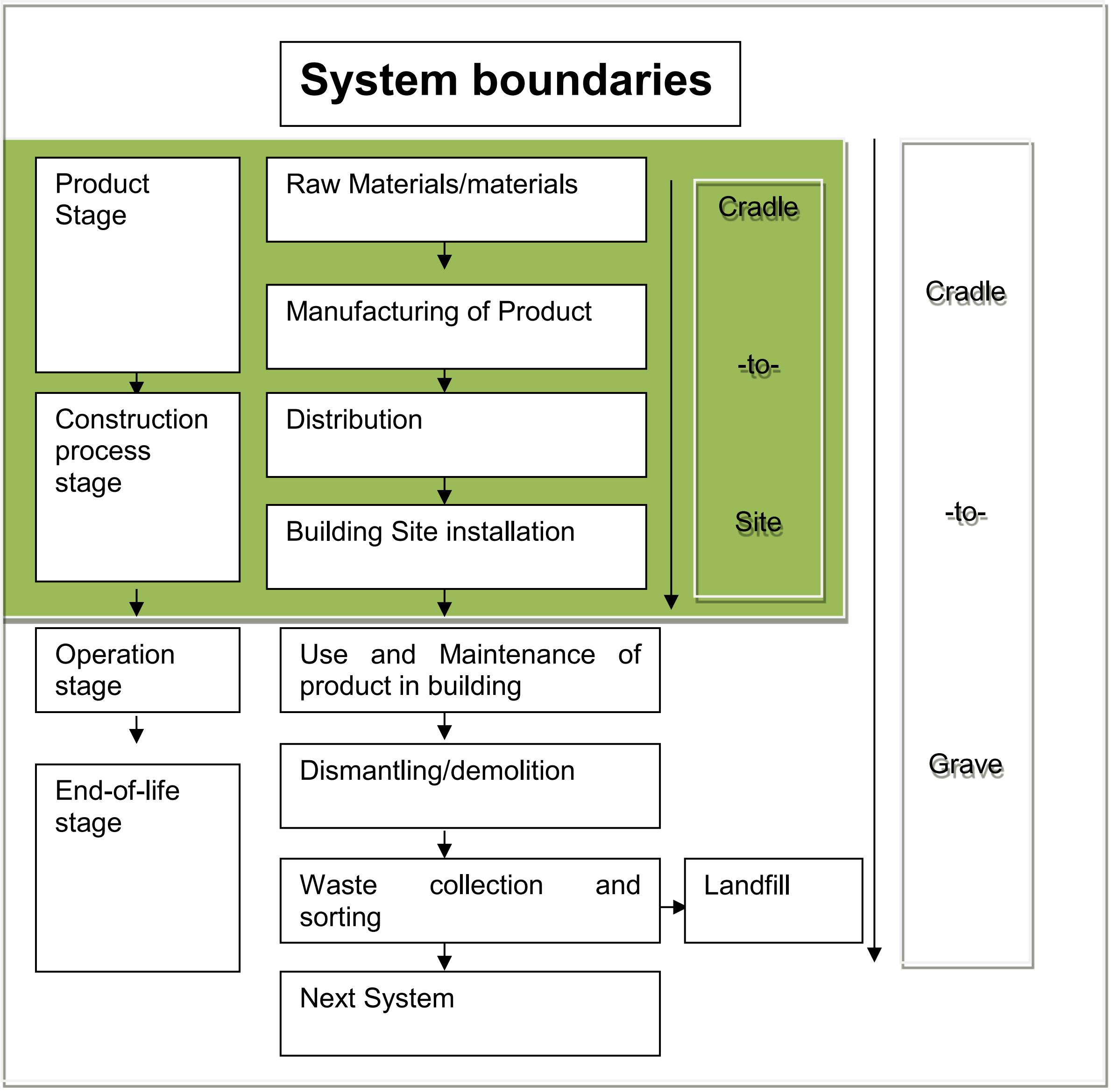


Figure 25: System boundaries used for this study

A.6.4 Inclusions/exclusions

GHG emissions through the life cycle from the extraction of materials to the opening of the building for use, are assessed and included. These are considered under the following headings:

- Embodied emissions.
- Transport of materials and systems.
- Construction process emissions.
- Emissions from waste – transport and landfilling emissions.

Excluded from the construction process is:

- The provision of infrastructure and capital goods such as roads, trucks, machinery etc, was not considered, as impacts were estimated to be negligible (Frischknecht, et al., 2007) and this coverage is not required by PAS 2050 (BSI, 2011).
- Internal services which are assumed to be identically-replicated in all four options, include:
  - Lighting.
  - Power supply.
  - Potable water.
  - Fixed appliances including hot water, cooking, space heating etc.
  - Non-fixed appliances.
  - Entertainment systems.

These elements are omitted as they were from the Beacon assessment of the Waitakere NOW home (Drysdale & Nebel, 2009) with the following reasoning: “The embodied impacts of building systems that provided a service such as electricity, lighting, extractor fans, solar hot water system etc, have been excluded ... because the decision to select these service systems is not governed by the materials that compose them but by the desire for the system and its benefits. In other words, installing these systems is less subject to material choices.” (Collins & Blackmore, 2010). Therefore, they are not relevant for our purposes.

- The GHG emissions due to the provision of human labour are excluded, as required by PAS 2050 (BSI, 2011).
- No consideration is made for the GHG emissions arising from the planning and consenting process (due to the definition of the boundaries of the study).
- The GHG emissions arising from the materials and manufacture of any packaging that is used to deliver the materials to site, are not included as these are different for different quantities of materials and means of delivery, which may have unfairly advantaged one of the options.

A.6.5 Functional unit

Definition of the “functional unit” is required by PAS 2050 (BSI, 2011), which is “the quantified performance of a product system for a building product that is used as a reference unit”.

In this case the functional/reference unit is provided by:

- The complete construction of a 120m² house, to receipt of code compliance certification and hand-over, to the specification provided for the KHH Ltd 120 m² “First Choice” house.

A.6.6 Data

A “bill of ”materials” was provided by KHH Ltd for the assessed house, as well as information on modes and distance materials were transported.

Materials necessary to ensure a construction compliant with the New Zealand Building Code (DBH, 2013) include[20]:

- Timber wall, floor, sub-floor and roof framing.
- Sub-floor concrete for pile foundations.
- Fibre cement weatherboard wall cladding.
- Longrun metal roof cladding.
- Aluminium exterior windows and doors.
- Timber-based interior doors and metal hardware.
- Soffit and fascias.
- Paint for interior and exterior surfaces.
- PVC rainwater system.
- Timber-based interior joinery.
- Fibreglass insulation to walls and ceiling, and polystyrene to underfloor.
- Timber piles.
- Plasterboard interior ceiling, wall linings and stopping.
- Timber-based kitchen joinery.
- Timber-based sheet flooring.
- Metal fixings and hardware.

The only difference in the materials used to construct the various prefabricated options were due to wastage rates.

A.6.7 GHG emission metric

[20] Given commercial sensitivities, the complete schedule of materials is unable to be released.

The metric for GHG emissions of mass of CO_2-e has been used in this work, as it is required by PAS 2050 (BSI, 2011). While it also aligns with the metric used for reporting against the obligations that New Zealand has under the Kyoto Protocol (UN, 1998), the two processes are independent.

A.6.8 Embodied GHG emissions

A measure of the embodied CO_2-e in a material or system refers to the quantity of gases which contribute to global warming (greenhouse gases) required to make and transport that material or system; from the extraction and processing of natural resources to manufacturing, transport and product packaging. Embodied CO_2-e is the "front-end" component of the life cycle impact of a material or item and typically is concerned with the life cycle extending from the cradle (source) to having the material ready for market at the factory gate.

A.6.9 Emission factors

A representative emissions factor can be developed for any particular product or system in accordance with PAS 2050 (BSI, 2011), which provides an assessment of the typical GHG emissions that the creation/use of that product or system is responsible for. These include the embodied emission factors as well as emission factors from systems and processes throughout the life cycle, within the boundaries of the study. Standard procedures to govern the development of emissions factors are under development[21]. However, debate remains about the attribution of GHG emissions for the amount of CO_2 that is incorporated in materials through natural processes. Of particular significance in New Zealand is the use of harvested wood products (HWPs) in housing and how the CO_2 is captured from the atmosphere as a tree grows.

> ... standard processes to govern the development of emissions factors are under development ...

A.6.10 Biogenic carbon

PAS 2050 (BSI, 2011) requires that any biological sequestration of CO_2 (biogenic carbon) be included in the emission factors. There is dispute among the building materials providers regarding the inclusion of biogenic carbon in GHG emission factors given:

- Including biogenic carbon attributes a significant benefit to HWPs and penalises materials such as concrete, as the sequestration of carbon in concrete through carbonation is not recognised (Haselbach, 2009). However, this study is not comparing timber and concrete, but is interested in non-renewable emissions, so the impact is not material.

[21] Currently there is no international standards method. However, processes such as the National Footprint Accounts' underlying methodology and framework (Borucke, et al., 2013) provide some useful guidance.

- GHGs emitted during harvesting, transport and processing operations are granted a positive number, and typically reduce the size of the larger negative number being the emission factor attributed to timber to account for biogenic carbon.

Figure 26 shows the proportion of embodied emissions that are within the various construction elements, which are the same for all the prefabricated construction systems. This house includes a light timber frame, timber-suspended floor on concrete piles, cement-based cladding and longrun steel roof, as detailed in Section A.4.

A.6.11 Biological carbon sequestration (biogenic carbon)

Trees effectively absorb carbon as they grow, where chemical processes convert atmospheric carbon dioxide and water into simple sugars through photosynthesis.

> ... biogenic carbon from trees is released when the timber from the trees decays ...

About 50 percent of the dry material in the main commercial timber species (*Pinus radiata L*) is carbon – this is largely in the form of cellulose (about 65 percent) and lignin (about 30 percent) (Garrett, 2009).

When trees are harvested, the harvesting operations are responsible for the emission of GHGs together with the transport, processing and treating of the timber that is associated with the conversion from tree to HWP.

The biogenic carbon from *P. radiata* is also released when the HWPs from the trees decay (insitu or in landfills), are eaten by insects, burnt or are subject to other chemical processes. Depending upon the process, the carbon may be released back into the atmosphere immediately (gaseous oxidation products from a fire) or over a longer time period if the biological material is incorporated into other organisms (eaten by borer and respired back to the atmosphere), transforms in a fire (solid carbonaceous materials incorporated in ash), is buried in a landfill (where methane may be a decomposition product) or becomes forest debris and humus.

Consequently a greater mass of CO_2-e can be released from landfill decomposition of both treated and untreated timber than is actually buried – in our case it is 1.3-times the mass of the timber over the 100-year assessment period[22].

[22] This factor comes from the application of the New Zealand landfill model (ERM, 2011).

The New Zealand construction industry makes significant use of the HWPs that have raw materials originating from forestry, particularly in the domestic construction sector where the BRANZ new dwellings' survey (Page & Curtis, 2011) shows that 93 percent of framing used in domestic construction is timber.

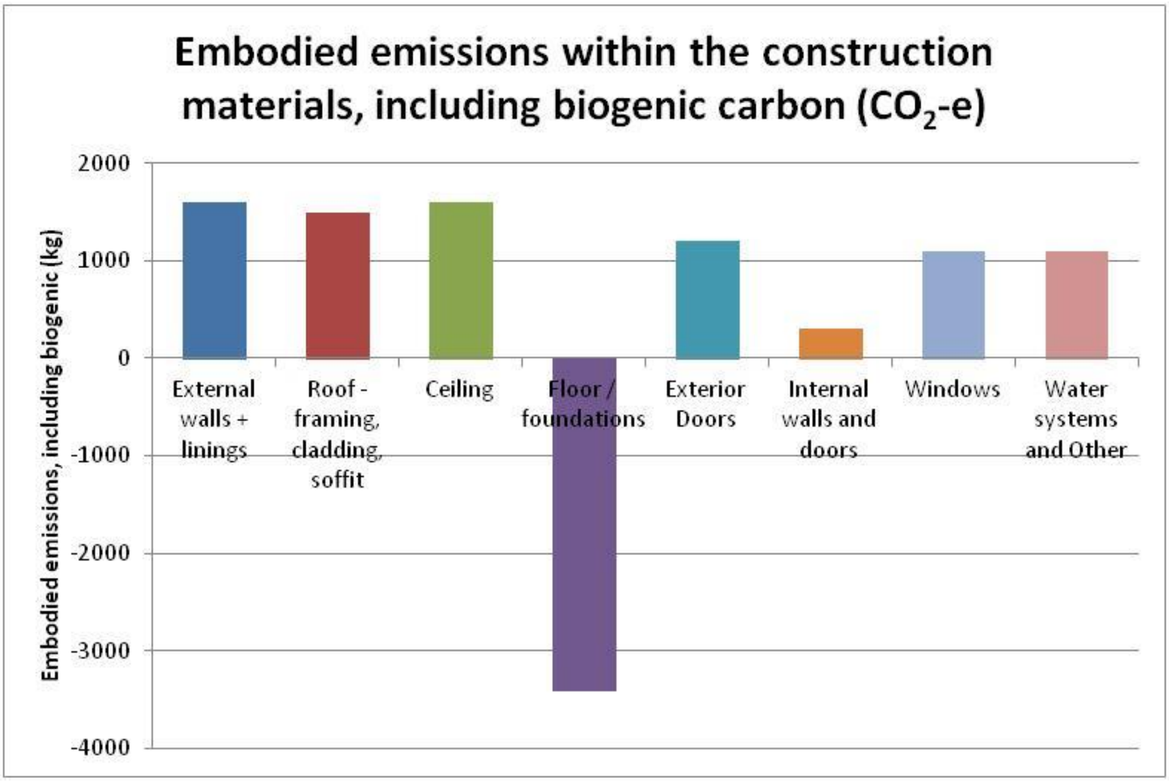


Figure 26: Material and system contributions to the proportion of GHG emissions in the 120 m^2 house, for the cradle-to-gate (factory) assessment

The effect of biogenic carbon can be seen in the large negative value of the floor and foundations. While some concrete is used around piles, the predominance of HWPs means that a suspended timber floor has sequestered large amounts of carbon. All other components have positive values, meaning that the negative effects of any HWPs are offset by the positive values of other materials, such as PVC and metal.

A.6.12 Sources of emissions factors

Where possible, emissions factors that were specific to New Zealand (Alcorn, 2010) have been applied and were used for over 95 percent of calculated emissions. When New Zealand-specific sources were not available, factors from the UK (DEFRA, 2008), EcoInvent (Doka, 2009) and the ICE database (Hammond & Jones, 2011) were employed.

While recognising that the non-New Zealand-sourced emissions factors are not geographically representative, given the small contribution to the total emissions, this is not viewed as being of significance. The emissions factors and sources of the emissions factors are listed in Table 5 where the factors in green have a negative emissions factor due to consideration of biogenic carbon.

Embodied GHGs in selected building materials				
Material	**Embodied CO_2**			
	By weight		**by volume**	
Aggregate	3	g/kg	4.5	kg/m³
Aluminium, extruded, anodised	16350	g/kg	44140	kg/m³
Building wrap	148	g/m2	0	kg/m³
Cement, average NZ	1025	g/kg	2000	kg/m³
Cement fibre board	725	g/kg	1030	kg/m³
Concrete block	112	g/kg		
Concrete 17.5 MPa	118	g/kg	280	kg/m³
DPM, Damp Proof Membrane	172	g/m2		
Electricity, average, NZ (MJ/MJ)	67	g/MJ		
Glass, float	1740	g/kg	4370	kg/m³
Glass, toughened	2450	g/kg	6180	kg/m³
Gypsum plaster board	470	g/kg	450	kg/m³
Insulation, fibreglass	770	g/kg	37	kg/m³
Insulation EPS, (Expanded Poly Styrene)	2500	g/kg	60	kg/m³
MDF, Medium Density Fibreboard	650	g/kg	500	kg/m³
Nails, galvanised	1750	g/kg		
Paper - wall paper	1,930	g/kg		
Paint, water-based	1640	g/kg	2130	kg/m³
Polyurethane wet area wall lining coating	3000	g/kg		
PVC, extruded, (Poly Vinyl Chloride)	4349	g/kg	5784	kg/m³
MEK, (Methyl Ethyl Ketone)	5000	g/kg		
Steel roofing 0.55mm, factory-painted	10,600	g/m2		
stainless steel	5457	g/kg	44747	kg/m³
Timber, kiln-dried, dressed, treated			-533	kg/m³
Timber, glulam, LVL			-552	kg/m³
HDPE	3447	g/kg	3257	kg/m³
LDPE	140	g/kg	4.7	kg/m³

Table 5: GHG emission coefficients

Sources were the following:

- For New Zealand-specific GHG emissions factors, the PhD thesis and allied work undertaken by Alcorn (Alcorn, 2010).
- For local transport fuel emission factors, additional information was extracted from information published by the Ministry for the Environment (MfE, 2011).
- For the GHG emissions factors from maritime transport, values from the Department for Environment, Food and Rural Affairs of the British Government (Defra, 2012) were used.

- The work of Hammond &Jones published as the Inventory of Carbon and Energy (ICE) ICE v1.6a (Hammond & Jones, 2011) provided emissions factors for polyurethane, PVC pipe, zinc and paper.
- For the GHG emissions encapsulated in building silicones, information was used from Eco-profiles of Silicones (Boustead, 2002).
- For the emissions associated with landfilled timber, the factors from the EcoInvent database (Doka, 2009) was used, as implemented in the New Zealand landfill model (ERM, 2011).

The GHG emissions embodied in the construction were then calculated by multiplying this emission factor by the weights and/or volumes of materials required to provide the assessed house.

The emissions factors that are sourced from the work of Alcorn (Alcorn, 2010) do not all include the emissions resulting from the management of waste streams, so are incomplete in this regard. However, they are retained as having geographically-relevant emissions factors is highly valued.

A.6.13 Transport GHG emissions

These emissions encompass all transport of materials and products from the manufacturer's (factory) gate through to the construction site. In the case of prefabricated options, this includes transport of materials and products to the yard where prefabrication activities take place, as well as transport of prefabricated products (walls, modules or whole house) to the construction site. For traditional construction, this includes transport of materials from factory gate direct to the construction site and in the case of onsite construction has been calculated without the intermediary of a building supplies merchant. The proportions of transport mode utilisation in Table 6 are in terms of quantity of GHG emissions from each source, with the emissions factors expressed in tonnes/kms. These represent the average GHG emissions from the relevant vehicle transporting typical loads for the case of the onsite construction both to the site and returning to the factory/warehouse. The values in Table 6 have been used as the basis for developing the emissions from the transport activities for other construction types.

Transport mode utilisation and emissions factor					
Vehicle	LGV	HGV	Sea	Air	Rail
Proportion	49%	47%	4%	0%	0%
Emissions Factor	0.54	0.13	0.013	-	-

Table 6: Emissions factors for transport of materials, services and goods. Sources: MfE, 2012; and Defra, 2008

Transport-related emissions arising in the supply chain leading up to the gates of manufacturers supplying materials and products for prefabricated or traditional builds, are included in embodied emissions factors used to represent these products – e.g. transporting of logs from forests to sawmills. The transport of waste is included in the waste chapter, Section A.6.18.

(Szalay, 2006) assessed that transport had a minimal contribution to the overall environmental impact of domestic construction, so did not specify actual travel distances for the delivery of materials, using an average of 50 km for all such deliveries. To assess the validity of that conclusion, this work has measured travel distances from manufacturers supplying materials and products to the KHH Ltd head office/yard/distribution centre in Mt Roskill, Auckland.

The transport of building materials is undertaken utilising many different forms of land and sea transport. For simplicity regarding land transport in New Zealand, heavy goods vehicles (HGVs) or light goods vehicles (LGVs) are used, applying emission factors from the MfE (MfE, 2012). Goods delivered from overseas are assumed to come via the most direct sea shipping route, using GHG emissions factors on a tonnes/kms basis (DEFRA, 2008).

A.6.14 Transport of completed building

This assessment is based on transport from the location of the nine KHH Ltd construction facilities in the North Island, using a population distribution function, where KHH Ltd sites are located in industrial areas often within 5 km of building merchants. The calculation of the representative distance serviced from each KHH Ltd facility is therefore derived in this work by inspection, as shown in Equation 1.

$$\mathrm{D_w} = \frac{1}{P_T}\sum_{n=1}^{9}\left(\mathrm{D_{cn}P_{cn}} + \frac{\mathrm{D_{rn}P_{rn}}}{2}\right) \qquad \text{Equation 1}$$

Where:

D_r = half the distance to the next KHH Ltd facility by road or half the distance to the furthest coast served by road in the region, where it is assumed that the population density reduces with distance from the centre of the region, so a factor of 0.5 is appropriate.

Dc = the distance to the centre of the closest main urban area (where main urban areas are defined by Statistics New Zealand as having a population of over 30,000 people as of 2001).

Dw = the weighted one-way distance calculated by this equation.

Pc = population of the closest main urban area.

Pr = population of the surrounding region including the main urban area.

PT = total population of the regions, where all population data is from Statistics New Zealand, 2011.

> ... a transportable home is carried an average distance of 30 km from the factory to the final site ...

This assumes that there is a linear reduction in the population density with distance from major town/city in a region where a KHH Ltd facility is located. This provides a first-order estimation of the representative distance served by each KHH Ltd location, being the average distance that will be travelled by a heavy goods vehicle with a completed KHH Ltd transportable house. This approach provides the distance of D_w as 30 km, which results in transport GHG emissions of 25 kg (CO_2-e) for the delivery of each complete house, based on use of an HGV. Interestingly, this distance exactly matches the 30 km free delivery distance that KHH Ltd provided. For the road transport of the sized house assessed (120 m²), there are no requirements for a guide vehicle and therefore no associated additional transport emissions. However, the empty return journey of the HGV must also be assessed according to the rules in PAS 2050 (BSI, 2011).

The same assumptions that were used to derive D_w for the completed building hold true for the transport of panels and modules from their manufacturing location to the building site. Hence $2.D_w$ can also be used for this distance, for which an HGV is employed.

Emissions from the distance travelled by mobile cranes are included in the construction emissions chapter, Section A.6.21.

A.6.15 Transport of other materials

KHH Ltd operates its own merchandising company, kitchen building and frame and truss manufacture, so all materials except for the windows and roof cladding are delivered on a single "B"-train to the yard from the KHH Ltd warehouse in Mt Roskill. Deliveries to the KHH Ltd warehouse are made from multiple suppliers. However, as each supplier delivery will service between five and 100 different builds, only this portion of the emissions are attributed to a single build, using an average of ten builds per supplier delivery to the KHH Ltd warehouse.

It is assumed that the panel and hybrid/module construction factories all have storage facilities at their factories/yards. However, as not all of the house can be built with modules or panels (see Section A.3.2) some of the materials must be brought to the site for inclusion in the construction – necessitating a larger number of supply trips.

Taking the known number of trips by HGVs and LGVs from the KHH Ltd delivery schedule from supplier to warehouse and from warehouse to yard, and using the figure of Dw as the one-way distance for a delivery together with the transport emission factors from MfE (MfE, 2012), provides values for the material transport GHG emissions, as shown in Table 7.

Transport emissions (CO_2-e)					
Type	Number of Material supply trips	Transport of materials (kg)	Number of component supply trips	Transport of major components (kg)	Total transport emissions (kg)
Onsite	28	420	1	1	421
Transportable	1	42	3	160	200
Panelised	12	190	5	50	240
Hybrid/modular	15	140	5	60	200

Table 7: GHG emissions from construction transport

This shows that the transport GHG emissions from a typical onsite construction are small (420 kg) compared to embodied emissions (5030 kg, being 8 percent), but are twice the GHG emissions from the construction of this building by the prefabricated methods. The sensitivity of these values to the assumptions is shown in Figure 27, where the onsite-build option emissions range from 420 kg to a more significant 840 kg. The transport GHG emissions for the transportable option, ranging from 200 kg to 350 kg, are best defined in the range of the panel with hybrid transport emissions less significant. This is largely due to the higher number of material supply trips required for the onsite build, where distance can make a large difference to the outcomes, whereas the prefabricated options have a lower number of material supply trips.

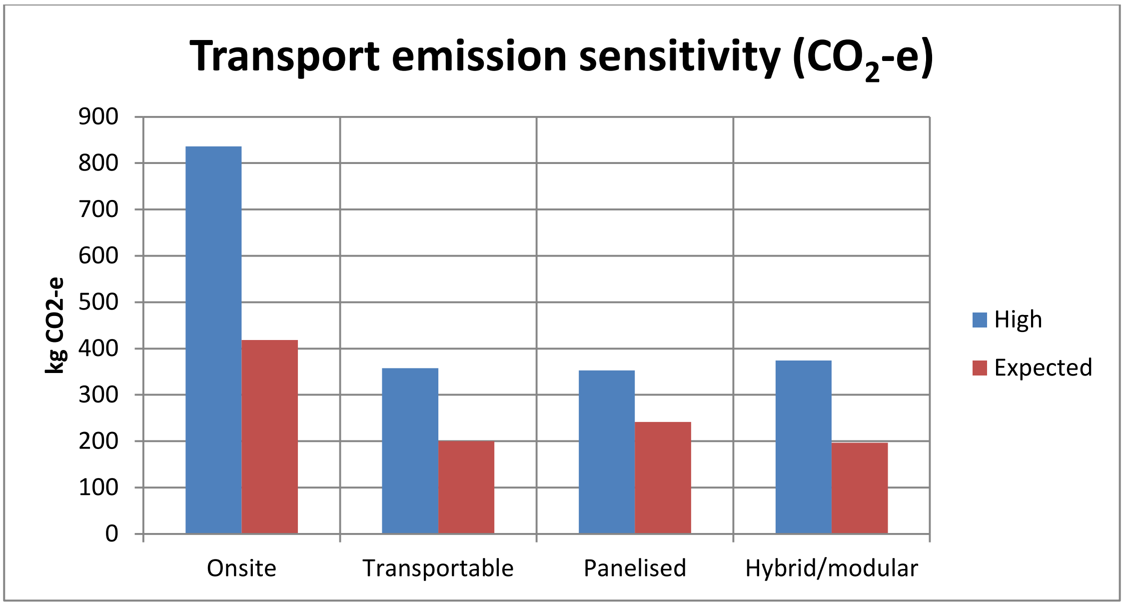


Figure 27: Sensitivity to assumptions of the transport emissions from the assessed options

A.6.16 Transport of labour/subcontractors

In accordance with the guidance of PAS 2050 (BSI, 2011), the GHG emissions related to the regular commuting of labour to and from the site are not included in this assessment, unless this is associated with material deliveries.

A.6.17 Construction GHG emissions

Construction and assembly processes producing GHG emissions from the construction of a house include the following:

- Waste, see Section A.6.18.
- Site preparation, see Section A.6.20.
- Construction fuel use, see Section A.6.21.

A.6.18 Waste stream management

Prefabricated construction has the benefit of enabling material sizes and quantities to be better optimised to minimise waste by specifying construction dimensions to make best use of the available material sizes. This minimises both the materials required and the waste produced from the offcuts and unused materials, with associated efficiency gains. However, it requires detailed design, high levels of specification and accurate planning and recording, which may introduce a cost-premium and a trade-off between material and time costs.

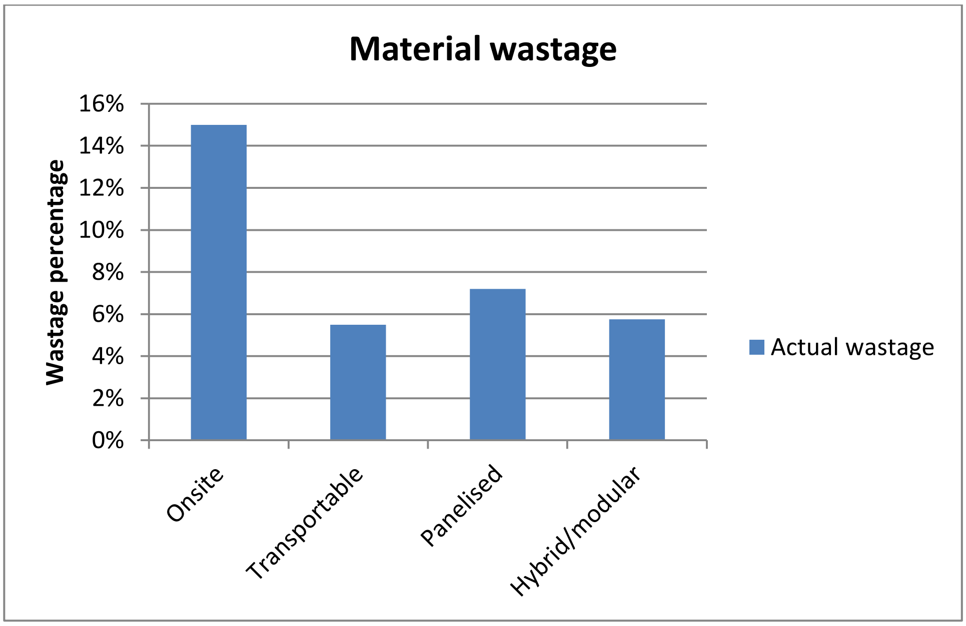


Figure 28: Wastage rates by construction approach

Figure 28 shows that typical onsite construction has 15 percent material wastage (BRANZ Ltd, 2011) mainly due to:

- Site cutting of timber, cladding and other building materials as buildings are not designed to suit standard material sizes.
- Inappropriate product application at design stage regarding irregular shapes and location of openings.
- The need to over-order to compensate for material defects, mistakes and to ensure that materials are available when needed.
- Rework due to lack of care taken in delivery, handling, storage, theft, cutting, fixing and protection after incorporation into the building.
- Reduced investment and accuracy in design and quantity surveying.
- Typical transportable construction in this work is assumed to have 5 percent waste in materials (CIRIA, 1997) while the construction of panels and hybrid/modules are assumed in this work to have a 2-3 percent material wastage rate[23] because:
- High design investment means that precise quantities and lengths of materials can be ordered in the sizes (or multiples of the sizes) needed and suited to the available material sizes.
- The factory/yard has other construction operations which can reuse offcuts.
- Mechanised and electronically-controlled cutting tables can optimise the use of materials.

[23] This wastage rate may be seen as low. However, according to discussions with New Zealand industry members, is achievable, particularly with mechanisation and CAD/CAM systems.

- Sensitivity analysis of the wastage rates for the panelised and hybrid/modular construction type[24], shows that the predictor variable (wastage rate) has a low importance for the response variable (waste emissions), therefore small changes in the wastage rate will result in little change in waste emission.

Of all the waste streams, the materials that cannot be reused in another construction operation or repurposed (e.g. timber used as firewood, stakes, shuttering, profiles, boxing etc), are sent to landfill. Only the HWPs degrade in a landfill over the 100-year period assumed in the PAS 2050 (BSI, 2011) assessment producing GHG emissions.

Where materials are found after purchase to be surplus to requirements and can be repurposed and included in the construction of different structures, then they are not counted as waste and not included in the assessment of embodied emissions (although their transport GHG emissions are still included). Hence, Figure 28 shows that prefabricated construction approaches that make use of bulk construction methods where materials left over from the construction of one unit are used in another unit, can have significantly lower waste volumes.

The figures in Figure 28 indicate that building panels and hybrid/modules are very efficient in terms of material utilisation, with these types of construction having a 2-3 percent wastage rate. However, a complete house (panel-build) only uses 60 percent open panels (roof, wall and floor) and 40 percent traditional construction, a hybrid house uses 50 percent modules, 25 percent open panels and 25 percent traditional construction, and a prefabricated construction still requires onsite foundation work and the connection of services so is actually only 95 percent constructed offsite.

The GHG emissions from waste generated onsite from the consumption and packaging of food for labourers has been excluded as they are related to anthropogenic work output and the boundaries of this system do not incorporate human energy.

A.6.19 Landfill emission

The emissions of GHG from landfills in New Zealand have been studied by the Ministry of Agriculture and Forestry (MAF)[25] resulting in the construction of a landfill disposal model (ERM, 2011) developed under the guidelines provided by the PAS 2050 (BSI, 2011) document.

Assuming that all waste construction timber is landfilled, the model is able to calculate the net emissions of CO_2-e over 100 years. The general processes are shown in Figure 29.

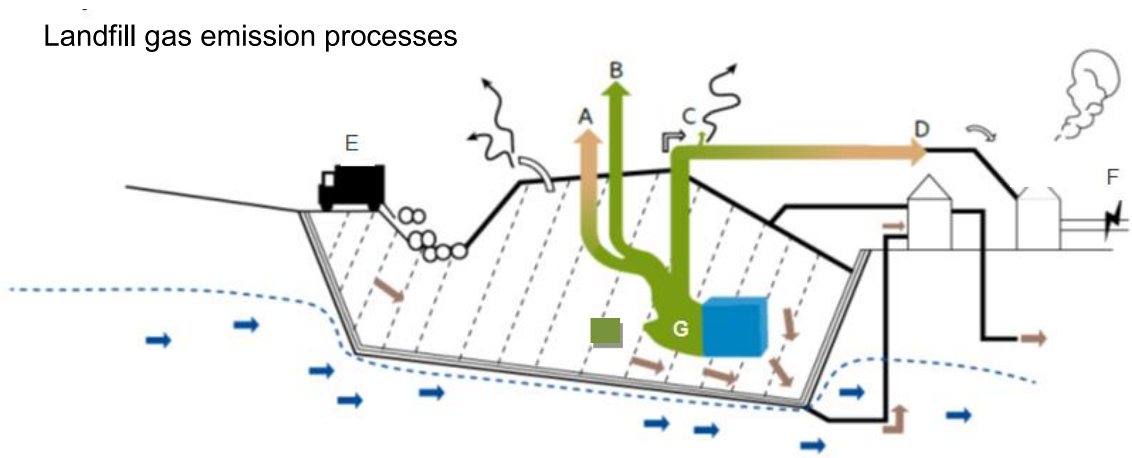
The assumptions used in the landfill model (ERM, 2011) include:

- Annex E of PAS 2050 (BSI, 2011) provides the equation to calculate the weighting factor for impact on radiative forcing due to time-distributed CO_2-e release over the 100-year analysis period – use of this factor is no longer mandatory, but provides considerably more accuracy in the calculations.

[24] When the wastage rate is double or halved there is a variation of only 20 percent in the waste emissions.

[25] In April 2012, MAF was amalgamated into the Ministry for Primary Industries (MPI).

- The timber has a decay rate which can be approximated as a linear relationship[26] over a 100-year period (PAS 2050) following a two-year latency period (McDevitt & Seadon, 2010).
- Timber in landfill releases 27 percent of its carbon over 100 years (Doka, 2009).
- 50 percent of the carbon is volatilised as CO_2 and 50 percent as CH4 (Ximenes, et al., 2008).
- 42 percent of the methane is captured and flared (or combusted to generate electricity) (ERM, 2011).
- Of the methane volatilised, 10 percent is oxidised to CO_2 as part of the methane anaerobic phase (Doka, 2009).
- Methane released is converted to CO_2 assuming the GWP of methane is 25 (BSI, 2011).



A: Landfill gas oxidised within cover layer and diffused as CO_2 to the atmosphere – 0.68 percent
B: Landfill gas diffusion to the atmosphere, CO_2 – 8.8 percent, CH_4 – 150 percent CO_2-e
C: Leakage of landfill gas collection
D: Landfill gas flared or combusted in a turbine or boiler – 4.9 percent CO_2
E: Deposition of organic materials
F: Export of energy from the system

Adapted from (EEA, 2006)

Figure 29: Landfill gas emissions processes – after EEA 2006

This means that for every kilogram of timber landfilled, there is a release of 1.3 kg of CO_2-e over a 100-year period from the landfill.

The waste emissions are sensitive to the assumptions about degradation rate in landfill. Alternative information to that imbedded in the landfill model from the European study (ERM, 2011) is provided from Australian data by (Ximenes, et al., 2008), New Zealand data (Alcorn, 2010) and USA data (Micales & Scog, 1996), which indicates there is not good agreement about landfill decomposition rates. If an

[26] Personal communication with SCION advised that while the decay rate will not be linear, this approximation will stand for this work.

alternative timber carbon release value of 17 percent (Ximenes, et al., 2008), 6 percent (Alcorn, 2010) or 3 percent (Micales & Scog, 1996) is used in place of the 27 percent value (Doka, 2009), the waste emissions from the landfilled timber for onsite construction drop from 1530 kg to 960, 320 and 180 kg. This is a variation over an order of magnitude and is shown in Figure 30. As we are not interested in the magnitude of the results, but only in the relative differences between the approaches (which does not change), this variation is not significant.

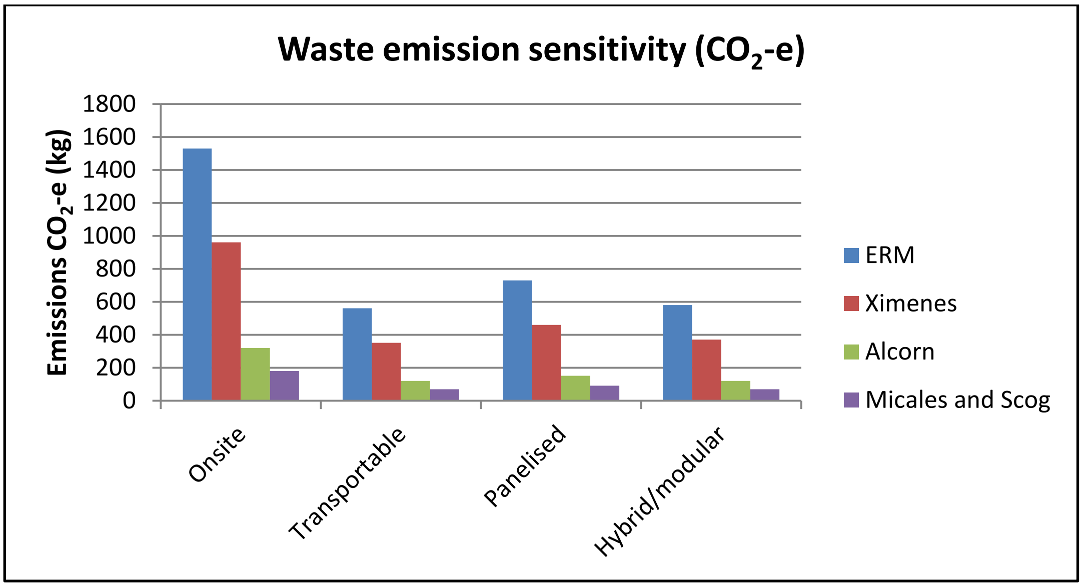


Figure 30: Waste emission sensitivity to HWP decomposition rate in landfill

The emissions from the transport of timber waste (and other waste) to landfill using the GHG emissions from Table 6 for HGV transport are shown in Figure 31, together with landfill gas emissions (ERM, 2011). The GHG emissions due to the transport of waste timber to landfill are insignificant (between 3-9 kg) they are included here for completeness.

A.6.20 Site preparation work

This work assumes the same preparatory site work requirements for all options, meaning that there are the same amount of GHG emissions from excavation and preparation, storm/surface water drainage, sewerage, potable water and the provision of electrical and information technology services[27]. While there is no differentiation between the emissions for each construction approach, the total is calculated below.

A.6.21 Construction fuel use

Construction transport is addressed in Section A.6.13, while the craneage, liquid and electric fuels are assessed in this section.

[27] While the USA has several guidelines for the reduction in GHG emissions on construction sites (as listed by Feniosky et al, 2011), New Zealand provides guidance at the level of waste stream management (BRANZ Ltd, 2011) rather than the level of GHG emissions.

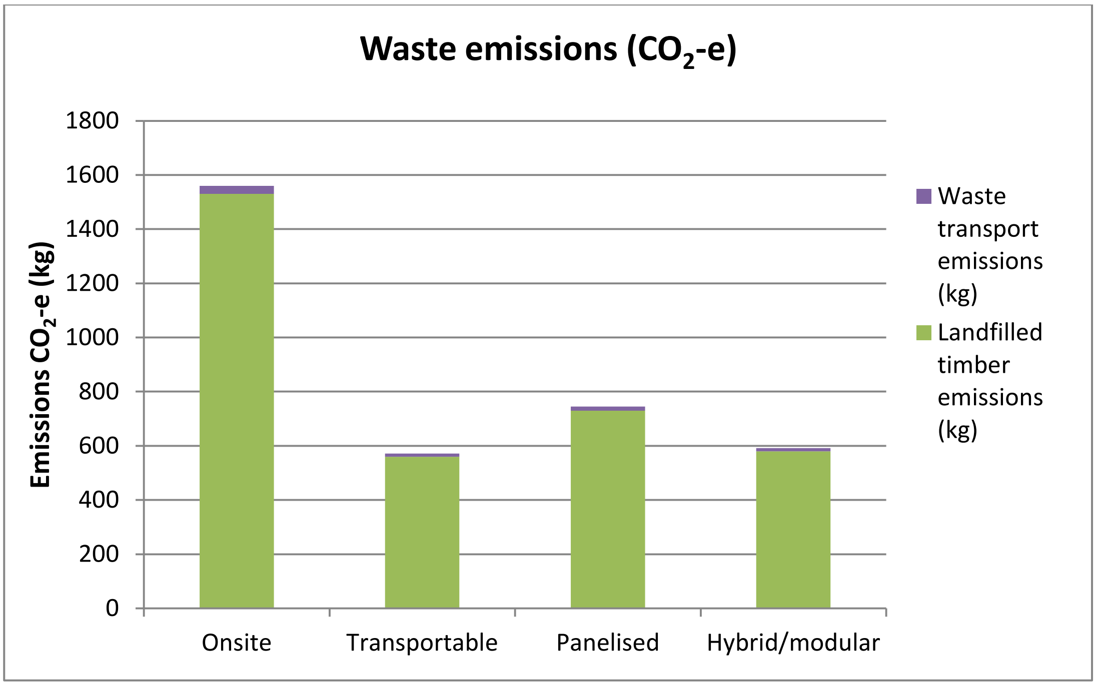


Figure 31: Emissions from waste transport and landfill gases

Liquid Fuels

An Australian study (Haynes, 2010) developed a model setting out the time/amount of use of varying types of construction equipment. Following consideration of the differences between Australian and New Zealand construction practices, this work assumes a half-day of operation of a petrol-fuelled small bobcat and a post-hole borer, then a further day of operation for the operation of diesel-fuelled concrete pumping and placing equipment, hiabs and miscellaneous diesel-fuelled operations. This results in GHG emissions from the consumption of 20 litres of petrol and 20 litres of diesel for the site work and foundation construction, totalling 100 kg CO_2-e. These are applied across all of the construction options.

Electricity

Typically a domestic construction site will have 230 V single-phase electricity available from a temporary power box installation until mains electricity is supplied to the house under construction. This fuel is used for handheld power tools, bench and mitre saws, a compressor and for heating, lighting and power for personal hygiene, access and refreshment facilities.

As no site measurements of fuel use (including electricity) were undertaken in this work, assumptions about the site utilisation of electricity have been made following discussions with the industry[28] as a measure of the differences in GHG emissions due to the use of site fuels and the timing of production activities in Table 8.

The number of days at each location is taken from the construction time values in Table 4.

[28] This includes anecdotal information and personal communications with residential builders and a prenail frame and truss supplier.

Construction emissions (CO_2-e)								
Prefabrication Type	Electricity at yard		Electricity at site		Diesel at yard	Diesel at site	Mobile Crane	Total emissions
	Utilised (%)	Time (Days)	Utilised (%)	Time (Days)	Fuel (l)	Fuel (l)	(Uses)	(kg)
Onsite	0	0	0.4	84	0	40	0	410
Transportable	0.6	69	0.6	3	10	40	0	500
Panelised	0.6	45	0.4	15	25	40	0	460
Hybrid/modular	0.6	50	0.4	15	20	40	2	640

Table 8: Comparison of the GHG emissions through construction site-related fuel combustion and use by prefabrication type

The assumptions (Haynes, 2010) include the use of single-phase, 15 amp, 240 V electricity for 40 percent of working hours (ten hours/day) for an onsite build, whereas an average of a single-phase supply for 60 percent of the time is used to construct panels. Haynes does not provide information about hybrid/modular or transportable options and none were available from KHH Ltd so the utilisation figures to build panels are used.

The emissions created by powder-actuated fasteners and other explosive devices are assumed negligible and are not included in the emissions calculation. Given the assumptions made, there is likely to be considerable error in the figures in Table 8. The data is provided to two significant figures, however is only correct to one significant figure. This is not a major problem as the total construction emissions (between 0.4 and 0.6 tonnes) are only around 10 percent of the total embodied GHG emissions (five tonnes) in this case.

Table 8 provides the figures calculated on the basis of the following information:

- The transportable house does not require a mobile crane, as suitable plant is available at the yard and the set-down at the site is performed with jacks.
- A heavy-lift mobile crane travels to the yard and then the site on two occasions to position the modules, also taking the panels for the hybrid/module build. The distance is taken as 30 km (see Section A.6.14).
- The emissions for the B-train carrying the modules and transportable unit are calculated in the transport chapter (Section A.6.13).
- The panels do not need a separate crane, but are positioned with a hiab on the delivery truck.

A.7 GHG emissions – Results

Using the method explained in Section A.6.8, Figure 32 displays the quantities of GHG emissions from a cradle-to-site analysis of the construction of the 120 m^2 house in the three prefabricated options in comparison to a traditional construction approach.

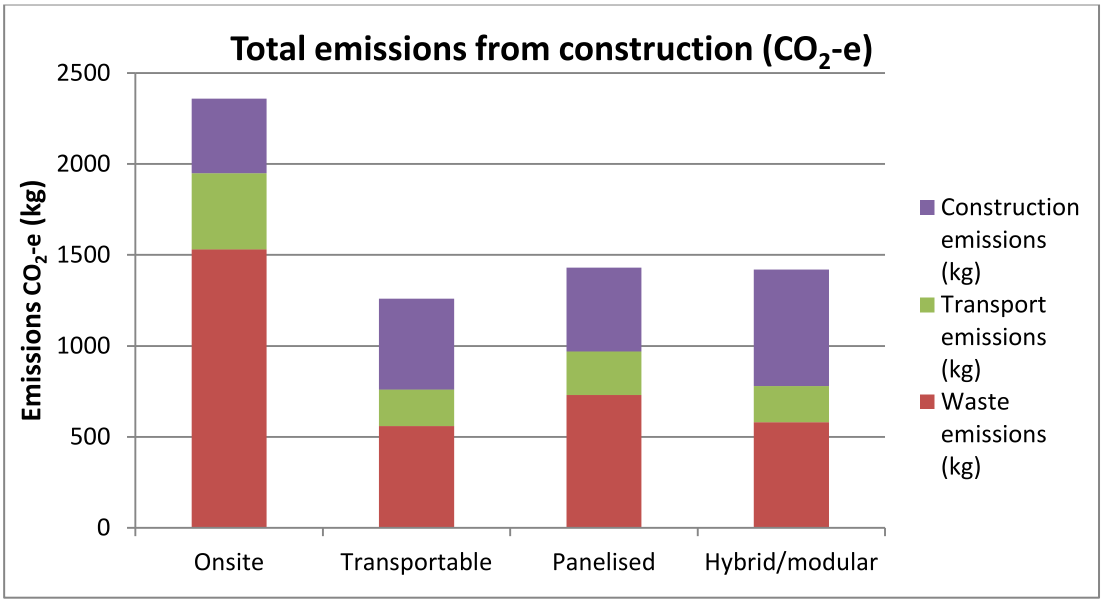


Figure 32: Overall GHG emissions by prefabrication approach

Each construction starts with the same materials, so all embodied emissions are the same (five tonnes). Between 60 and 70 percent of the GHG emissions are embodied in the construction materials and half of these are contained within the external cladding (walls, roof, windows and external doors). The next most significant contributor to embodied emissions is the foundation and flooring, constructed as a suspended timber floor. While material choices significantly impact the embodied emissions in construction, this work is concerned about construction, transport and waste emission differentials. Each construction type has different waste management processes, relies on different transportation requirements and includes different construction processes, which are all reflected in the GHG emissions in Figure 32.

> ... the onsite construction of the 120 m² house is responsible for the emission of 7.4 tonnes of GHG emissions, being 61 kg/m² ...

Adding the waste, transport and construction emissions to the embodied GHG emissions provides the total GHG emissions in Figure 32 that are attributed to the different prefabricated construction approaches.

The onsite construction of the 120 m2 house is responsible for the emission of 7.4 tonnes of GHG emissions, being 61 kg/m² of interior floor area (without garage) using the traditional site build approach. This reduces to 6.3 tonnes (52 kg/m²) for the transportable offsite prefabricated approach and to 6.5 tonnes for the panelised and hybrid/modular approaches.

This compares to a small house (88 m²) in the UK (Monahan & Powell, 2011) where with masonry cladding (and structure) the embodied carbon totalled 35 tonnes, being

405 kg/m². When a prefabricated larch cladding was used the embodied carbon dropped to 270 kg/m², reflecting the lower embodied carbon figure in timber, but also still being penalised by the use of a concrete raft floor and internal plastering.

Work performed in New Zealand by Beacon Pathway (Drysdale & Nebel, 2009) resulted in 11 tonnes of GHG emissions from construction (which included biogenic carbon and a concrete floor) giving a figure of 75 kg/m².

A.8 Conclusions – Case study

All of the offsite-based construction methods have lower total GHG emissions than the onsite-built house, constructed in the conventional manner; however, the differences are small.

The offsite construction of a transportable 120 m² house has:

- Up to 15 percent lower CO_2 -e emissions from the embodied, waste, transport and construction GHG emissions than the onsite construction of the same house.
- GHG emissions of between 52 kg/m² and 62 kg/m² of floor area, for the transportable construction and the onsite construction respectively.
- Capital costs that depend upon the internal rate of return required on the capital investment, but which are up to 12 percent higher than onsite building for the purchaser.
- Financial benefits for the manufacturer from greater levels of throughput, faster construction and higher margins.
- Up to 50 percent of the embodied emissions are contained in the exterior claddings of this lightweight house.

The work also found that:

- The typical distance that a KHH Ltd building is transported has been calculated from a population distribution function to be 30 km.

This means that there are GHG emission advantages from the utilisation of prefabrication in the construction of this simple house, although this could vary with increasing complexity and size of housing, together with the volume of production.

This work has shown that the major contribution to GHG emissions from the construction sector is from the embodied emissions in the construction materials that are chosen for the build.

Although not the purpose of this work, it is suggested that attention should now be turned towards the reduction of GHG emissions in construction, by:

- Reducing the use of construction materials with high levels of embodied GHG emissions – for example by encouraging the use of materials with low embodied emissions and disclosing the GHG emissions in a completed construction
- Reducing the amount of GHG emissions embodied in necessary construction materials – for example by investigating lower-energy processing or manufacturing methods for existing materials, or
- Reducing the environmental impact of embodied emissions – for example by identifying means of increasing the recycling and repurposing of materials in existing construction to displace the need for the production of virgin materials.

A.9 Assumptions – Case study

Limitations of this study include:

- The specific panelisation and modularisation information obtained from the industry – see Section A.3.2.
- The house performance is identical irrespective of construction method
- The economic parameters of throughput, profit margins and cost of time – see Section A.5.2.
- The boundaries of the study from the cradle to the occupancy of the dwelling – see Section A.6.3.
- The assumption that water use is not significant – see Section A.6.3.
- The implementation of PAS 2050 (2011) as the basis for the environmental assessment in this study – see Section A.6.3.
- The exclusion of the provision of infrastructure, utilities and fixed appliances from the analysis – see Section A.6.4
- The use of a single set of construction materials for all construction options – see Section A.6.6.
- The use of CO_2-e as the GHG emission metric – see Section A.6.7.
- The use of specific GHG emissions factors – see Section A.6.9.
- The inclusion of biogenic carbon – see Section A.6.10.
- The derivation of the “weighted distance” for transport emission comparison – see Section A.6.14.
- The interpretation of industry information about material transport requirements – see Section A.6.15.
- The exclusion of anthropogenic emissions from labour and the transport of labour – see Section A.6.16.
- The choice that site preparations are the same for each prefabricated option – see Section A.6.17.
- The embodied energy coefficients of window components have been added to provide emission factors for complete windows, as the factory-added GHG emissions from the construction of window systems are not available. The same windows have been used in all four scenarios, so there will be no effect on the GHG emission differentiation, but they will affect the total GHG emissions.
- Assumptions about material wastage and repurposing obtained from industry contacts – see Section A.6.18.
- The assumptions about site fuel usage variation based on construction time – see Section A.6.21.
- This is not a full LCA study or carbon footprint and the system boundaries are detailed in Section A.6.3.

APPENDIX B REFERENCES

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APPENDIX C PREFABRICATION SHARE IN BUILDING MODELLING

Prefabrication by component Year ending December 2012				
	Component as % of total value of bldg (1)	Percent of bldgs with prefab component (2)	Total consent values $M/yr (3)	Prefab $M/yr
New residential			4816	
Component				
Wall frame prefab	17%	94%		772
Roof trusses	6%	95%		275
Wall clad (AAC panels)	9%	4.4%		19
Solid wood house	85%	1.7%		70
Transportables (4)	92%	1.2%		53
Metra panel houses	40%	0.2%		4
Light steel frame	15%	4.4%		32
Modules (5)	50%	0.1%		3
			New residential total =	1227
			New housing prefabrication share=	25%
Housing A&A			1188	
Wall frame prefab	15%	80%		143
Roof trusses	5%	70%		42
			Residential A&A =	184
			HousingA&A prefabrication share=	16%
Non-residential bldgs		% of total cost of bldg that is prefabricated (2)	$M	
Hostel		6%	67	4
Motel/hotel		11%	109	12
Health		0%	373	1
Education		9%	495	47
Social/cult		3%	358	12
Retail		4%	668	25
Office		16%	746	123
Warehouse		14%	269	36
Factory		2%	529	12
Farm		10%	238	23
Miscell		3%	40	1
			3891	297
Modules (eg education, hotels) (5)		0.5%		19
		Total non-res bldgs =	3891	316
			Non-residential bldgs prefabrication share=	8%
		All bldgs total	9895	1727
			Pre-fabrication as a % of all buildings value =	17%

(1) Source: Rawlinson Construction Cost Handbook
(2) Source: BRANZ Materials Survey
(3) Consents values for the year ending Oct 2012. Statistics NZ
(4) From an analysis of a few months of Whats-On datasets
(5) Modules share for residential and non-residential is a BRANZ estimate and is very approximate

Table 9: Prefabrication share in building works economic modelling

APPENDIX D PREFABNZ TOOLKIT

The PrefabNZ toolkit is located on the PrefabNZ website at the following location (http://www.prefabnz.com/Community/Wiki/).

The developers' manual for the toolkit is included below.

D.1 Preface – PrefabNZ toolkit

The purpose of this document is to document the development of the PrefabNZ toolkit, an Excel-based prefabrication calculator. This document gives an overview of the function of the tool, as well the internal structure, including Visual Basic for Applications (VBA) code.

The toolkit was initially developed in summer 2011/12 by Kade Motley and John Burgess at BRANZ for PrefabNZ with support from Victoria University of Wellington. Further updates were performed by Alexander Kane and John Burgess at BRANZ in March 2013.

All sheets are protected with the password: pr3f@b&BRANZ.

D.2 Objective of the tool – PrefabNZ toolkit

The user enters basic details of a proposed house and the tool will make recommendations as to what type of prefabrication techniques are feasible for the project and provide an overview of the time, financial and environmental advantages of using prefabrication over traditional construction.

D.3 Overview of worksheets – PrefabNZ toolkit

There are six worksheets available to the user, another three can be brought up as reference when necessary and four are hidden from the user which are used by the developer.

D.4 User Interface worksheets – PrefabNZ toolkit

- Home Page
- Site
- Structure
- Construction
- Results
- FAQ

D.5 Reference worksheets – PrefabNZ toolkit

- EQ regions

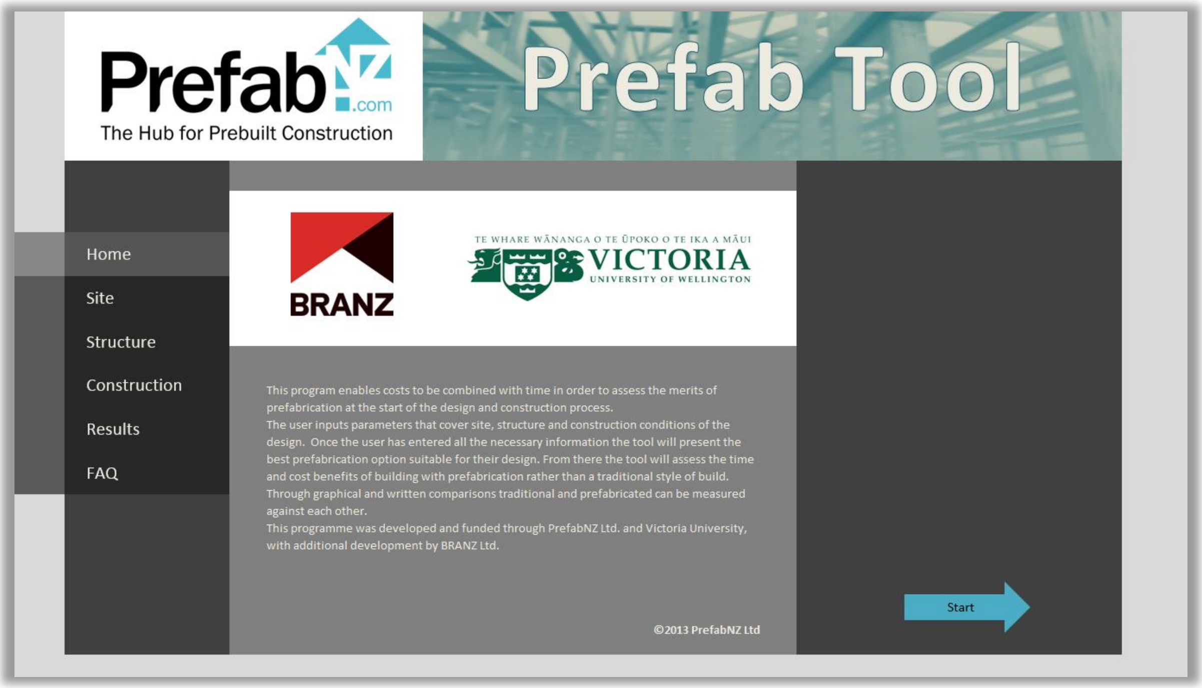
- Exposure map
- Wind regions

D.6 Developer worksheets – PrefabNZ toolkit

- text_sheet
- print_sheet
- data_sheet
- tracking_sheet

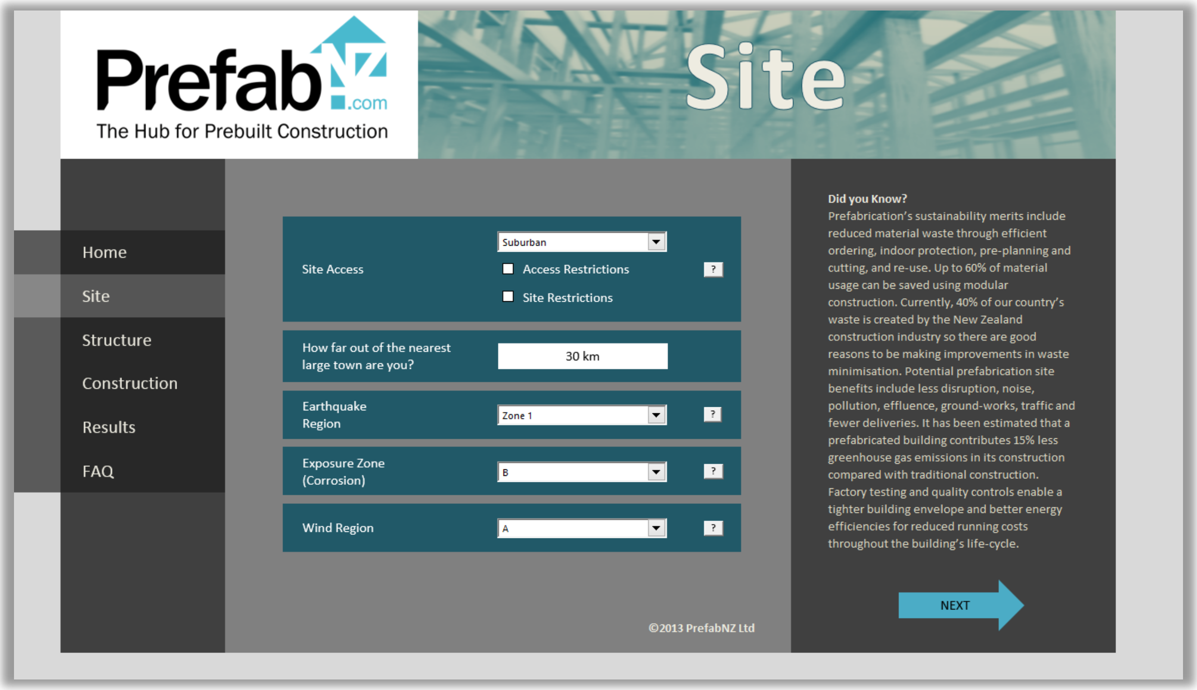
D.7 User interface worksheet content – PrefabNZ toolkit

D.7.1 Home page



Displays the PrefabNZ, BRANZ and Victoria University logos and textual information about the tool.

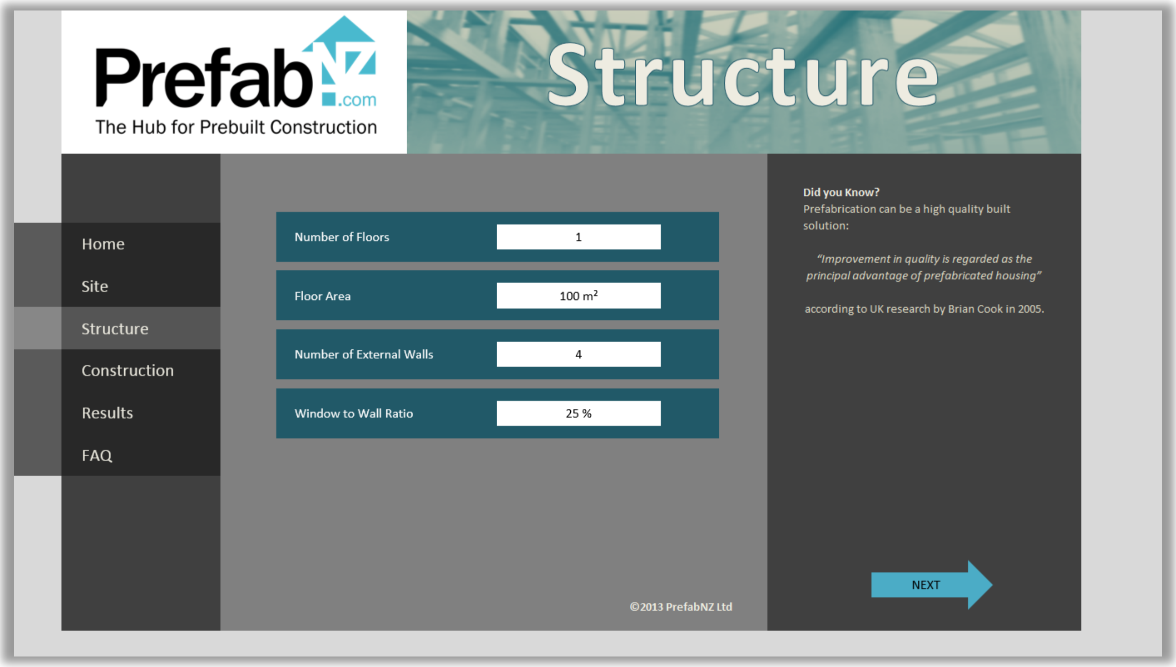
D.7.2 Site page



"Did you know?" box on the right.

- Main panel has user input for:
- **Site access**: dropdown (Urban, Suburban, Rural), two checkboxes (Access Restrictions, Site Restrictions) and a help button (info_site_access popup)
- How far out of the nearest large town are you: button (brings up enter_Distance popup to enter distance in km)
- **Earthquake region**: dropdown (Zone 1, Zone 2, Zone 3) and a help button (info_eq_region popup, contains button to take user to EQ Regions page)
- **Exposure zone** (Corrosion): dropdown (B, C, D) and a help button (info_exposure_zone popup, contains button to take user to Exposure Map page)
- **Wind region**: dropdown (A, W, Lee Zone) and a help button (info_wind_regions popup, contains button to take user to Wind Regions page)

D.7.3 Structure page



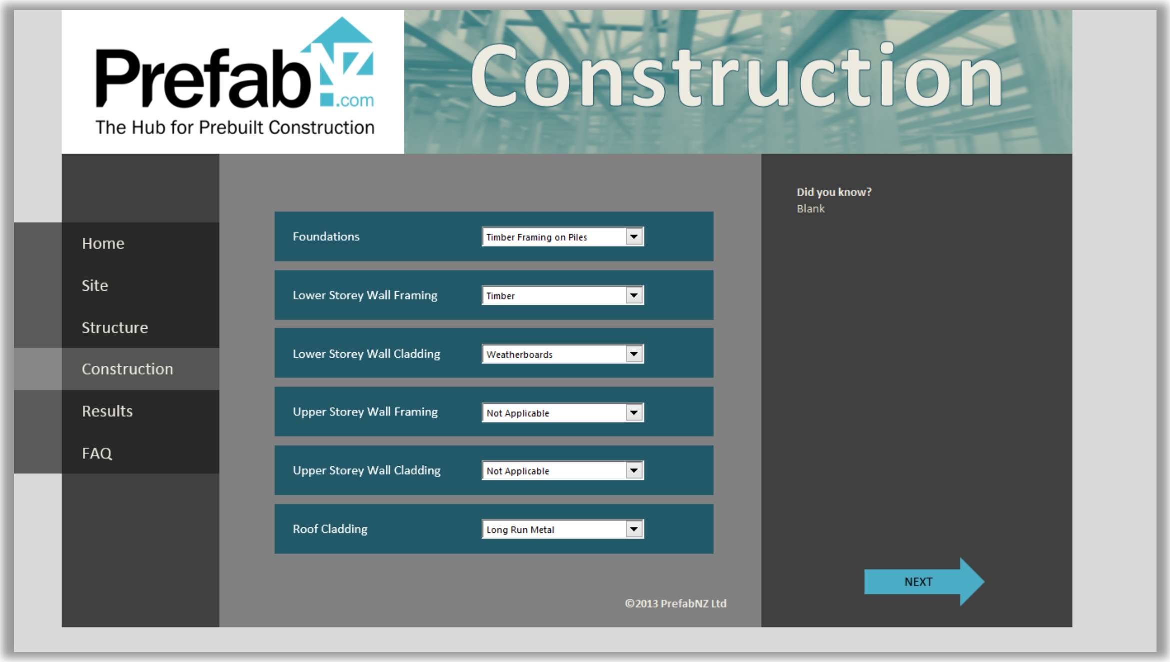
"Did you know?" box on the right.

Main panel has user input for:

- Number of floors: button (brings up enter_no_of_floors popup to enter number [1-3])
- Floor area: button (brings up enter_floor_area popup to enter number [10-300])
- Number of external walls: button (brings up enter_external_walls popup to enter number [4-20])
- Window to wall ratio: button (brings up enter_window_ratio popup to enter number [0-50])

If a number is entered outside the required range then an alert will appear to advise the user and the number will be adjusted to the nearest acceptable value.

D.7.4 Construction page



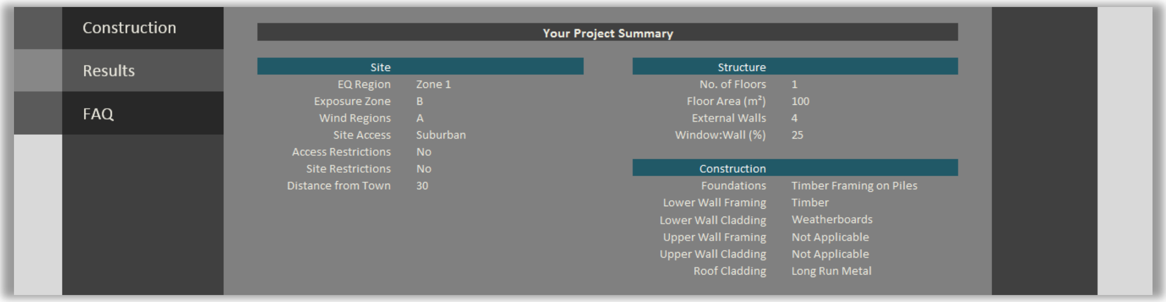
"Did you know?" box on the right.

Main panel has user input for:

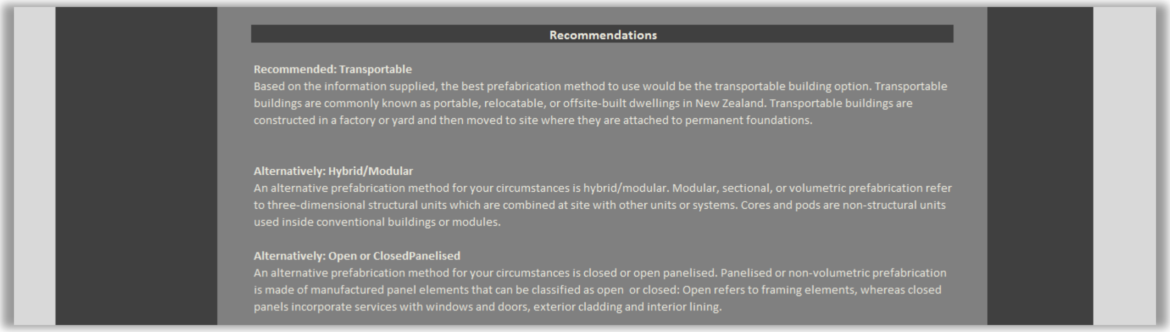
- Foundation: dropdown (Timber Framing on Piles, Concrete Slab on Grade)
- Lower storey wall framing: dropdown (Timber, Steel, Masonry)
- Lower storey wall cladding: dropdown (Weatherboards, Fibre cement/Plywood, Brick Veneer, Plaster/Stucco, Steel)
- Upper storey wall framing: dropdown (N/A, Timber, Steel, Masonry)
- Upper storey wall cladding: dropdown (N/A, Weatherboards, Fibre cement/Plywood, Brick Veneer, Plaster/Stucco, Steel)
- Roof cladding: dropdown (Longrun Metal, Metal Tiles, Concrete/Clay Tiles)

D.8 Results page – PrefabNZ toolkit

Results page starts with disclaimer text.

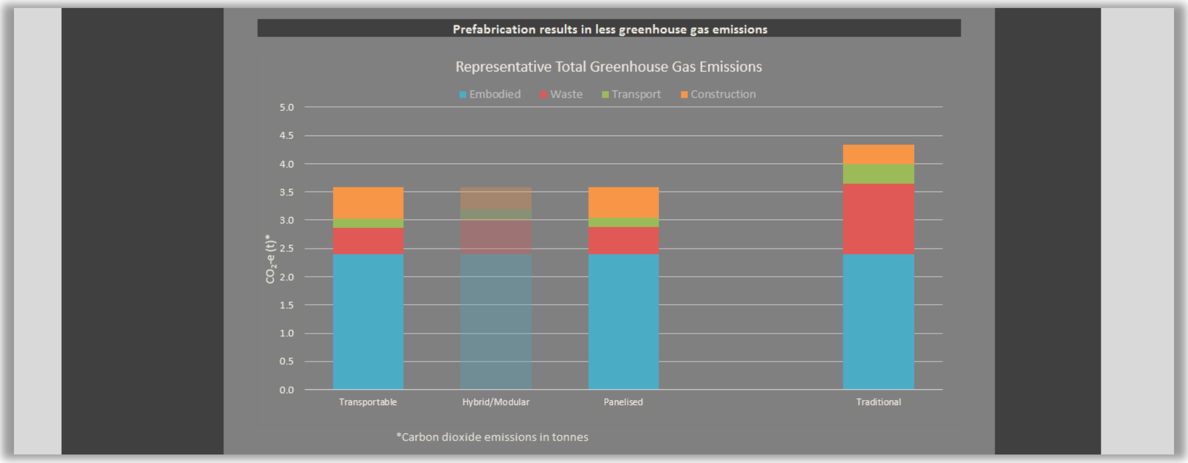


Followed by three tables depicting the user inputs from the three previous pages.

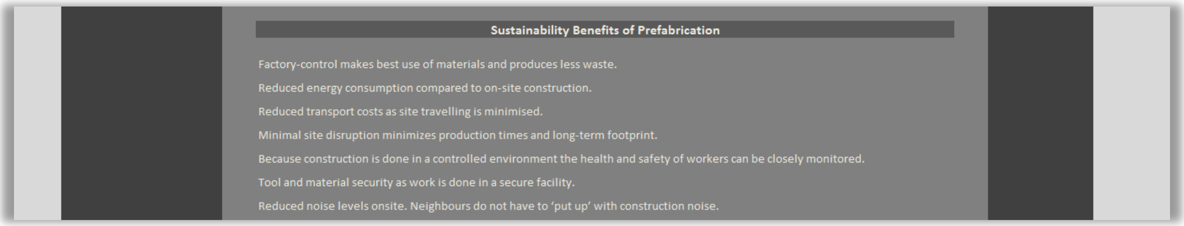


Then the tool makes a recommendation of construction method. There are five possibilities: No Prefabrication; Transportable; Hybrid/Modular; Open Panelised; or Closed Panelised. Up to two alternative options are presented.

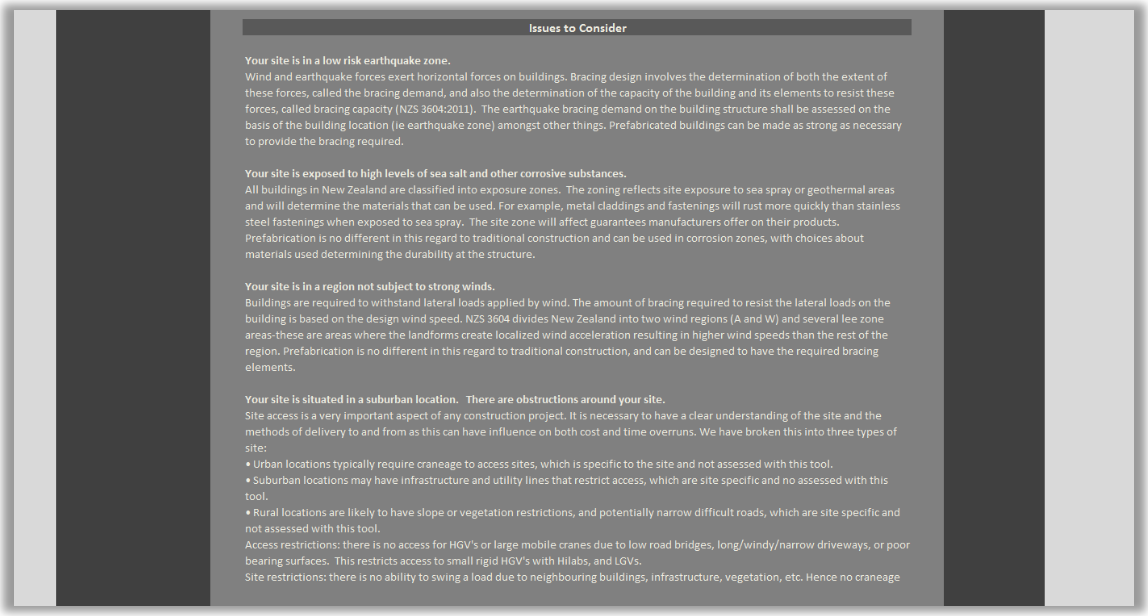
A bar graph shows the typical time of construction for the house as per the data provided for the four different options (Open and Closed Panelised are treated as one). Options which are not available to the user are greyed out.



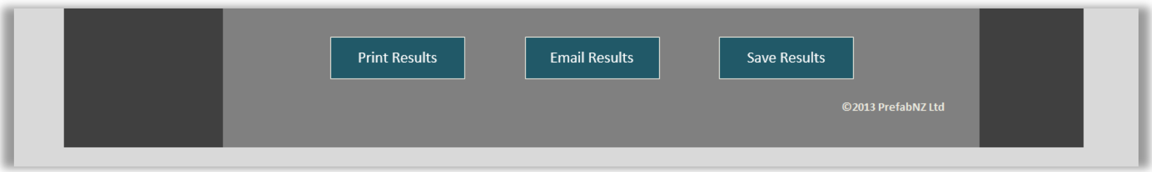
Followed by a similar plot showing typical greenhouse gas emissions broken down by source: Embodied (from materials); Waste; Transport; and Construction. These are based upon the data the user has provided.



There is some (static) text about the sustainability benefits of using prefabrication.



Additional text covers earthquake, corrosion and wind effects on building design. Site access, particularly for prefabrication is also discussed (the body texts are identical to the ones displayed in the popups on the Site page). The titles for each section are customised depending on the user input.



Lastly there are three buttons at the bottom of the page: Print Results; Email Results; and Save Results. In each case the version of the results on the print_sheet is used to produce two pages. In the case of Save and Email a PDF is produced (and attached to a new Outlook email).

D.9 FAQ Page – PrefabNZ toolkit

A page of text in question-and-answer format.

D.10 Reference worksheets – PrefabNZ toolkit

These are each accessed via the help popups on the Site page. They have maps of New Zealand showing how the country is divided into regions for earthquake vulnerability, sea spray exposure and wind speeds. These are all copied from NZS 3604:2011. The worksheets are hidden until accessed via the help popups and are hidden again afterwards. Each contains a button to return the user to the Site page.

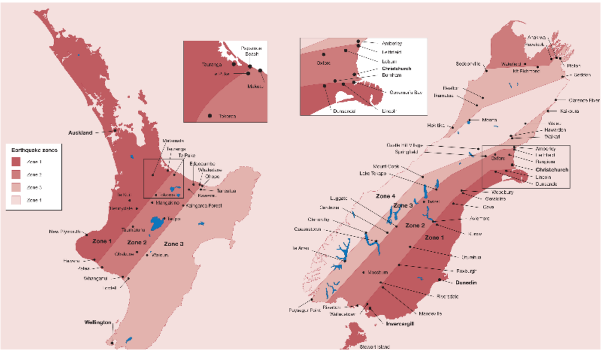
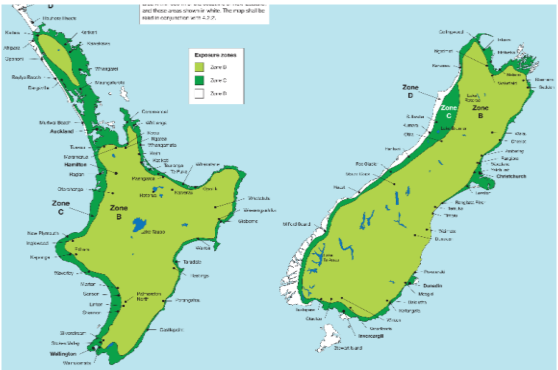
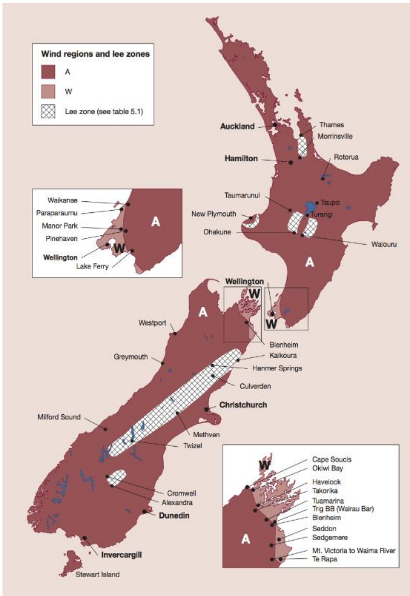


Figure 33: New Zealand data for Prefab tool





D.11 Developer worksheets – PrefabNZ toolkit

D.11.1 Text_sheet

This is where the majority of text in the document is stored. Other cells and popups link to cells in this sheet. The reason for doing so is to aid the editing process, particularly as some pieces of text are only displayed to the user under certain circumstances.

D.11.2 Print_sheet

This sheet has identical content as the Results page, but in a printer-friendly format – smaller fonts, white background, page numbering etc. The worksheet will make this sheet visible for an instant during print, save or email methods.

D.11.3 Data_sheet

All user inputs are linked directly to this sheet. Dropdowns have input ranges and target cells. Numeric entry popups have target cells. The data from the cells in this sheet are used for calculations.

D.11.4 Tracking_sheet

Most calculations occur in this sheet, which contains the logic to decide what types of prefabrication are viable and the calculations for the two bar graphs. These are based on "typical" data, with modifiers based upon the user input.

D.12 Tables – PrefabNZ toolkit

D.12.1 Prefabrication requirements

	Transportable	Modular/Hybrid	Panel (Closed)	Panel (Open)
Restrictions	No Access Restrictions	No Site Restrictions	No Site Restrictions	No Site Restrictions
Floor Area	≤ 140 m^2	≤ 300 m^2	≤ 300 m^2	≤ 300 m^2
Number of Floors	1	1-2	1-3	1-3
Distance From Town	≤ 30 km	≤ 150 km	≤ 200 km	≤ 50 km
Window to Wall Ratio	≤ 30%	≤ 35%	≤ 50%	≤ 50%
External Walls	≤ 6	≤ 12	≤ 20	≤ 20
Framing	—	Not Masonry	Not Masonry	Not Masonry
Foundation	Timber Subfloor on Piles	—	—	—

Table 10: PrefabNZ toolkit input parameters

D.12.2 Time of construction

Total build time:

$$T_B = B \cdot \alpha \cdot K_N$$

$$\alpha = \frac{\text{Floor Area}}{200 \text{ m}^2}$$

$$K_N = \frac{K_T}{80}$$

K_T is the sum of K_e values selected by construction materials.

Build	B
Transportable	72 days
Hybrid/Modular	36 days
Panelised	60 days
Traditional	84 days

Table 11: Build timetable (PrefabNZ tool)

Construction Material Time Factor	K_e
Subfloor framing	
Timber framing on piles	10
Concrete slab on grade	30
Floor cladding	
Exposed/carpeted concrete	10
Timber floor boards	20
Sheet flooring	10
Lower wall framing	
Timber	20
Steel	10
Masonry	20
Lower wall cladding	
Weatherboards	20
Fibre cement/Plywood	10
Brick Veneer	20
Stucco/Plaster	20
Steel	10
Upper wall framing	
Timber	20
Steel	10
Masonry	20
Upper wall cladding	
Weatherboards	20
Fibre cement/Plywood	10
Brick Veneer	20
Stucco/Plaster	20
Steel	10
Roof Framing	
Roof Trusses	20
Skillion Trusses	10
Roof cladding	
Profiled aluminium/zinc coated steel	10
Asphalt shingles	10
Concrete/clay tiles	15

Table 12: Time factor table (PrefabNZ tool)

D.12.3 Greenhouse gas emissions

Base emission levels are for a house with 120 m^2 floor area, timber-framed, timber foundation, fibre cement cladding and steel longrun roof.

Base Emission Levels (kg CO_2-e)					
Type	Embodied	Waste	Transport	Construction	Total
Traditional	5030	1500	420	410	7400
Transportable	5030	560	200	670	6500
Panelised	5030	730	240	460	6500
Hybrid/Modular	5030	580	200	660	6500

Table 13: Base GHG emission levels (PrefabNZ tool)

Per floor area:

Base Emission Levels (kg CO_2-e/m^2)					
Type	Embodied	Waste	Transport	Construction	Total
Traditional	41.9	12.5	3.5	3.4	61.3
Transportable	41.9	4.7	1.7	5.6	53.8
Panelised	41.9	6.1	2.0	3.8	53.8
Hybrid/Modular	41.9	4.8	1.7	5.5	53.9

Table 14: Base emission levels normalised to floor area (PrefabNZ tool)

Modifiers to transport (per floor area)

Let *d* be the distance from town in km (minimum value of 30), then the transport emissions per square metre are:

$$e_{\text{trans}} = m_{\text{trans}} \cdot d + k_{\text{trans}}$$

	m_{trans}	k_{trans}
Traditional	0.117025	0.000000
Transportable	0.011743	1.327000
Panelised	0.052856	0.411617
Hybrid/Modular	0.038811	0.505050

Table 15: Transport modifiers for distance-related emissions (PrefabNZ tool)

Modifiers to Embodied

The following numbers are added (or subtracted) to the embodied emission levels per square metre if these modifications are used.

Final values for emissions are calculated by multiplying the modified emissions by the floor area of the house.

Construction Material-Embodied Emissions	
Concrete slab on grade	51.0
Steel framing	20.0
Weatherboards	-18.0
Steel Cladding	4.0
Concrete Tile Roof	-4.6

Table 16: Normalisation factors for material-embodied emissions (PrefabNZ tool)

APPENDIX E NON-RESIDENTIAL SURVEY

NON-RESIDENTIAL

Please give this form to the builder or designer to fill out for the building consent listed over the page.

Contract value of work (incl sub-trades) $ .... incl GST

Type of Building .... (state type) e.g. Office, school, farm building etc

	tick	floor area		
New	☐	.... sqm	Number of storeys:	....
Addition	☐	.... sqm	Average storey height:	.... m
Alteration	☐	(describe alterations)	....	

Are you claiming "green" building features? Yes / No **If Yes, what type?** ....

Main Structure

Concrete Frame ☐ Timber Frame ☐ Concrete block ☐ LVL ☐ Glulam ☐

Steel Frame ☐ Tilt Slab ☐ Other (state) ....

Floor Base Material

Concrete .... sqm Particle Board .... sqm Plywood .... sqm Other (state) .... sqm

If concrete, have any steel deck trays been used? **Yes / No** (circle one)

Partition Wall Framing (tick one or more)

Timber ☐ Steel ☐ Concrete ☐ Other (state) ....

Wall Infill Framing (between main frame) (tick one or more)

Radiata ☐ Steel ☐ Douglas Fir ☐ Concrete block ☐ Other (state) ....

Prefabrication

Are any prefabricated components used? **Yes / No** If yes, describe applicable component(s) below:

Prefab Frame .... **Prefab Floors** ....

Prefab Walls .... **Prefab Other** ....

Insulation

(tick one or more)

	None	Pink Batts	Bradford Gold	Premier	Knauf Earthwool	Autex Greenstuf	Other Polyester	Wool	Polystyrene	Other (state)
Wall insulation	☐	☐	☐	☐	☐	☐	☐	☐	☐	....
Ceiling insulation	☐	☐	☐	☐	☐	☐	☐	☐	☐	....

	None	Expol Warmfeet	Polystyrene (not Polythene) Under Slab	Pink Batts Snug Floor	Sisalation Foil	Ribraft Floor	Cupolex	Other (state)
Floor insulation	☐	☐	☐	☐	☐	☐	☐	....

	Builder	**Other (please specify)**	
Insulation Installer (name)	☐	☐	....

Building Wraps

	Flamestop	Thermakraft	Bitumac	CoverTek	Pauloid	Tyvek Supro	Other (state)	Watergate plus	Tekton
Roof Wrap	☐	☐	☐	☐	☐	☐	☐	☐	☐

(tick one or more)

	Flamestop	Tyvek	Thermakraft	Coverup	Home RAB	Fastwrap	Other	Watergate	Tekton	Ecoply Barrier	Bitumac	Pauloid
Wall Wrap	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Wall Cladding State type and approximate % wall coverage

e.g. Concrete block, 75%
Clay Brick, 15%
Cedar WB, 10%

Other examples include: tilt slab, concrete block, steel zincalum, glazing, alumunium, radiata WB, linea WB etc.

Type .... % area ....
Type .... % area ....
Type .... % area ....

	Hardies	BGC	CSR	PRIMA	Other	Eterpan
If Fibre Cement cladding is used, who is the manufacturer?	☐	☐	☐	☐	☐	☐

Fibre Cement product used as Applied texture finish sheet, Flat sheet, FC plank (7.5mm), Linea (16mm)

If solid plaster, what backing was used? Fibre cement, plywood, paper, Triple S, block/brick, metal lathe

Wet Area Linings (bathroom, kitchen, laundry etc)

Please state the approximate square metres used

Formica Aquapanel	Seratone	Villaboard	Hardiglaze	GIB	Aqualine	Other	(state)
m^2	m^2	m^2	m^2	m^2	m^2	m^2	....

Roof Cladding (only applicaple if there is new roof cladding)

What roof cladding was used? (circle one or state below)

metal tiles, prepainted corrugated, trough zincalum, other steel profiles, concrete tiles, butyl, asphalt shingles,
other (state) .... **Approx. Roof Area:** .... sqm

Type of roof structure Timber ☐ Steel ☐ Concrete Slab ☐

Thank you. Please fold this form, and freepost it in the return envelope Aug-12

Figure 34: Non-residential survey form for the prefabrication monitoring tool