Role of Prefabricated Modular Housing Systems in Promoting Sustainable Housing Practices

Thesis submitted in fulfilment of the requirements for the Degree of Master of Engineering by Research

By

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Thank you all,

David R. Oxley III
Declaration

I, David R. Oxley III, hereby attest that all of the work contained herein is the product of my own effort. It is my belief that no included material has been previously written or published by another individual except where due reference and credit has been given. I also certify that no part of this work has previously been presented for degree or award at any university. This thesis represents work carried out over the time period from August, 2004 to March, 2006.

David R. Oxley III
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Publications

The following publications present articles based upon the work reported herein.


2. Oxley, D., de Silva, S., Xie, Y.M. (2005) "Possible Sustainable Outcomes Through Prefabricated Modular Housing Systems," Dream it, Create it, Live it: Young Engineers Australia, 2005: Year of the Young Engineer, Australia
Summary

The use of modular construction systems for residential purposes currently represents a very small proportion of all housing construction. The focus of these systems is on niche markets typified as cheap alternatives, homeowner involvement in construction or adaptations to construction constraints (build time availability, site access, etc.).

Governments, regulatory bodies and industrial members are progressively moving towards increased environmentally sustainable practice. This progression is evidenced by the development of design and construction rating tools and the introduction of statutes and regulations governing construction and design.

This work investigates the improvement of residential construction practice in terms of environmental sustainability outcomes through the use of modular housing systems. Two key aspects of environmental sustainability identified are embodied energy and material waste reduction. A modular system has been investigated because methods and procedures that directly relate to these two areas are well addressed by such systems.

In order to validate the potential of modular systems in this environmental regard, three main areas have been addressed. The first is the ability for modular systems to generate the type of floor plans currently offered by Australian high-volume builders. Second, the environmental improvement potential offered by modular systems is addressed. Lastly are the issues of structural performance and the means of the tailoring of prefabricated modular systems to residential construction standards.

Through the treatment of these three areas, potential benefits of modular systems are identified, with future work necessary to implement such benefits highlighted. The need for such improvements is noted, and a framework for evaluating future developments in this area of research is presented.
Chapter 1

Introduction

1.1 Background

Sustainable housing is a very important issue. Increasing population and metropolitan expansion ensures the necessity of continual residential development; while advancements in construction technology and environmental impact measures drive the advancement of construction methods and practices. While worldwide views on housing differ along cultural lines, the requirement for homes is universal. The majority of new housing development within Australia occurs in the suburban sector, meaning a large proportion of new construction consists of low density, individual, single family dwellings (Minnery, 1992). The Australian method of construction for this type of development is predominately Site-built, Timber-framed, Brick-veneered Construction [STBC]. With the advent of environmental programs such as the Victorian Building Commission’s [VBC] 5-Star Rating (VBC, 2004) and the Green Building Council of Australia’s [GBCA] GreenStar Program (GBCA, 2005), there is a shift towards greater environmental sustainability in housing. Recognizing the importance and benefit of this change; can high volume development methods be driven towards increased sustainability through the use of modular housing?

High volume domestic construction occurs when a single contractor, utilizing various sub-contractors, builds a large number of homes in a single neighbourhood or development. This is done economically by virtue of economies of scale; meaning as the number of homes increases, the price per home decreases. This is the case because certain elements, for example home designs, need only be complete once per design, regardless of the number of times they’re used. Once a contractor has developed a handful of house plans they can then alternate which plan is used periodically so that not all of the houses in a neighbourhood are the same. This method of organization allows sub-contractors to get used to a particular design and thus become more efficient at its construction. In addition to the savings gained from a familiarity with the plans, the designer does not need to invest design resources (architecture, drawing examination and signing, etc.) for each house built.
STBC presents its own set of benefits and detriments. Currently one of the trade benefits for this method is the extensive infrastructure in place specifically geared towards this manner of construction. Most potential problems, ranging from supply delays to construction error, have been encountered many times before and there are methods in place to deal with them. While these methods are not necessarily the most cost-effective or environmentally friendly, there are few unknowns regarding the process. Another benefit has to do with the planning flexibility achievable with STBC methods. Potential designs exhibit near absolute freedom at the planning stages and until they are actually built, plans are almost endlessly customizable. Naturally constraints of money and structural safety must be observed, but the potential is far beyond what is utilized by the vast majority of domestic construction.

As the infrastructure is very large and perceived to work well (or work well enough), there is a great resistance to change to more prefabricated methods. This resistance stems not only from the fact that it is a profitable industry, but also from the customer perception by the general population; Davis (1995) notes that the attitudes/preconceptions of unattractive or low quality housing are “persistent”. In addition, Leet (2005) observes that “purchasing a house or apartment is the biggest economic commitment most adult Australians will make”; thus ‘standard’ or ‘no-risk’ solutions are understandably very popular. In addition to the financial side, attitudes of what a house is and how it should be built are unique for every culture and they often give way to strong prejudices with regard to housing construction.

The above mentioned resistances and prejudices are not detrimental in and of themselves. However they become so when they prevent alterations to the current method when they are needed. One key area in which alterations are needed is the environmental impact and sustainability of STBC practice or alternative approaches to residential construction as discussed in this research work.

1.2 Areas of Concern

One key issue involving environmental impact is the material waste generated by STBC practice. Currently most build sites have a bin that is filled with scraps of
lumber, bits of pipe, chunks of concrete and all sorts of various odds and ends. Ekanayake and Ofori (2004) estimate that Australian construction accounts for 20–30% of all waste that ends up in landfills. The scraps of lumber could possibly be used on another build site. The excess concrete might be used as aggregate somewhere else (Heritage, 2002). These steps are not often taken because the economics of organizing and timing the transportation are not viewed as being ineffective or inefficient. Often the cheapest and easiest solution is to haul these materials off to be dumped. Efforts to alter this practice have in recent years been made to improve the end destination of material waste (Forsythe et al, 2000), but these have predominately targeted non-residential construction.

Another key issue is the embodied energy contained within each new house. Embodied energy is a measure of the energy used, both directly and indirectly, in the process to fabricate a product. This measure includes not only the energy used to recover the raw material and the processing of the material, but also in the transportation of the material, the final product, and the workers fabricating the product, the manufacture of the packaging of the product, etc. The Commonwealth Scientific and Industrial Research Organisation (2004) [CSIRO] reports that currently the level of embodied energy for a house on the day of completion is roughly equal to the energy required to operate and maintain the house for the first 15–30 years of its life (the large variation a result of very different climate, construction and lifestyle situations). Operation and maintenance includes heating, cooling, lighting and the powering of the home. Improvements are presently being made to the efficiency of heating and cooling system, insulation and lighting systems, driving down those costs and energy requirements. The decline of embodied energy is not at present keeping pace with these improvements.

Environmental issues are already driving many aspects of current product and process innovations, notably in areas such as water conservation and operational energy efficiency, and are beginning to drive innovation within the commercial construction sector. Government programs and initiatives, including assessment tools such as the US Green Building Council’s Leadership in Energy and Environmental Design [LEED] and Green Star in Australia, are beginning to drive commercial construction practice in the direction of greater environmental sustainability. The domestic
construction industry is just now beginning to look in this direction with both LEED and Green Star developing assessments of home construction.

One of the observations in the decision to pursue an investigation toward improved sustainability in residential construction through modular housing is the proportions which embodied energy resides within a house. Nearly 50% of a completed home’s embodied energy can be linked to the materials and construction of the exterior envelope (Ting, 2006). Thus by using a modular system, automatically the exterior and interior walls are addressed, covering a significant proportion of the embodied energy that is sought for reduction.

1.3 Problem Definition

The present pattern of metropolitan development for most Australian suburbs is the spreading of low density suburban housing (Minnery, 1992). These developments are relatively affordable but environmentally unsustainable. There are recent and current government initiatives to address the issue of sustainability through community awareness and federal funding for research and development but it is as yet unknown what level of impact these will have. The traditional practice widely utilized by high-volume builders for low density domestic housing is site-built, timber-framed, brick-veneered construction [STBC]. This on-site method of construction yields excessive wastes (materials, time, energy, etc.) making it a non-sustainable practice. There is a growing trend of using prefabricated methods to minimise material waste as well as improve upon time utilization. The goal of this project is to establish whether or not a Prefabricated Modular Housing System [PMHS] can influence traditional practice in the direction of greater environmental sustainability. This will be investigated by developing a modular system and investigating its ability to serve as an adequate alternative to STBC methods. The modular system development will include specific explorations into the planning flexibility potential of modular systems, the structural robustness of the modules themselves and the resulting structure as well as the relative environmental and sustainable performances of the modular system. These investigations will be complemented by consideration of several important issues including constructability, transportation, fabrication, quality control, claim
arbitration and build duration. So as to simply and comprehensively illustrate findings as to not only the performance of the proposed modular system but similar potential systems as assessment tool will also be developed to provide a framework for comparison between the various methods of residential construction.

1.4 Research Significance

Allard (2005) examined the Australian construction industry in terms of residential, non-residential and engineering sectors. Of these, residential construction represented roughly 40% from 2000-2004. According to McDonald (2003) the Australian domestic construction industry is predicted to supply 1.1 million new homes between 2002 and 2011. These figures establish that the domestic construction industry is not only very important to the growth and wellbeing of Australia; but also that it is a sector in which even slight improvements to the efficiency of the methods used may yield significant gains due to the scale of operations.

As illustrated above, economic and environmental improvements to the industry can achieve significant gains. In addition to this, increases in the products and processes aimed at increasing sustainability, employed by the general population, serve to further educate and influence the people (Wood, 2005). This shift of not only practices but of the cultural opinion of the importance and viability of sustainable practices can only improve the state of our relationship with the environment.

1.5 Objectives

Several key objectives have been set to give the project a conscientious and manageable structure.

i. Review current residential construction practises with an emphasis on environmental performance.

ii. Examine recent policies and research that affect the direction of residential construction or that may be applied to the further development of prefabricated methods.
Introduction

iii. Investigate prefabricated housing systems against planning flexibility, structural adequacy and transportability to act as a viable alternative to traditional STBC practices, thereby catering to high volume builders.

iv. Establish a framework in which performance and improvements can be measured for residential construction.

1.6 Scope of Works

i. Investigate the ability of prefabricated modular systems to provide adequate flexibility and quality performance as required by high volume development.

ii. Demonstrate that the proposed system is technically viable in terms of both structural and transportation considerations.

iii. Demonstrate that the proposed system provides improved environmental sustainability compared to existing practice.

iv. Explore the potential for modular systems gaining market share as well as the possible adaptation of prefabricated construction practices impacting upon current methods.

1.7 Organization of the Text

The thesis is structured to present each broad topic area in its own chapter. This will provide a clear narrative through the ideas of the project while treating each individual topic in a comprehensive way.

Chapter 2: Literature Review – This chapter briefly presents the current state of several topics integral to the area of improved environmental performance in housing; touching on areas such as: sustainability, modular housing solutions, performance assessment, and automated design. The goal is not a full exploration of these areas, but rather to
contextualize the direction of the rest of the thesis.

Chapter 3: Methodology and Framework—Establishes the methodology driving the work and from that presents a proposed design and rating framework as a flowchart.

Chapter 4: Modular Approach to Home Design – Evaluates the level of flexibility currently provided by the market, how well a rough modular system performs, and investigates techniques that may be employed to improve the performance of modular systems.

Chapter 5: Environmental Performance – The two key areas of embodied energy and waste generation are discussed, along with other issues such as assessment and cultural attitudes.

Chapter 6: Structural Validation and Optimization – This chapter establishes the structural requirements that may be encountered by a modular system, analyses various materials for performance against those requirements, and investigates optimizing the structural form of the modules themselves.

Chapter 7: Conclusions and Recommendations—Presents conclusions from the research and recommends future avenues of investigation.
Chapter 2

Literature Review

2.1 Introduction

As previously discussed, there are number of areas in residential construction, both globally and in Australia, that would benefit greatly from some form of improvement. The targeted areas treated here are in terms of environmental sustainability, specifically dealing with embodied energy and material waste. Before addressing these areas, a brief overview of some of the more general trends involved with residential construction is presented.

This chapter gives an account of the current Australian residential construction market, some of the current modular systems utilized and the policies and attitudes that have fostered a growing interest in construction reform.

The chapter will present observations on some of the identified problems facing residential construction and some of the approaches that have been used to address them. Housing is a topic that many disciplines – including social wellbeing, economics, engineering, planning, urban development, etc. – have a stake in, and as such holistic treatments of housing are difficult.

2.2 The Australian Housing Market

Australia’s population, despite a large amount of space to work with, is heavily localized around urban centres. Because of this combination of space and an urban-centric focus, suburban sprawl dominates the current residential housing market. Kennedy and Robertson (2003) reported that between 1996 and 2001, 75% of the 612,170 new dwellings reported were separate houses. It was also found that nearly half (47.4%) of all dwellings reported 3 bedrooms, with 89.1% of the nearly 7 million homes having 2, 3 or 4 bedrooms. The Australian Bureau of Statistics (2005) [ABS] reported that in 2003, the average size for new home construction was 227.6 m², a 20.6% increase from 188.7 m² in 1994.
The Housing Industry Association (2005) [HIA] collected data regarding the number of housing starts in Australia, both across the states and generally by type of dwelling (house or multi-unit) from 2001 and projected to 2008. Table 2.1 presents the national findings.

<table>
<thead>
<tr>
<th>Australia</th>
<th>Houses*</th>
<th>Multi-Units*</th>
<th>Total*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001/02 (a)</td>
<td>113.630</td>
<td>50.777</td>
<td>164.41</td>
</tr>
<tr>
<td>2002/03 (a)</td>
<td>112.087</td>
<td>57.646</td>
<td>169.73</td>
</tr>
<tr>
<td>2003/04 (a)</td>
<td>117.484</td>
<td>54.761</td>
<td>172.25</td>
</tr>
<tr>
<td>2004/05 (a)</td>
<td>105.629</td>
<td>51.533</td>
<td>156.16</td>
</tr>
<tr>
<td>2005/06</td>
<td>101.703</td>
<td>48.968</td>
<td>150.67</td>
</tr>
<tr>
<td>2006/07</td>
<td>107.832</td>
<td>48.446</td>
<td>156.28</td>
</tr>
<tr>
<td>2007/08</td>
<td>114.011</td>
<td>50.033</td>
<td>164.04</td>
</tr>
</tbody>
</table>

Table 2.1- HIA statistics and projections for house and multi-unit starts in Australia, (a) = actual, *thousand starts

Table 2.1 clearly illustrates the fluctuations observed in the housing industry. The economic and social reasons for these fluctuations are numerous and difficult to predict with good accuracy. In spite of these fluctuations, notably the drop in starts during both 2004/05 and 2005/06, the total number of starts presents an industry responsible for a significant amount of work being done. Figures 2.1, 2.2 and 2.3 present the value of that work being done economically.
Figure 2.1- HIA forecast of residential work done in Australia

Figure 2.1 shows, for the same time period as Table 2.1, the economic value of residential work done in Australia. The top most line represents the total value of residential construction observed (or predicted). This total value is found by adding the middle line, New Residential Construction (both individual homes and units) and the bottom line, Renovation Construction. Economically, renovation construction is almost as important as new construction, which indicates that substantial work is being done on existing structures. This assessment supports the idea of designing for deconstruction, as opposed to demolition. The theory being that planning for deconstructing instead of demolition has both economic and environmental benefits.

Figure 2.2- HIA forecast of non-residential work done in Australia
Figure 2.2 presents the total value of non-residential work done in Australia. The HIA defines non-residential in two categories: engineering and non-residential. Engineering construction represents roads, dams, and various other infrastructure projects; non-residential covers industrial and commercial construction, warehouses, office buildings, etc.

Figure 2.3 presents the total value of construction carried out in Australia, showing the relative contributions of both residential and non-residential construction.

![Value of Total Construction](image)

**Figure 2.3**- HIA forecast of all construction work done in Australia

As illustrated, residential construction contributes slightly more than non-residential construction. This is an important fact as it indicates that, economically, residential construction is a sector that warrants attention and offers a large potential for improvement scaling (meaning modest improvements may have significant absolute effects).

Australian urban development is at times an uneasy issue, particularly concerning the placement of all this new construction. An example is Millar’s (2005) report on the uncertain future of Melbourne’s growth. The ‘Melbourne 2030’ plan as proposed in 2002 aimed to reduce the sprawl by housing more people in apartments close to public transport; however the government’s stance to preserve so-called ‘green wedges’ from development seems to be softening due to pressure from developers, planners, and the population’s “quarter-acre dream”. Recently, Miller and Guerrera
(2005) reported that Melbourne growth boundaries in Casey-Cardinia, Hume, Melton-Caroline Springs, Whittlesea and Wyndham have been extended, allowing for 220,000 new homes over 25 years. In addition, the plan includes an $8000 tax for each housing lot to help fund services for the development. This plan, as with most, is heavily supported by some and bitterly opposed by others. The importance of planning and community involvement in development is more important now than ever.

Housing culture plays a strong role not only in the size and placement of homes, but also in their construction. Populations rejecting one housing solution in favour of another based on perception is a well known occurrence. One example is the rejection of Japanese prefabricated housing units after the 2004 tsunami on the basis that the foam and steel was not proper for housing. Another extreme example occurred in the US in 2004 when legislation was passed in Colorado banning placement of manufactured homes on any lot not previously zoned for them (Lurie, 2005). The zoning for such homes had been done decades before and displayed the popular preconception that prefabricated housing was of poor quality and was suited only to housing the lower classes. Arguments for repealing the legislation must counter notions and generalities as opposed to hard facts. These attitudes present a challenge when attempts are made to alter the delivered homes, as such care planning must go into new approaches to residential construction.

The nature of Australian demands has affected the manner in which industry provides services. From 1986 to 2001 it was found that the Australian construction industry has increasingly subdivided through the use of subcontractors and an increased number of smaller firms (Toner, 2005). Manzi (2005) points to Australian capital cities currently facing an over-supply of rental units, and suggests that “house prices are at unsustainably high levels”.

Australian culture highly values home ownership. Coupling this with an increasing desire to own a newly built home has seen a rise in the market for built-to-order homes on developer land. This system provides a straightforward path to newly built home ownership as the developer and housing options come with the land, simplifying the process while retaining for the owner the choice of design specifics.
2.3 Performance Analysis Developments

Rivard et al (1995), estimate that building envelope shortcomings are responsible for 50% of building deficiencies. These shortcomings and deficiencies relate to energy efficiency (usually in terms of temperature control), as well as unnecessarily inflated repair costs over the lifetime of the building. To improve this situation work was done to create a computerized approach to integrated envelope design. The concepts of design integration and working from a firm understanding of all of the myriad components involved in construction are both at the heart of many of the construction improvements that have been made in recent years. Improved system and builder integration and communication can greatly improve process and product efficiencies across a wide range of areas. Improved quality control presents itself as a remedy for this issue. One method of ensuring a higher standard of quality is through carefully controlled environments, such as is found in many prefabrication operations.

Work has been done by a number of organizations to attempt to formalize the method of improved integration by way of up-front assessment of both building and construction performance. Soebarto and Williamson (2001) found that while rating schemes can provide a picture of performance (in terms of energy for example); they are currently ill suited to be used in the evaluation of design solutions.

2.4 Residential Construction Innovation

The variations and advancements in residential construction have both a wide range of objectives as well as solutions. The drivers may be reduced cost for the consumers and builders, improved quality, more efficient outcomes or in order to achieve compliance with a new regulation. Occasionally a single of these will spur product or process advancement, but more often it is a combination of these, all of them affecting a wide range of housing aspects.

2.4.1 Sustainable Development

One important driver in recent times is the objective of greater sustainability of construction or ‘green’ construction. The shifting of materials and techniques used in all industries today towards a state of greater environmental responsibility shows no
sign of slowing down. New initiatives and programs, inventions and innovations are continually attempting to better man’s relationship with the Earth. One key area that has generated not only much publicity but also a lot of excitement has been that of construction, both residential and industrial.

Governments worldwide, through pieces of legislation such as the Kyoto Protocol and other similar documents, are seeking to reduce greenhouse gas emissions, and thereby slow the damage being done to the atmosphere; and influence the effects these pollutants are having on the weather. Australia’s CO\textsubscript{2} emissions from concrete production have been reduced by 21% per tonne of cement between 1990 and 2004, but increased production during that time has seen the actual level of reduction fall by just 3.6% over that period (Carey, 2005). These figures have led individuals to search for other means of dealing with the emissions problem. One example is eco-cement. Eco-cement acts as a CO\textsubscript{2} sink, absorbing CO\textsubscript{2} as it cures and converts it to carbonate. By mimicking nature’s processes of greenhouse gas repositories, there is potential for the built environment to assist in the solution of this global problem.

A myriad of other new technologies and methods exist to better the environmental standing of construction. Reducing water use through low-flow shower heads and toilets, from the use of water tanks for more efficient water usage through to full-scale water recycling, and energy implications from solar panels incorporated in building designs. All of these developments are being increasingly incorporated into new housing designs, and it is important that new systems fully employ these systems to achieve the best possible environmental solution.

One of the barriers to these solutions and many like them is the framework in which they are planned for and justified. The decision guidelines governing the employment of many of these technologies are not primarily grounded in an eco-centric view. One key example of this is the education of the public with regards to water use. Eco-centric goals would promote continual education and awareness of water issues regardless of the season or the catchment levels. Resource preservation is often highlighted in an ad hoc manner, i.e. during a drought. Another important issue is the lack of a universally accepted definition of sustainability (Quaddus and Siddique, 2004) from which evaluations and decisions can be made and supported. Adding to
the problem, Tisdell (2004) notes that “traditional economics are likely to be in partial or in total conflict” with ecological goals. With neither a common goal nor an accepted starting point, the resolution of varying societal aims for prosperity for both the economy and the environment is not a straightforward matter.

2.4.2 Modular Housing

The sector of residential housing is a complex industry guided by varying materials, cultural values, occupant needs, and climate pressures. Among the various types of low-density construction, site-built are overwhelmingly the most popular. The US market in 2000 found 94% of 1.24 million single family homes were site built (Elshennawy et al, 2003).

Modular housing is increasingly being used in Australia, typically in the area of medium to large, single client developments. One example is the use of precast modular concrete units to build a 132-bed aged care facility in Melbourne’s north (“Modular Precast”, 2005). These types of facilities are ideally suited for modular construction because they afford the developer a high degree of control on the design and they provide a project size large enough to generate economic and environmental efficiency benefits. This may occur because increased upfront costs yielding long-term savings are more pronounced when one individual or entity is looking across a large number of units; a situation that does not often occur with single family dwellings.

Increasingly, prefabricated housing has been investigated and experimented with by designers and architects. Reed (2005) notes several key points that have spurred this interest, including:

- The speed of construction offered by prefabricating elements
- The challenge to produce high-quality, aesthetically pleasing modular solutions
- The ability for these new homes to provide excellent environmental benefit
Some other methods have been investigated for the employment of prefabrication. One such method employed the notion of ‘community’ building, where labour for house construction was localized by employing one member of, say, 5 families, to build 5 homes, one being their own (Baschieri, 1998). From a social point of view, organization along these lines can have powerful positive benefits with regard to community involvement and engagement, and could potentially lay the foundation for community programs and education (recycling and water conservation for example) that have shown to dramatically increase program results. The physical layout and design of the houses themselves as well as their relationship to one another can certainly foster the community as well as precipitate efficient building practices.

Within the modern, urban Australian context, community building does not seem a likely solution. However the concept of engaging the community in a number of ways for a variety of reasons is taking hold. One method is through increased education programs at school, allowing the children to take the lessons into the home (Wood, ere speaker, 2005). Raising awareness and engagement between scientists, engineers, architects, builders and home owners has potential to improve the practices impacting on the environment.

2.4.3 Houses of the Future

Recently Sydney Olympic Park hosted the Houses of the Future exhibition (Sydney Olympic Park Authority, 2005). The exhibition displayed six concept homes each primarily built with a different material, all geared towards a more ecological impact. Each home had to be prefabricated for transportation and construction in less than 4 days, environmentally sustainable as far as construction and operation were concerned, and were required to meet the New South Wales BASIX guidelines (a new environmental rating tool).

The six featured homes were as follows:

- Concrete House
- Steel House
- Cardboard House
- Glass House
Each house, though not able to approximate current high volume construction (more notably in terms of size, the future homes designed were all quite small), provided an excellent opportunity to explore and develop a wide range of solutions to construction.

The cardboard home, though not suitable as a permanent dwelling, offers great potential for temporary or relief housing. There have been instances where the ‘temporary’ construction, quick and cheap but of adequate quality, has become permanent when the decision is made that it is good enough. Cardboard and similar temporary measures do not suffer from this feeling of wasted resources as they cannot provide permanent solutions. They are also built with materials very cheap and easy to recycle, providing excellent ecological alternatives to typical temporary construction.

The steel, concrete and glass houses all offer unique, futuristic housing solutions. Alien to current typical high-volume construction, these homes fit right in at more trendy, architecturally minded locations such as in city centres or in upmarket beach homes. Each house uses its chosen material to its utmost potential to provide a welcoming space with the dwelling space and environmental considerations in mind.

The timber and clay houses provide excellent configurability and adaptability to lot conditions. In addition the clay house offers exceptional thermal mass for energy saving heating and cooling methods.

All of the houses present innovative architectural and engineering exploration on a range of issues. The potential for further housing innovation is in no way slowing down. The drivers of energy and material efficiency will continue to push the industry. Governmental initiatives, social concerns, as well as the heightened awareness of operating cost will all ensure that the methods used to build houses continue to change and adapt. Exhibitions such as this continue to push the boundary
of acceptable housing solutions. This broadening of attitudes affects the community, and will thus indirectly influence the current market.

2.5 Sustainability

Sustainability is at the heart of the recent understanding of environmental practices. Current industrial and societal aspirations to improve environmental sustainability are driving many aspects of product development and refinement, as well as government and industrial practices and initiatives.

2.5.1 What is Sustainability?

Ecological and environmental concerns have been around for many thousands of years. In the industrial setting, they come down to the impacts –real or perceived– that particular practices have on the environment. Direct impact on plant and animal species is a well documented cause for action. Recently focus on resources and a more systemic approach has engaged with many areas of society, often under the banner of sustainability.

The now-traditional concept of sustainability was first put forward by Brundland (1988) as ‘a means of meeting current needs without sacrificing the ability for future generations to meet their needs’.

While the fundamental concept is straightforward, consensus on exactly how to define the concept or how it is to be achieved has yet to be reached. Popularly the concept is understood in terms of so-called environmental sustainability. Environmental sustainability is concerned with the ability of future generations to make use of natural resources and enjoy the environment as we are. This notion of sustainability ties in directly with material use, environmental destruction, species extinction, etc.

But there are several other aspects of sustainability that must be considered when attempting to better the “sustainability” of any industry.
2.5.2 The Triple Bottom Line

In business, and domestic construction is very much concerned with the business aspect, often success and failure is defined by the ‘bottom line’. The bottom line is concerned solely with the economics of any venture. Has there been a return on the investment? The bottom line functions as a single benchmark of performance, vast amounts of information and complex relationships boiled down to a single figure.

As sensibilities broaden and success and failure cease to be defined by dollar amounts, the bottom line tells us less about what has really happened with a project or a proposal. Using the bottom line model and the notion of sustainability, a new measure, the Triple Bottom Line [TBL], was introduced. The TBL approach seeks to simplify the measure of not one but three areas of concern: economic, environmental, and societal (sometimes referred to as cultural).

The TBL Approach:

- Economic: a measure of the monetary performance of the project or venture.
- Environmental: a measure of the environmental impact, positive or negative, resulting from the matter in question.
- Societal: a measure of the impact on the society, often in terms of benefits provided to those affected by the project.

The TBL approach establishes a framework in which the three aspects are interrelated, which leads to a trade-off mentality. Often this approach presents itself as an optimization problem where, for example, $x$ units of economics are equal to $y$ units of environmentalism. This technique creates an atmosphere in which the selling off of environmental gains for monetary returns is any easy move to rationalize.

This is not to say that the TBL is not a useful tool, but the conditions and relations used at the outset of any investigation are open to a wide interpretation of how to be sustainable. This leads back to the original problem of defining sustainability.
Pope et al (2004) notes that TBL assessments tend to consider a “direction to target” ideology. This means that the particular assessment ultimately evaluates a project or plan as having a positive or negative effect on sustainability. The concern is that this frame of mind is, in many cases, not a sufficient driver of change and innovation.

2.5.3 Sustainability Strength

In addition to methods to evaluate sustainability, sustainability itself has been examined as having varying degrees, typically referred to as strong and weak sustainability. As with much of this area, there is little agreement on what these terms mean.

Thorns (2004) identifies two different models of sustainability, strong and weak, based on the interaction of the three areas dealt with by the TBL, society, economy and the environment. He identifies weak sustainability as a fragmentary interaction of the three forces, occasionally overlapping but not necessarily unified in their goals or input. Strong sustainability on the other hand finds society and economy imbedded within environmental concerns, ensuring the overriding focus is the environment. He sees strong form as “fully embracing the multi-dimensional and extensive understanding of sustainability” and the weak form “largely only about taking on some of the rhetoric and focusing more on the management of the biophysical/environmental resources.”

This picture of sustainability has merit in that the current banner of sustainability flies over a very wide range of activities and goals, some only superficial concerned with or adapted to the environment.

Gutés (1996) assigns quite different definitions and uses to the terms of strong and weak sustainability. Strong sustainability “regards natural capital as providing some functions that are not substitutable by man-made capital.” Weak sustainability is “equivalent to non-decreasing total capital stock.” This method of looking at an economy as a whole, leading to evaluation on a ‘weak sustainability index’, attempts to assign a useful, tangible aspect to sustainability.
Unfortunately the inconsistent views put forth prevent focused approaches addressing issues and proposing solutions based on a ‘strength’ analysis.

### 2.5.4 Sustainability Prism

Yet another way to look at sustainability, extending from the three-sided notion of sustainability previously seen, is through environmental space and the prism of sustainability (Spangenberg, 2002). The sustainability prism adds to the environmental, social and economic view of the TBL approach by including an institutional component as well. Factoring in institutional considerations is important, especially when evaluating the sustainability of an industry such as residential construction. Figure 2.4 shows the prism with its four corners and various linkages between them.

![Prism of Sustainability](image)

**Figure 2.4- Prism of Sustainability**

The prism’s base is derived from a TBL approach, economic, social and environmental. The addition of the institutional imperative provides a theoretical context to describe and factor in intangibles that find no real place within other views of sustainability.

By applying the added dimension to the sustainability concept, many more necessary aspects of cultural interaction and business are framed with one another. Typically concepts such as ‘justice’ and ‘care’ are embodied in codes of ethics or practice by
companies or organizations, but not involved in the formalization of understanding a goal as important and open to interpretation as sustainability.

This method is helpful when viewing industries as a whole, stepping back from individual projects as is typically the case. This added dimension provides some groundwork for approaching the sustainability of home construction more holistically. This holistic facet of innovation and advancement increasingly pervades industrial changes, from project based interdisciplinary cooperation (a focal point in modular design) to more general practice shifts.

2.5.5 Sustainability as a Tool

The various concepts and models described above are all seeking to understand and describe the concept of sustainability, each to differing ends and degrees of complexity. With regard to environmental sustainability, success or failure is often determined not by the results but by the preconceived rules. Some of the strongest results achieved along the lines of environmental sustainability, such as the WasteWise program (discussed in Section Chapter 5.4.2), have been in one area cited as needing improvement to which plans of action were developed.

Following that, the focus of this project is primarily embodied energy and waste generation, not as the two keys of sustainability, but as two aspects of home construction that, once targeted, can be improved to help ensure a more prosperous future.

2.6 Topological Programming

For the human designer, or even the average homeowner, envisioning the possibilities of home layout design is a rather straightforward process. Certain constraints such as maximum dimensions or cost must be catered too, but by and large it’s a fairly fluid endeavour. The designer can draw on the experience of previous house designs encountered, either as a guide for elements found pleasing, or as an example of a design aspect to avoid. Further tempered by personal taste and the specific requirements of use; and quite quickly a floor plan, in a general form, can take shape.
The trick with automated processes is giving the computer the tools to recognize a good design from a bad one. One key example is in the adjacency of spaces. A designer would naturally put and ensuite next to the master bedroom, and generally place the meals area close to the kitchen. The computer must be instructed in some manner to replicate these expectations.

Geometric expectations are reasonably straightforward to satisfy. Providing the computer with a minimum and maximum area for a bedroom, as well as a range of length-to-width ratios, means that any bedroom generated would be able to function as a bedroom; neither being too small, nor having an impractical shape. The task of dictating spatial relationship based on room function has been investigated and several solutions have been used.

Medjdoub and Yannou (2001) provided the computer with specific instructions for the placement of various spaces. They used commands such as “room1 is on the south wall of on the north wall of the placement space” and “the living room and the kitchen are adjacent”. These commands, establishing the ‘topological constraints’, let the computer explore a range of layouts, while always generating solutions that are recognizable as functional living spaces. In the case of these constraints, ARCHiPLAN was used to evaluate and display solutions to an apartment problem.

Another approach taken to topological investigation was investigated by Michalek, Choudhary and Papalambros (2002). This solution was predominately focused on the geometric organization of a space. The designer provides the computer with general room dimensioning information (areas, living-to-access space ratios, etc.) as well as the linkages between all of the spaces (bed1-hall, bed2-hall, dining_room-kitchen, etc.). Orientation is not defined as was done by Medjdoub and Yannou (2001), so the range of floor plans from a visual point-of-view can be extensive, but they will all operate in very similar ways.
A novel approach was presented by Arvin and House (2002). By modelling a house as a physical model, they allow the computer to explore a very wide range of solutions. First, each room is presented as a mass. These masses can be manipulated geometrically, as in the other examples. In order to model adjacency, the masses are connected by springs, modelling the ‘adjacency objective’. The spring constants associated with each linkage are increased and decreased based on how important it is that those two spaces be immediately adjacent (1.0 for immediate adjacency, 0.3 for convenience, to 0.0 if it is unimportant). They also included a ‘separation objective’, which functions as the opposite of adjacency. This allows stipulation for space separation in a house, for private vs. public spaces, or for the master bedroom and the rumpus room.

By using these and other objectives (gravity- ensuring there are no gaps, alignment- ensuring the computer favours evenly proportioned rooms, etc.), what begins as a web of rooms and links becomes a potential house layout design.

These approaches illustrate the power of automated techniques in the area of layout planning. Each approach utilizes checks to optimize against certain criteria. This functionality provides an ideal framework for modular utilization as checks could be designed for a range of issues from roofing consideration to construction order.

Establishing that modular systems are adequate for home design is one important aspect of this project, but exploring the potential for more efficient design approaches is the next step. As automation becomes more commonplace and sophisticated, improved integration among many different aspects of design will result; and along with this improvement will be the efficiencies gained with regard to energy consumption, operational costs, etc.

2.7 Module Design and Analysis

For the majority of residential construction, especially traditionally built homes, the fundamental structural principles and practices have not changed much over the past
few decades. Conscientious structural design is important during three phases of a prefabricated building’s life: transportation, construction, and occupation.

The importance of adequate occupational performance is clear; underperformance can result in property damage, or worse personal injury. Proper design during construction insures not only occupational performance, but worker safety, and allows a project to stay on budget and schedule. Delays in construction due to damage or improper fit can cost time and money, not to mention the time and money if elements must be replaced outright. Finally there is transportation. Elements must be designed so they can survive the transportation itself, as well as the loading and unloading, which can often place the most unusual and therefore critical loads on elements.

Traditional framed home construction benefits from its outstanding performance of transportation and construction. Timber studs are easy to move, in bulk by machines and individually by workers. Houses are also built from the ground up and there are rarely any times during construction that brief unnecessary loads must be imposed upon elements (as may be the case with, say, concrete formwork supporting the concrete before it becomes self supporting).

The same bottom-up approach is typically used for all prefabricated methods for home construction. Modular elements must, however, be designed to withstand the unique forces experienced during the assembly process.

Structural analysis packages such as SpaceGASS and SAP 2000 can be used to analyse an element’s performance under a variety of loading conditions, not simply at the occupational stage, but the transportation and assembly as well.

The ability to analyse and predict performance is very important, but the advances in those performances stem from the improvements in materials and methods used to construct the elements. As the investigated modules are essentially a collection of walls, the steps in taken in the area of panels and thin structures is of vital importance.
Some of the best performers in strong, lightweight panels are so-called Structural Insulated Panels [SIP]. A SIP (Figure 2.5) is constructed by sandwiching structural and insulative foam between wood sheets. These offer improved handling and insulative attributes as well as providing the more typical wood surface for standard home finishing. The panels can be made quickly and customized as needed.

Modular systems take these panellized arrangements one step further and deliver freestanding elements of various shapes to be put together in any one of numerous configurations. The mechanisms of the structural elements for modular systems vary with the geometric configurations and materials used; but speed, reliability and often customization are all readily achievable attributes with modular systems.

This investigation touches upon several varied areas of concern. Much work has been done, as illustrated previously in this chapter, in all of these areas. The following three chapters break them up so as to more coherently deal with the issues. Many of the interrelated aspects of environmental research, construction and design/planning are just recently coming into focus.
Chapter 3
Methodology and Framework

3.1 Introduction

When investigating the place modular housing may have within residential construction, several aspects of housing must be addressed. Three core elements of the topic have been identified for exploration: sustainability assessment, planning flexibility and structural engineering. Figure 3.1 illustrates how these three elements are all separate in certain respects but interrelated and integral to one another in others.

![Figure 3.1- Three key aspects of Modular Housing investigation](image)

Each of these elements has been expanded below to illustrate the various paths undertaken to develop a complete investigation of the topic.

1) Environmental Performance
   a.  Establish targeted areas for investigation and improvement.
   b.  Determine current performance levels in targeted areas.
   c.  Propose modular performance, either through inherent mechanisms or through revised practices.

2) Planning Flexibility
   a.  Evaluate current levels of flexibility employed and the methods to achieve them.
b. Explore modular performance with respect to transportation and final layout options.
c. Recommend further steps that can be taken to improve upon state of modular performance in this area.

3) Structural Engineering.
   a. Evaluate what standards are required.
   b. Explore different solutions to meet those standards through both material and mechanism choices.
   c. Present initial results from structural analysis of varying solutions.

3.2 Market and Industry Context

The aim of this work is not simply to develop yet another prefabricated housing system to cater to a small niche in the market place, but rather to seek methods to improve upon the state of residential construction at large, in this case through the use of a modular system. By developing a Prefabricated Modular Housing System [PMHS] for domestic projects, the immediate aim is breaking into the market place; the ultimate aim is to leverage the current practice (timber-framed, brick-veneered construction) in the direction of sustainability.

There are many different ways to conceptualize the market, and thereby develop methods to shift or alter the practices in that market. Figure 3.2 illustrates the assumed general form of the market pathways of innovation and assessment.

![Figure 3.2- General market structure](image-url)
Figure 3.2 is comprised of five critical components.

- **Market**: the industry at large; representing the products, services, producers and consumers.
- **Gaps**: aspects of the market that are noted to have shortcomings, perhaps advertisement efficiency, product quality, etc.
- **Rating/Assessment**: an investigation to quantify gaps or approve new products or methods making their way into the market.
- **Improvements**: specific targeted areas identified by the gaps and rating activities.
- **Innovation**: development or refinement of some product or process as guided by the goals set at the improvement stage.

In addition to these five components, there are two loops present in the chart. Loop 1 follows the path from the Market to the Market Gaps to Rating/Assessment and through back to the Market. This loop illustrates the direct link between performance and expectation of current practices and products. In many instances faults are noted in a product or process, and the measures grow to reflect these faults, in spite of there not being a ready solution to them. Loop 2 flows from the Rating/Assessment to the Improvements to the Innovations back to the Rating/Assessment phase. This describes the research-oriented aspect of product development, external from market impact and feedback. Communication and linkage between these two paths is vital to the conscientious improvement of methods geared towards environmental interaction.

Each step is not necessarily a formally defined step or action, nor are they always ordered as above. Progressive refinement, as distinct from innovation, describes many changes to a product or process regardless of the motivation behind those refinements. Often the ‘gaps’ are nothing more than a desire to capture more market share. When this is the case new products (perhaps of varying colours or other aesthetic variation) may be developed to capture more of the market while not fundamentally improving the product. This can be seen in current housing practice by the proliferation of new house designs. Often a company will have various ranges to cater to particular lifestyles or economic situations. While each range is often an
innovative way to address a particular issue, the many resultant designs don’t necessarily take the concept further.

But in the case of housing there is typically a reason something is changed. Figure 3.3 builds upon Figure 3.2 by applying it to the scope of this study.

The five components in Figure 3.3 are:

- **High Volume Construction**: the sector of residential construction concerned with building a large number of homes of similar design, examples of industry players are Metricon, AV Jennings, Simmons, Porter Davis, etc.
- **Environmentally Sustainable Practices**: the concept and goal of environmental sustainability, acting as a driver for improved environmental responsibility.
- **Rating Tools and Legislation**: various Green Building Councils around the globe have developed guidelines to foster environmental or ‘green’ design and construction; additionally regulatory bodies have been actively seeking various policy changes to improve current or established practices.
- **Improvements**: specific targeted areas identified by the gaps and rating activities.
- **Prefabricated Modular Housing**: investigated as a method of improving the environmental impact of residential construction.

While there are many aspects of home construction that would be very worthwhile to investigate, the two key areas to be addressed are the embodied energy and material waste aspects of high-volume construction within Australia. Through an investigation
of the embodied energy composition of typical housing as well as steps taken both domestically and internationally, improvement in these two areas is being considered through the use of prefabricated modules for home construction.

By aiming to use a modular system for high-volume construction, not only does the environmental performance and potential improvement need to be investigated, but the modular system itself must be shown to provide an adequate alternative to current housing construction. To this end, there are three major components to this project: the environmental impact and performance of both current methods and the proposed modular system, the ability for the modules to provide standard floor-plan solutions and improve layout flexibility, and the structural/engineering aspects of modular systems.

The first step of the investigation into the PMHS is to identify the perceived Market Gaps the PMHS will be used to remedy. This is a two-fold process as there is a wide range of aspects that may be evaluated. From this investigation of current practice, the specific path towards the objective became clearer as the specific avenues of interest and scrutiny were reduced.

3.3 Targeted Areas and the Design of the PMHS

The PMHS at issue is concerned with and limited to improving the sustainable performance of the walls and exterior envelope of single-story, single dwelling homes. However a complete assessment of sustainable performance of PMHS includes the following areas:

- Embodied Energy [EE] – a measure of the energy required to build the completed structure, including material acquisition, processing, construction and transportation
- Life-Cycle Performance – durability, required maintenance and potential renovations during life-cycle
- Building Energy Costs – energy consumption as affected by envelope
- Waste Generation – from both manufacturing and construction
• Recyclable Materials Used – to produce the product
• Material Recyclability – excess materials or the ease of structural deconstruction and re-use

Figure 3.4 provides a simple graphical representation of the concept of not only the objectives of this project by also of sustainability in general, which is often viewed more as a continual process of improvement as opposed to an achievement of particular levels.

![Figure 3.4- Three-pronged environmental sustainability goal](image)

While not directly under the heading of ‘sustainable performance’, the following areas should be considered to make the PMHS viable and practical within the market:

• Structural Suitability and Optimization – both during and after construction
• Layout Flexibility – to cater to a wide range of homeowner needs with minimal production alterations

These two aspects are very important as structural stability is crucial to first and foremost safety, and secondly to quality of life and property protection; layout flexibility is important to make the modular system economically viable and robust to implement in the high-volume builders market.

Full product design and detailing of the PMHS is unfeasible within the scope of this project considering the time limitations, however a framework can be proposed in order to achieve previously discussed outcomes. As such the important issues
addressed will include the viability for the system to perform appropriately with respect to layout and structural adequacy. The general steps are as follows:

- Design System Geometry – establish several modular components that can be placed together in a variety of ways so as to obtain a range of different floor plans from the same production line
- Address Structural Suitability – perform accepted analytical tests on the proposed system to ensure that the system meets all relevant codes of practice

The general framework presented below in Figure 3.5 proposes a process for developing a fully rendered PMHS.

![Figure 3.5 - Generalized PMHS design process](image)

The process presented fits very well with the generalized market structure of Figure 3.2. Once the initial product has been formulated, a series of assessments must be made before it makes its way into the market, where the refinement process can start all over again. The scope of this project targets the elements of ‘Feasibility Testing’ as the Layout Flexibility and Structural Analysis aspects are to be investigated in order to establish that there is no fundamental reason why a modular system cannot comply with these requirements. Further work is required to develop this concept.
through a detailed design and detailing phase, which is not within the scope of the study.

### 3.4 Development of a Rating framework

Rating Tools are becoming an important part of building design and legislation. Evaluations on aspects from water usage to community impact are being developed and considered when making decisions about development, and the same is becoming true for building aspects housing as well. The presented rating framework may be used to evaluate the fitness of the PMHS to improve upon current practice with respect to both sustainable performance, planning flexibility and structural merits. Far from being a simple comparison of the proposed PMHS with current practice, this tool may be developed with flexibility in mind and possibly the underlying organization can be used to evaluate other modular systems or perhaps other construction methods in general.

Figure 3.6 represents the initial form of the rating frameworks. Note that the three main external sections: Gaps, Innovation and Market; are present in the generalized market structure presented in Figure 3.2.
Chapter 3

Methodology and Framework

Figure 3.6- Initial rating framework flow and layout

The general approach taken with the proposed rating framework assumes evaluation based on two classes of determinants: requirements and weighted performance measures. Requirements are important for two reasons; they ensure safety and a minimum level of performance. Weighted performance measures are instrumental in guiding the outcomes of using any tool. For instance, fundamentally similar tools may be used in two areas and the importance of water-conservation performance may be much more important in one area than the other. Rather than simply not evaluating a performance measure where it’s not crucial, weighted systems provide a context and method of evaluation. This is important for tracking and encouraging continual improvement across a range of areas.
3.5 Evaluating Leveraging Capabilities

In the pursuit of further sustainability within the domestic construction industry it is important to assess the influence a new modular system may have upon current practice. While fundamental shifts toward prefabricated home construction have taken place in several countries, expectations for the Australian market are more modest in the short and medium term; influence is not expected to be significant or revolutionary, but rather of a driving nature. Hopefully it will be concluded that points addressed by new systems and techniques are indeed important and that solutions can be found to improve them, either with said new systems or through some other modification of current practice.

In order to draw conclusions regarding the potential influence, several key questions must be asked:

- Are the gaps identified truly gaps?
- Is it worth seeking solutions to the problems these gaps represent?
- Does alteration to current practice provide desired outcomes?
- Can a Modular System offer the required alterations?

Many methods can be employed to address these questions – research, discussion, surveys – these methods are currently used by companies and governments to guide action and policy. As the answers are dependent on cultural values, environmental and economic situation, as well as location, results and conclusions speaking to the best course of action is rarely unanimous. This inherent variability supports the use of rating tools – such as the current tools mentioned above and the framework elaborated upon below – as they provide a consistent means of communication while providing the customization for necessary variability.

3.6 Formalization of the Rating Framework

The fundamental goal of the rating framework is to provide a structure in which housing construction can be evaluated and continually improved as a modular system.
By addressing this aim, the framework as presented below can be used by as a guide to developing a modular system and certifying its performance merits. The exact arrangement of the flow chart can be altered to improve its usefulness as strictly a rating device or comparison facilitator. Likewise, the design structure and flow may not exactly mirror a firm’s organization, but the identified elements are fundamental to the process addressed.

The objectives for expanding and formalizing the rating framework concept proposed upon above are:

- To provide a simple rating method reflecting the performance of housing systems with regard to both environmental sustainability and economic performance.
- To generate a basic framework for housing system evaluation that can be improved upon through the addition of more extensive evaluative capabilities.
- To establish key aspects that must be addressed during the conception and design of housing systems.

It is important for straight-forward output to be available for initial comparison and assessment. Output interfaces and options play a key role in this objective, but it is beneficial for the assessment algorithm to be geared towards this goal from the beginning. The ability to boil down a large amount of data to a single conclusion is important for this type of application because the results are not meant to inform a handful of technical people. The results should be accessible to a wide range of people who are all influential in the housing industry.

Providing an adaptable framework is significant given the changing environment of housing solutions and environmental goals. Within this adaptable system, however, it is important that certain key elements are provided to establish a consistency parallel with the consistencies present in all housing construction.

The flow chart is conceptualized based on an evaluation of the key issues to be addressed was performed. These key issues arise when developing a modular housing
system where improved sustainability is a primary goal. This evaluation led to the identification of three key points (discussed previously):

- Environmental Performance
- Planning Flexibility
- Structural Stability

These three key points were used as the foundation for the flow chart’s organizational structure. The flow chart has five operational levels. The five levels represent five components involved in design and rating/certification.

Level 1- Identifying design/assessment criteria and system design  
Level 2- Architectural and Structural Design phase  
Level 3- Planning Permit satisfaction phase  
Level 4- Environmental and Feasibility performance assessments  
Level 5- Performance rating and Certification

The front-runners of environmental evaluation schemes of buildings such as LEED, GreenStar and BREEAM all use a credit/point system focused solely on design aspects found here in Level 4, specifically targeting the environmental performance and measures. Level 4 evaluates not only the environmental and economic situation during construction, but also accounts for the operational phase of a building’s life as well. The inclusion of aspects surrounding the environmental operation of the structure addresses the limitation of the other schemes in their ability to influence upstream stages of a product or to challenge existing gaps.

With this framework however, it is important that the user have a method for evaluating the overall fitness of a system before resources are used to further develop it or it is put into practice. The framework provides that structure as a guide for that process.

Each level is comprised of one or two components. Each component looks at a unique aspect of analysis and judgement of the housing system. The sections grouped
into the each level exhibit functional similarities. All levels must be addressed and considered to arrive at a complete, viable system and certified system.

3.7 Individual Level Investigation

The following elaborates on the levels and the component sections of each. Figure 3.7 first illustrates the structure of the whole flowchart, and Sections 3.7.1 through 3.7.5 each address a level individually.

![Diagram](image-url)

**Figure 3.7- Flow chart framework overview**
3.7.1 Level 1: System Conception & Module Design

Level 1 begins with the establishment of the design criteria based on various identified requirements and relevant building and design codes. From these established foundations, the design of the modules can proceed (the process of going from requirement establishment to module conception and investigation is covered in Chapter 4). At this stage the codes and requirements are used to guide decisions regarding module and system mechanics; in following levels, these guidelines are used to validate and certify particular aspects of the system, continually progressing towards a viable complete system.

3.7.2 Level 2: Architectural & Structural Design Phase

Level 2 addresses two components of modular design, the architectural and structural aspects. Architectural considerations are concerned with the topological and geometric planning and layout of the modules and resultant plans (discussed in Chapter 4) and the structural considerations address the physical soundness of the structure during construction, transportation, assembly and occupation (discussed in Chapter 6). Sections 3.6.2.1 (Architectural) and 3.6.2.2 (Structural) below present each individual portion of the flow chart. It is challenging to accurately illustrate the refinement loops that are present when these two areas are concerned. The Architectural portion is presented first because it is assumed that layout generalities will be addressed prior to structural design. Following this initial first pass, adaptations and refinements to the system in one aspect will affect the other. For this reason Level 2 is only satisfied once both portions are satisfied.
3.7.2.1 Level 2a: Architectural Design

**Architectural Design**

![Architectural Design Flowchart]

This portion of the flow chart contains three fundamental elements: PMHS Layout Performance, Flexibility Requirements and Flexibility Assessment. PMHS Layout Performance is a measure of the abilities of the system design (formulated in Level 1). The Flexibility Assessment judges this ability against the previously mentioned flexibility requirements. If the flexibility is found to be acceptable, the process may continue to Level 3 (contingent on satisfaction of the structural component). If the ability is not satisfactory, then a redesign is called for. The redesign may require fine-tuning or it may require a substantial alteration to the approach. After these changes, the assessment process can begin again with new PMHS performance parameters.

3.7.2.1 Level 2b: Structural Design

**Structural Design**

![Structural Design Flowchart]

The structural design portion operates in the same manner as the architectural. System information is assessed against codes and standards to determine if the system can be described as structurally adequate. If it is, then the next level is approached, if
not, redesign must occur. Generally current housing practices exhibit well understood structural performance. Conventions make both design and assessment straightforward and predictable. With the continuing introduction of new materials and mechanisms for structural elements, this framework allows for all manner of structural assessments.

3.7.3 Level 3: Planning Permit Phase

![Planning Permit Phase Diagram](image)

**Figure 3.11-** Level 3: Planning Permit Phase

Level 3 is the last section primarily concerned with the design of the system. Planning permits are a crucial element of the residential construction industry. Procedures and guidelines vary slightly from state to state and council to council, often the outcomes are the same but the specific documents and schemes differ by municipality. As this is a necessary element, it has been pulled out into its own section to emphasise its importance. Additionally, while portions of the codes directly affect the structural and architectural components, some aspects are not as easily compartmentalized. Failure to satisfy the necessary requirements necessitates amending the design of the system. This work may come under the architectural or structural heading, or it may be a requirement external to those areas. By placing this section before the assessment and rating areas, it ensures that only viable systems are rated.

3.7.4 Level 4: Environmental and Feasibility Assessment

After a system has been approved, assessments can begin with regard to several areas. The specific areas targeted here are environmental performance and the constructability and logistical situation. Environmental performance (investigated in
Chapter 3  
Chapter 5) is of growing importance (refer to Section 2.4.1) to the Australian community; as such it has been included first. Construction and logistical matters deal with the specifics related to construction (scheduling, supply, transportation, etc.) and the economic aspects demonstrated by the system. This organization is closely mirrored the TBL approach to sustainability (previously discussed in Section 2.6.2); the only difference being that the social component is not explicitly formulated here. This assumes that social issues are addressed by other aspects in the framework. This organization improves upon the practice of using current environmental tools as a measure or driver to sustainability, as these tools are ill-equipped to give a good overview of a system’s performance, linking environmental and economic factors together, which is very important for commercial ventures.

3.7.4.1 Level 4a: Environmental Assessment

The environmental assessment operates similarly to current rating tools such as LEED and GreenStar in scope. Benchmarks are used to set the levels assessed against. While there is no defined minimum level of performance in this framework (this operates simply as a rating exercise), the capacity to place hurdle requirements is inherent in the structure. Thus ‘Results 1’ may be preceded by a pass/fail element, ensuring that reported results conform to a given standard.

The results represent information about performance that will be used for the rating at the conclusion of the framework. These results can include any type of information required by the Assessment Matrix (discussed below in Section 3.6.5).
3.7.4.1 Level 4b: Construction & Logistical Assessment

As mentioned above, the construction and logistical assessment deals with the tasks of organizing and paying for home construction. The Construction Assessment is more an indicator of the feasibility of using a modular system in a particular location as opposed to the system itself. Redesigning in this instance may mean returning to the fundamentals of the system, however it may require a reorganization of the resource (material, time, labour, money, etc.) availability as pertains to a particular instance of system use. Following this investigation an assessment on the economics of the system use is evaluated. This economic analysis may be directed at several different parties. Property developers may be interested in different things than the PMHS builders are, and homeowners have different requirements again; and at all three levels the level of detail and expertise may differ.

The economic analysis in the framework is geared more towards providing comparisons among different solutions, both at the housing level (STBC vs. PMHS) and at the amenity level (payoffs of different cooling or water systems, etc.). By fostering an environment of comparison, gaps and innovation are more readily identified and driven.
3.7.5 Level 5: Rating & Certification Phase

![Figure 3.14- Level 5: Rating & Certification Phase](image)

Level 5 evaluates the results from Level 4 through the use of an Assessment Matrix [AM] in order to produce a single rating of the system. The AM can take on a variety of forms in terms of how it handles the information it is given.

One method could make use of a credit/point system (as employed by LEED and GreenStar among others). This system awards points based on performance. For example one construction point could be awarded if 15% of the structure is built with recycled materials, two points if it’s 25%. This method simply adds up the points at the end and delivers a score. This system is adaptable because weightings can be given to different categories to increase or decrease their relative importance.

Another method can use a slightly more complex approach and deliver ratings based on several areas, either based individually on a credit system or through some other calculation method. This approach addresses the holistic aim of residential construction practice improvement across a number of areas because the performance at each level is highlighted, especially in a comparative usage. Result presentation is vital to making an informed decision. Due to this options should be included for graphical display of results and the interrelation of data. This approach is based on the Green Star system of providing summaries of a building’s performance in the
various environmental areas, allowing redesign to be focused on the most crucial areas.

*Evaluation and rating are two very important tasks when developing a new product or process, or seeking to alter an existing product or process. Having a framework to make sense of individual goals, how they relate to each other and having a basis for comparison against similar ventures helps to yield the best results. In this case the goal is shared by many organizations: commercial, special interest, and regulatory. This area is important, and this importance continues to grow as a greater understanding of the implications of inaction is developed. Figure 3.15 presents the full flowchart with each of the above components.*
Chapter 3

Methodology and Framework

Figure 3.15- Full methodological framework flowchart
Chapter 4
Modular Approach to Home Design

4.1 Introduction

The use of modular techniques to fabricate housing is not a new or unique concept. The use of modular packages to quickly erect homes on site is very popular in several parts of the world (Scandinavia being the foremost example of adoption of this approach), as well as having a place in Australia through a range of local contractors.

Most of these systems were designed specifically as modular systems to adapt to a particular climate or fabrication situation. These systems come in a variety of shapes and sizes, from domes and pyramids to average-looking rectangular structures.

Providing a PMHS house entails the assembly of a set of prefabricated modules on-site in such a way that current layout standards as well as all relevant building codes are satisfied. In addition to this basic requirement, the ultimate goal is that once assembled, the modular house should not perform substantially differently from current STBC methods.

The challenge faced when trying to adapt a PMHS to current Australian practices comes primarily in designing a set of modules that are able to approximate the dimensions and layouts currently offered by STBC methods.

4.2 Need for Flexibility in Planning

It is important to assess the degree of the modular system’s flexibility as this is a key area in terms of the marketability of the system. As the sustainable benefits cannot be realized if the system is not being utilized, the system must cater to the demands of the Australian public.
Homeowners in general are interested in owning a unique structure, their home. The time and logistical benefits of mass housing replication (as practiced in previous years, notably after the Second World War) are unfeasible in light of the reluctance of society to this approach. Though houses of a particular style often look similar, they subtle differences are enough to satisfy this uniqueness requirement.

There are two fundamental methods of providing this uniqueness: altering façade appearance among houses and providing entirely distinct layouts. Façade alteration is a relatively simple matter. Several techniques include: mirroring layouts, replacing a single double garage door with two single garage doors, altering the entrance path, as well as producing the same plan in entirely different architectural styles (one builder provides Contemporary, Manor, Mediterranean and Traditional façades, among others). Roofing can also play a role in the aesthetic separation of homes. While roofing solutions are often based on cost and function, there is a wide range of designs that can be utilized to give the home a distinct look (altering pitch, use of gables, etc.). Producing different floor plans yields different house forms, from single storey to double storey, etc.

In practice, these two solutions are used in tandem to provide a wide range of home designs without requiring the resources to develop them all from scratch. In attempting to emulate the success of this approach, the proposed modular system must include the ability to yield several different floor plans from the same design set in order to provide the manufacturing benefits sought.

4.3 Problem Definition

The investigation of the layout capabilities of the modular system is two fold. First it must be established that a house designed with modules can provide a contemporary layout, in terms of size and function, similar to those houses being produced by high-volume builders in Australia. Secondly it must be demonstrated that a set of modules is capable of producing several different configurations in satisfaction with the requirements of standard house design and efficient production methods.
There are two main aspects of housing layout design, identified here as topological and planning. These two areas are each important to good housing design, and are often dealt with simultaneously. However, much work has been done in the areas of both formalizing and automating these topics, so they will be treated separately in the initial stages of the investigation, being combined to produce a finished floor plan.

4.4 Initial Investigation

The initial parameters and approach method provide a simplified framework from which the flexibility potential and limitations of a modular system can be gauged. The foremost goal at this stage of investigation is to demonstrate that the level of flexibility offered by a modular system is compatible with the needs of the high-volume housing market. There are two key elements to establishing this compatibility: dwelling size and multiple configurations.

The question of dwelling size is approached as simply an exercise in imitation of the current market. This was done in an effort to alter as little as possible about what the homeowner receives after construction. The current trend for new Australian home size is a slow and steady increase. Though not all designs supported by the modular system will be exceedingly large (indeed the smaller and more efficient, the more environmental the design is), the capability of the system must be proven to current builders, and large achievable floor plans will be one of the criteria. As discussed previously, the ability to provide a number of different configurations is an important element of efficiently producing the desired range of housing options.

4.4.1 Topological Concepts and Design Trends

The topological design of a house is concerned with the relationship between different spaces based on their use, not on their size. This is an important aspect in that it aids the organization of the layout by providing a means to constrain design configurations (which is particularly important in the automation of the process). Topological treatments can range in precision from distinguishing between ‘personal area’ and ‘common area’ through to ‘bedroom 1’ and ‘bedroom 2’.
Topological design usually takes the form of flow charts with links between the different areas. These links typically represent access ways between the areas. An access way might be a hallway, a doorway, or perhaps even an indication that there is no barrier between the areas (such is often the case with a kitchen and meals area). The consistent nature of some of the links reduces the potential number of combinations in configuring a number of different elements. An example of a typical consistency is an exclusive link to the master ensuite from the master bedroom.

An excellent example of the influence that the topology of a house has is the placement of the television in the home. The use of space and family dynamic can be drastically altered when the television is moved from one room to another. Placement of appliances and furniture can drastically effect the time spent in a space by a family.

Typical high-volume home design employs a few generic space types to be freely used by the owner for a variety of activities. Custom designs focus on the wants and needs of a specific owner, offering perhaps a library with excellent morning light, very open to the external environment, or a dedicated home theatre. Each a straightforward concept, but each space would be poorly used for the other activity. Considerations towards this balanced availability of space use often generate homes that initially tend toward generic; however this allows for homeowners more control in the final set-up of their home.

Scott (1906) observed that “the suitability of a house to the entertainment of guests…seems to be the ruling idea in modern planning”. Current Australian attitudes are not as rigidly defined by etiquette as they were, but the planning of modern homes is still very much modelled on past principles. Homes can generally be divided into three sections for living that are labelled here as: Formal, Common, and Personal.

- Formal – used by guests or for more structured family occasions, comprised of the dining room, and lounge.
- Common – used by the whole family as it includes the kitchen, meals area, and rumpus room.
- Personal – comprised of the family’s bedrooms and personal bathrooms.
Figure 4.1 shows these general designations in a simple linear hierarchy. This organization illustrates the various sectors of a home, where any one family member has a place on all three levels, the family as a whole has a place on the top two levels, and entertained guests reside only on the top level.

Of course there is no catastrophic breach of etiquette if a dinner guest is entertained in a family room or perhaps the kitchen; but the general layout of the house should not necessitate a guest to pass through common or personal areas to get to the formal ones. One standard exception to this is passage to the backyard for barbeques, etc. As will most design issues, there are few strict rules, but myriad trends to act as a guide.

Often multi-storey houses use the vertical break to separate the Common/Formal and Personal spaces. If the house is designed for a large family, the master bedroom may be found on the ground floor with the children’s living space situated on the first floor.

In single-storey layouts, there is no vertical break available. A number of different layout approaches can be used, often employing some element of flow progression into the heart of the house to the dining and socializing areas, either bypassing or restricting access to the family Common and Personal areas. This approach provides privacy for the family by creating space breaks. This segmentation of space is also
useful for organizing formal presentation by limiting the areas that must be fit for public gatherings.

### 4.4.2 Room Sizing

Geometric planning is concerned with the sizing and physical placement of the modules. This area is very important in that it relates to the packing and transportability of the modules, the placement process of the modules, and it affects the marketability of the system because it dictates the house size available. The two key initial parameters for home design and selection are typically size and the number of bedrooms. For any plan, modular or otherwise, to be competitive keeping pace with current housing-size conventions is important (as previously seen in Lit. Review the convention for home sizing is increasing).

There are two key considerations when beginning to investigate this aspect of the design. Providing standard room sizes is very important to the commercial success and thus the leverage power of the system and the transportability of the system are vital so that the system is logistically feasible for deployment. Consideration of both these areas was applied to the investigation at the early stages to ensure the feasibility of the approach.

Observation of 52 current home designs, on offer from four high-volume builders, formed the base of data on the room sizes encountered in the Australian market.

Each room was classed as one of the following:

- Bedroom – sleeping quarters for children or guests.
- Master Bedroom – sleeping quarters for the homeowners.
- Family Room – common gathering area typically used by the family.
- Dining Room – either a formal space for meals or a less-formal meals area for family use usually adjacent to the kitchen.
- Kitchen – food storage and preparation area.
• Bathroom – space with a vanity, shower/bath utility, and in the case of an ensuite, a toilet (separate toilet services have not been included in the sizing data).
• Laundry Room – any space for laundry services or general indoor utility room for storage or indoor/outdoor transition.
• Rumpus Room – space intended for family use, typically used by the children.
• Sitting Room – formal reception/visitation space.
• Study- quiet adult space for use as an office, library, etc.

52 home designs from four high-volume builders were evaluated for room dimension and sizing data. Graph 4.1 illustrates box plots for each of the above mentioned space designations. For each data set, the areas from the houses is displayed with a box, whose lower bound is the 1st Quartile, upper bound is the 3rd Quartile, and the line within the box represents the median. The whiskers represent the room sizes outside the majority (with ‘*’ denoting out-lying data points far from the body of points).

![Box plot of Current Market Areas by Room](image)

**Figure 4.2**- Box plot of current market areas by room
To give a clearer picture of what Figure 4.2 illustrates, Figure 4.3 and 4.4 below present the data of the bedrooms and master bedrooms as histograms.

![Histogram of Bedroom Sizes](image)

**Figure 4.3**- Histogram of bedroom sizes with normal fit

As indicated by the box plot, current Australian bedrooms are reasonably consistent in their size options (a 7.2 m² difference between the maximum and minimum observed data points). Figure 4.4 shows the master bedroom data. Putting aside the difference in the number of data points (each house has one master bedroom, but often 2 or 3 bedrooms), note the much wider distribution of options (a 23 m² difference between the maximum and minimum values).
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Modular Approach to Home Design

The data suggests that certain spaces are very well suited to modularization. Highly uniform specifications, for bedrooms, bathrooms, laundry rooms, etc. all have dimensions easily encompassed by modules and their consistent use at those sizes is well documented. The larger spaces are not well suited to single module construction,
but the space can easily be created through various techniques (discussed in Section 4.8.1). Table 4.1 below presents the area and dimension averages for each room type from largest to smallest. ‘Area’ is not derived from the listed dimensions, ‘Calculated Area’ is. The dimensions are presented to give an indication of the general shape of the rooms. The data was collected such that for any space, the longer dimension was calculated as the length, and the shorter the width.

<table>
<thead>
<tr>
<th>Room Type</th>
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<td>Width (mm)</td>
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<td>3798</td>
<td>17.3</td>
<td></td>
</tr>
<tr>
<td>Dining Room</td>
<td>13.8</td>
<td>4288</td>
<td>3183</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>Bedroom</td>
<td>10.9</td>
<td>3472</td>
<td>3119</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>10.7</td>
<td>3704</td>
<td>2877</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>10.2</td>
<td>3420</td>
<td>2970</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>Bathroom</td>
<td>4.9</td>
<td>2800</td>
<td>1748</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>Laundry Room</td>
<td>4.1</td>
<td>2450</td>
<td>1675</td>
<td>4.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1- Room area and dimension averages

The organization of space in many of the houses presented a few interesting trends. Often houses are organized as roughly two lines of spaces, with a main access way through the middle of the linear home arrangement. This is typically not the case should a second storey be involved. Stairway access is frequently directed into the centre of the second storey, providing a more communal structure.
Figure 4.6 presents a single-storey floor plan offered by Metricon. The flow of the plan is very linear, with formal and common areas in a central location to the left-hand side of the plan, while personal spaces are adjacent to the common areas (with the exception of the master bedroom). This is quite a common arrangement of spaces as there is good separation between the adult and child areas, all well as a generally open plan along the left-side of the home with the sitting area merging into the kitchen/meals into the family area.

A two-storey example is illustrated in Figure 4.7. Also on offer by Metricon, this shows a plan whose personal space has all been moved up to the second storey. By organizing the home in this way, the formal sitting and dining areas are the first encountered on the ground, proceeding on into the common family areas. Note how the family/rumpus area is not two separate rooms as much as it is a single space divided in two. This illustrates the ease with which aesthetic dividers can shape the usage of space within a home.
The communal structure is typified by terminating a main access way in such a way that the continuing branches flow from a usable space, not simply the end of a hallway. This is often desirable as it opens up space and can improve the feeling of the house.

The most efficient way to achieve this effect is through the use of negative space. Surrounding an open area with modules provides an efficient method of expanding the house size while using the same amount of material. This approach can also provide the observed organizational structure of opening up the floor plan to less defined transitions of space. Floor coverings and colouring are all ways to indicate a transition without solid physical boundaries. This is often seen with the transition from tile to carpet. Of course there are good functional advantages to tile over carpet, especially in areas such as the kitchen; but the tone that is set for a space with carpet is quite different to that of hard flooring.
4.5 Room Arrangement

Initial room arrangement conducted by hand may begin in a less than formal manner. Conventions discussed above (size, general layout) are often intuitive starting points for any home design. Though beyond this work, cultural conventions would seem to play a large role in this process. From these initial conceptions the spaces identified and sized (perhaps from information similar to that given above) are progressively arranged in a variety of combinations in order to get a feel for the various forms the plan may take.

Far from being simple trial and error, this process exhibits strong interaction by the participant. At each step issues can be observed and evaluated based on their progression towards an ideal solution, though the solution is not yet known. It is this facet of layout design, the shaping of the problem in terms of better and worse refinements that suggest this task may benefit from some form of automation; contingent on being able to formally and quantitatively describe the parameters used to make those judgements.

As mentioned previously there are several general conventions utilized when organizing the layout of a house. These conventions can be simple guides along which to structure the organization of the floor plan; or they can be complicated architectural considerations regarding the aesthetics and use of the inhabited space.

With high-volume construction, complicated architectural is not often explored. Certainly aesthetics are important, but the goal is a pleasant, attractive looking home, not any statement or direction upon the living environment.

4.5.1 Access and Topological Considerations

If the goal is to have a functional house, then the means are the topological considerations and constraints imposed upon the design process. As mentioned, these topological considerations deal exclusively with the use of space and its position relative to other spaces. The relative positioning deals with direct access as well as special closeness.
Often the access from one space to another is the key consideration (as demonstrated by the range of solutions identified in Section 3.7). An example would be the stipulation that the ensuite should connect with the master bedroom, or that the kitchen should link with the meals area. These directly affect the functionality of the house, and are often one of the key areas homeowners concern themselves with, i.e. the ‘flow’ of the house.

But the topological design also deals with the less tangible aspects of the space usage. One of the prime examples is the potential noise generated by areas. Acknowledgment of this aspect of family life, particularly in households with several children, can drastically alter the design. Rumpus rooms, home theatres, these types of areas may be ill placed if situated such that they share a wall with a bedroom or two (particularly if it is the master bedroom). In addition to wall sharing, ‘line of sight’ as it relates to both visual privacy and noise transmission is an important consideration as well (further discussed in Section 4.9.1) Another example of non-access related design is the practice of situating spaces with utilities close to one another. This not only saves on materials and inner-wall space, but can also reduce annoyance should noisy pipes be a possibility.

4.6 Floor Plan Design

Following from the considerations mentioned above several fundamental topological ‘branches’ begin to emerge during the process of combining spaces towards a workable floor plan. Each branch encompasses a range of its own characteristic plans, placing the master bedroom apart from the other bedrooms in one branch and with them in another, but within the branches the differences among plans might be very minor, perhaps the only difference between A and B is that the access to the half-bath is on the left side of a room instead of the right. However these differences are important because they may alter the appearance of houses from the outside, and that is where the aesthetics of uniqueness are very important in large developments.

From the step of space arrangement, access ways and separations must be placed. In traditional construction the walls are simply placed around any area that should be
isolated (as in a bedroom) or where the functionality is required (to support something or hang cabinets on perhaps). With the modular approach, the process of placing walls becomes less straightforward.

As the goal of this modular system is to utilize rectilinear modules to enable the construction of a variety of distinct floor plans, the approach taken here was to preliminarily evaluate several trial modules by exploring a variety of floor plans, and then to investigate the range of floor plans that could be available to that particular combination of modules.

### 4.7 Module Design

From the floor plans, a number of module-ready spaces can be identified. Bedrooms, bathrooms, the laundry, a study; these areas lend themselves to direct modularization very well as they are usually comprised of 4 walls with one (possibly two) access points. Other areas of the home (depending on size) can follow the same pattern, or may be ‘enclosed’ by modules with three sides.

Once several modules can be identified, the floor plan can then be recreated (to varying degrees of exactness) through the use of negative space: creating interior space outside of the modules through the use of the floor and ceiling (illustrated in Figure 4.14 below and further defined and illustrated in Section 4.8.1).

#### 4.7.1 Plan Formulation

Below is an example of the above process. A number of modules are configured in several different ways without the use of negative space to demonstrate the flexibility available. Seven simple floor plans for a single-bedroom home utilizing the same eight modules, with the same fundamental topological constraints imposed. An example of the topological link constraints are:

- Ensuite access from Master Bedroom
- Kitchen access to Dining Room
- Entry access to Family Room
It can be observed that there are a number of doorways that cannot or need not be used as access points. As the modules will be designed and analysed with these openings in mind, they will not pose a structural problem, and therefore can simply be filled with insulation and covered with finishes. A homeowner need never know about them, or perhaps they can serve for potential access points for future renovation.

Figures 4.12a, 4.12b and 4.13 below show the dramatic size increase possible through the use of negative space.
The preceding modular system is inefficient from a number of perspectives. Packing efficiency and ease of roofing would need to be improved upon before this system could be considered viable. However, it does illustrate several important aspects of modular performance.

- Rectilinear modules can be combined in such ways as to yield a large number of differing geometric constructions.
- The use of pre-cut doorways, from an arrangement point-of-view, is a viable option for increasing the organizational potential.
- Inefficiencies such as double-walls can be avoided to a large degree through conscientious design and module placement.
4.8 Combination Analysis

The number of unique designs possible from the modules and branches presented above is roughly 25, each design offering varying degrees of difference from one another. Through the use of negative space and thereby different branches of topology (due to the inclusion of different spaces and organization) the number of floor plans doubles to around 50 configurations. Several of these possibilities are impractical from an efficiency standpoint; typically in terms of foundation and roofing design, impacting on the ultimate cost. With the use of aesthetic treatments to further distinguish similar houses from one another, only a relatively small number of plans are necessary to make a given set of modules practical; thus even with an acceptance rate as low as 10% five different designs can be produced. The introduction of another module generates an entirely new set.

4.8.1 Additional Flexibility Expanding Methods

Negative space is a concept used often by architects and artists; here it defines an interior living space created by surrounding it with modules, therefore not enclosed by the modules themselves. This can clearly be seen in Figure 4.14 below. Provided the wall finishes surrounding the negative space are ‘interior’ finishes, it is indistinguishable from the module interiors.

![Figure 4.14](image)

**Figure 4.14**- Each shape can be made with four squares (grey space negative)

Negative space can also be created through the use of panels. The introduction of a single sized panel make the generation of hallways very simple. Hallways provide
not only privacy through access offsets, but can alter both the interior flow of a home, as well as the aesthetics from the outside. Figure 4.15 below presents a simple illustration of the previous point. The lines of sight available to the right figure are substantially less than on the left. This is not only important for privacy issues, but also can provide additional noise-control measures.

![Figure 4.15- The privacy in the right figure is greatly increased](image)

The possible combinations for layout design expand tremendously with the use of negative space and individual panels to fill and create doorway offsets.

### 4.9 Floor Plan Refinement and Optimization

The plans and models illustrated above provide a sense of the potential for a limited number of modules to be configured in multiple ways to produce distinct arrangements as necessary for high-volume construction. The following section explores refining initial plans through interactive manipulation. In addition to aesthetic refinement along certain guidelines, quantitative measures of initial and refined plans are presented to give an indication of the ability to track changes as well as begin to frame methods that may be used to assist automated optimization and design.

#### 4.9.1 Module Specifications

After consulting the governing legislature regarding load sizes for transportation by truck (VicRoads, 1999); the maximum external dimensions could be set. The transportation of oversized modules, given their monolithic (non-divisible) characteristics, is covered under a Class 1 exemption of dimension limits (provided
the vehicle is safely fit to transport them). For this investigation, the external limits were set at 4.84 m by 3.57 m, with the modules envisioned to ride lengthways on the truck.

Assuming a wall thickness of 120 mm and 80 mm clearance, the optimal module sizes that can be created are illustrated in plan in Figure 4.16. The five modules enclose an area of 49.1 m$^2$. Through the use of two sets, usable inter-module space is 98.2 m$^2$.

![Figure 4.16: Five Telescopic Modules packed and unpacked (m)](image)

The five modules presented above have areas presented in Table 4.2 below.

<table>
<thead>
<tr>
<th>Module Dimensions</th>
<th>Usable Interior Area (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External (m)</td>
<td>Internal (m)</td>
</tr>
<tr>
<td>4.84 x 3.54</td>
<td>4.6 x 3.3</td>
</tr>
<tr>
<td>4.44 x 3.14</td>
<td>4.2 x 2.9</td>
</tr>
<tr>
<td>4.04 x 2.74</td>
<td>3.8 x 2.5</td>
</tr>
<tr>
<td>3.64 x 2.34</td>
<td>3.4 x 2.1</td>
</tr>
<tr>
<td>3.24 x 1.94</td>
<td>3 x 1.7</td>
</tr>
</tbody>
</table>

Table 4.2- Telescopic module dimension and area data

Recalling Figure 4.2, Figure 4.17 presents the room sizing data previously explored along with lines illustrating where the telescopic modules fit based solely on their usable interior area.
Figure 4.17 illustrates that to a great extent these modules have the capacity to fulfil the roles of individual rooms on their own. With the exception of the rumpus room, some examples can be found in the current market where a module would not be perceived as ill sized. However, marketability and consistency to current trends illustrates that the family room and to a lesser extent the sitting room would be ill suited for composition with a single module. As will be seen, these areas can be created through the use of negative space.

As previously demonstrated with the models, the placement of doors is a constraint to organization, but does not necessarily preclude a variety of plans from being formulated. Aesthetically doorways and unused doorways present little problem. Windows, while presenting a similar challenge, are slightly more complex in their implementation.

Structurally windows may present more of a challenge than doors due mainly to their size. Small windows, or tall thin windows, within a wall don’t present much of a problem as the mechanics of a transom (the element above a door) are simple to apply, diverting forces around the opening and down. Wide windows present a
problem as the strength or rigidity of the transom element may need to be significantly increased. However, the existence of full bay windows and walls of non-load bearing glass demonstrate that designs can incorporate large windows or openings. The key aspect of this part of design is to conscientiously place windows in conjunction with roofing elements so as to ensure the proper level of structural support.

4.9.2 Preliminary Design

Two sets of the telescopic modules pictured above were to be used to generate the floor plan of a single storey, 4-bedroom home. The initial topological step was taken to roughly structure the organization of the house. Figure 4.18 illustrates the general topological areas, as previously discussed in Section 4.5.1.

![Diagram of topological areas]

**Figure 4.18-** Initial topological conception for design

From this rough conception, Figure 4.19 was generated. The method used was akin to trial and error. From the information presented in Figure 4.14, it was initially determined which modules would probably be used for which rooms. The active placement was carried out in a circular manner, progressing around the central space ensuring enclosure. The resulting plan is presented as Figure 4.19.
Design Plan 1 follows the initial topological conception in that there are roughly three sections to the house, with the personal and common areas linking around the formal space. The entrance opens into a large area for entertaining, family gathering, eating, etc. The plan could contain several partitions, which could be semi-structural panel elements, or could be physical (screens) or aesthetic (floor transition) breaks. The inclusion of these partitions (as was seen in the two storey plan between the family and rumpus rooms in Figure 4.7) shows the versatility of structurally open areas. To the left is the common side of the home, laundry, kitchen, and a small bathroom for guests as well as module for use to these ends. The right side of the house provides space for the living area. By separating the bedroom and bathroom entrances with a hallway, privacy is maintained, and the parent’s bedroom is kept separate from the children’s quarters.

The plan suffers from several serious shortcomings however. The efficiency of laying this foundation and roofing the structure is not acceptable as efficiency of material use (discussed in Section 5.4) is one of the prime objectives of modular construction. In addition the footprint is ill suited to make efficient use of typical plot sizes.
Table 4.3 contains several parameters of Design Plan 1. Following the table there is an explanation of each of the rated categories.

<table>
<thead>
<tr>
<th>Plan</th>
<th>Usable Area (m²)</th>
<th>Negative Area</th>
<th>Panel Lg. (m)</th>
<th>Foundation Efficiency Envelope (m)</th>
<th>Foundation Efficiency Footprint (m²)</th>
<th>BR</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>193.2</td>
<td>20</td>
<td>95.0</td>
<td>88</td>
<td>224.2</td>
<td>0.39</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4.3- Design Plan 1 performance

Table 4.3 evaluates the design on four aspects: usable area, panel length, foundation efficiency and roofing efficiency.

The usable area (reported both in square meters and squares as both are routinely encountered in the Australian housing industry) is a measure of the internal floor space accessible to homeowners (therefore this measure does not include the area taken up by walls).

The panel length measures the quantity of panelling that is required to create the building envelope. Partition elements are not included as there placement is not fundamental to the design.

Foundation efficiency is a measure of how efficient the boundaries enclose the footprint area by the Boundary Ratio [BR], defined as the boundary length divided by the area. This gives an indication of how compact the overall shape is. For any area, the most efficient shape with regard to the boundary to area ratio is a circle. Equations 4.1 and 4.2 define the area and circumference of a circle, respectively.

\[
\pi * r^2 = A_c \quad \text{Equation 4.1}
\]

\[
\pi * 2r = C_c \quad \text{Equation 4.2}
\]

Where:

\(\pi = \) the ratio between a circle’s circumference and diameter \(\approx 3.14159\)

\(r = \) radius of the circle

\(A_c = \) area of the circle

\(C_c = \) circumference of the circle
Ratios between the area and the border vary with scale, but as a circle is the most efficient, the most efficient ratio for a given circle with area $A$ and thus radius $r$ is derived in Equation 4.3.

$$\frac{C_C}{A_C} = \frac{\pi \cdot 2r}{\pi \cdot r^2} \rightarrow \frac{2}{r} \quad \text{Equation 4.3}$$

By using the area formula (Equation 4.1), Equation 4.3 can be rewritten as Equation 4.4:

$$\frac{C_C}{A_C} = \frac{2}{\sqrt{\frac{A_C}{\pi}}} \quad \text{Equation 4.3}$$

Equation 4.3 represents the ideal ratio for efficient area enclosure. For quadrilateral shapes, a square exhibits the most efficient shape. For a given area, Equation 4.4 gives the boundary ratio if that area is formed as a square.

$$\frac{B_S}{A_S} = \frac{4\sqrt{A_S}}{A_S} \quad \text{Equation 4.4}$$

Where:
- $B_S =$ boundary of the square
- $A_S =$ area of square

For Design Plan 1, the boundary ratio was found to be 0.39. For a square of equal area, the ratio is 0.266, and for a circle it is 0.236.

Figure 4.20 plots Equations 4.3 and 4.4. Where the independent variable (x-axis) is a given area and the resultant y-axis value is the boundary ratio for both a square and a circle.
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Ideal Boundary Ratios

![Graph showing ideal boundary ratios for circle and square enclosures.]

**Figure 4.20**- Boundary ratios for circle and square enclosures

Other rectangles would not be quite as efficient as the square, but in terms of practicality, there is very little difference between a square and a rectangle as far as foundations the size of a house are concerned; in spite of this, evaluating the boundary to area ratio acts as a simple indicator on the compactness of the foundation design.

The value of ‘4’ given for the roof represents the general number of individually pitched sections required to roof the structure. This measure is based on very rough roofing practice, as the number of possible roofing options for any structure is vast. The roofing method here assumes a main double-pitched section with off-shoot sections as required; thus a simple rectangle would receive a value of 1, while a T- or L-shaped structure would receive 2. If slight overhang were accepted, many current single storey designs would only require 1 roofing section. However, in practice a single uniform roof is not aesthetically pleasing, viewed as boring or mundane, but aiming for this trend provides some guidance for design refinements.

**4.9.3 Design Refinements**

From Table 4.3, there are two main quantifiable goals that should be achieved while refining Design Plan 1; they should ideally be achieved without sacrificing floor area or material commitments.
1) Reduce the BR
2) Reduce the Roof value

By keeping to the original topological conception and the general plan layout, rearranging the modules is a relatively straightforward activity. In this case the activity is highly interactive; few moves must be made prior to being rejected. The result is Refined Plan 1, illustrated in Figure 4.21.

![Figure 4.21- Refined Plan 1](image)

The only complete module relocation occurred with Bath 1, all of the other modules are in relatively the same position, but they have been shifted to provide clean outside lines. Table 4.4 gives the performance of Refined Plan 1 in terms of the above measures alongside Design Plan 1.

<table>
<thead>
<tr>
<th>Plan</th>
<th>Usable Area (m²)</th>
<th>Negative Area (m²)</th>
<th>Panel Lg. (m)</th>
<th>Foundation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>193.2</td>
<td>20</td>
<td>95.0</td>
<td>88</td>
</tr>
<tr>
<td>Refined 1</td>
<td>210.7</td>
<td>22</td>
<td>112.5</td>
<td>68.3</td>
</tr>
</tbody>
</table>

Table 4.4- Refined Plan 1 performance
As demonstrated in Table 4.4, Refined Plan 1 improves upon Design Plan 1’s performance in each area: the usable floor area has increased by nearly 10%, reduced envelope panel length saves on material, the Boundary Ratio has been reduced (for 241.2, a square is 0.257 and a circle is 0.228), and the roofing may be much more straightforward.

![3D view of Refined Plan 1](image)

**Figure 4.22** - 3D view of Refined Plan 1

The rather large amount of open space in the centre of the plan can be used effectively through the use of partitions or perhaps in another version the long panel wall can be drawn in to create an external space with a foundation and a roof.

### 4.9.4 Additional Designs and Refinements

Following the same process as described above, from different topological configurations, three more Design Plans were generated. Following are Figures 4.23, 4.24 and 4.25 illustrating these new plans. Accompanying them are Tables 4.5, 4.6 and 4.7 rating the performance in the same manner Tables 4.3 and 4.4 did previously.
Design Plan 2 organizes the topological space in a slightly similar manner to several current plans, with the master bedroom separated from the other bedrooms by placing it just at the front entrance. The roof value of 2 is received because, allowing for slight overhang, all but the kitchen and dining room modules can be situated under one section.
Preliminary Plans 2 and 3 are very similar. They clearly illustrate one method current homebuilders use to increase their design range. By stretching key dimensions of the home, floor plans can really open up and enclose large areas. This is evidenced by the increase in size 186.35 as opposed to 150.5, a 24% increase. However this increase has greatly complicated the roofing of the plan.
Design Plan 4 illustrates a different approach, with the main flow and dividing axis of the house through the middle (very similar to the single storey plan seen in Figure 4.6.

The above four plans from a topological stand point are quite similar. To some degree the master bedroom is separated from the other bedrooms. Privacy to the children’s section of the house is maintained and can easily be increased through the addition of a small partitioning wall.

Following the generation of the Design Plans, the Refined Plans were created using the same principles as applied to the first example. The performance measures were
used to guide the refinements, taking care to improve or unchanged the various aspects. An important outcome of increasing the rectangularity of the footprint in addition to the affect on the foundation and roofing it also has an effect on how the house presents itself to the street and may be a determining factor in how it will make use of the yard.

Figures 4.26, 4.27 and 4.28 (and their accompanying performance tables) represent only one possible move from the preliminary plans illustrated previously, neither the preliminary plans nor their refined counterparts represent the full potential of combinations possible; from this scope of the organizational power of such a modular system can be more fully appreciated.

![Figure 4.26- Refined Plan 2](image)

<table>
<thead>
<tr>
<th>Plan</th>
<th>Usable Area</th>
<th>Negative Area</th>
<th>Panel Lg. (m)</th>
<th>Foundation Efficiency</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m²)</td>
<td>(Sq.)</td>
<td></td>
<td>Envelope (m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Footprint (m²)</td>
<td>BR</td>
</tr>
<tr>
<td>Design 2</td>
<td>150.3</td>
<td>15</td>
<td>52.1</td>
<td>64.3</td>
<td>0.36</td>
</tr>
<tr>
<td>Refined 2</td>
<td>165.2</td>
<td>17</td>
<td>67.0</td>
<td>64.0</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 4.8- Refined Plan 2 performance
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Figure 4.27 - Refined Plan 3

<table>
<thead>
<tr>
<th>Plan</th>
<th>Usable Area (m²)</th>
<th>Usable Area (Sq.)</th>
<th>Negative Area</th>
<th>Panel Lg. (m)</th>
<th>Foundation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 3</td>
<td>186.2</td>
<td>19</td>
<td>88.0</td>
<td>4.9</td>
<td>74.2 213.9 0.35</td>
</tr>
<tr>
<td>Refined 3</td>
<td>189.7</td>
<td>19</td>
<td>91.5</td>
<td>4.1</td>
<td>72 217.4 0.33</td>
</tr>
</tbody>
</table>

Table 4.9 - Refined Plan 3 performance
Each plan, to varying degrees, exhibits improvements over the first iteration. Without more specific guidelines such as climate, lot size, directional positioning (impacting the effect of sunlight) it is difficult to further refine the plans. Refined Plan 3 did not change significantly from Design Plan 3, largely just exhibiting a straightening of the exterior walls. Against the other plans, this organization does not seem ideal, especially in terms of roofing. However, on the right plot, or with homeowner input into interior partition placement, this plan could display several key advantages over the other plans.
The full potential of modular flexibility would never be realized if this method were the only one employed. It provides a good starting point, but is slow and inefficient for the task of evaluating numerous plans.

4.10 Automated Techniques for Design and Optimization

Several different approaches have been devised as solutions to the task, but there is an underlying similarity in their method as they attempt to explain to a computer what constitutes a good design.

The fundamental idea is to provide a computer with as few constraints as possible, and have it generate one or a number of layouts. Utilizing computers for this type of work relates directly with their use in determining least distance paths or optimized arrangements. Some of the first attempts to have a computer check the functionality of an arrangement were in factory layout settings.

While not closely related problems on the surface, both factory layout and house layout can be approached with the same tools. Each problem looks at the uses of a range of spaces (rooms or different machines) and their spatial relation to one another. In a production setting, Machine A must follow Machine B; just as in a house the ensuite must access the master bedroom. It might be convenient for box storage to be
next to Machine C, just as it’s convenient for the meals area to be adjacent to the kitchen.

The balance of topological configuration and spatial relationships must come together to allow any automated approach to generate a meaningful layout. There are several different ways in which these two facets of the problem have been addressed.

4.10.1 Optimization Techniques

The logical benefit of computer use for design is the ability to evaluate several or even many solutions and pick either the best or several that outperform the others. The key issue that must be addressed is how the computer will evaluate a given solution. Aesthetic judgements are still left to architects and homeowners; but mathematical expressions describing the ratio of living space (rooms) against access (hallways) and utility space (laundry), or the efficiency of the walls gauged by what area they enclose, are excellent measures that the computer can carry out, and that tell the designer something important about the solution.

Historically optimization on projects has been geared towards the costs involved, or on larger projects optimizing the work schedule for the quickest build (which directly translates into money). In recent years the drive towards environmental sustainability has increased the use of environmental measures while evaluating design solutions.

The evaluation of different parameters can be done by a wide range of techniques. Simple mathematical expressions can be figured for each solution, and then the maximum or minimum determined. Figure 4.30 and 4.31 show two simple floor plans. Each floor plan has been evaluated for Living Space Ratio [LSR] (Equation 4.5). In this case the LSR is simply the percentage of the plan that is not hallway. If we choose based on greatest liveable space then the floor plan with the highest ratio is preferred.
\[ \frac{A_{B1} + A_{B2} + A_{LR}}{A_T} = LSR \]  

Equation 4.5

Where:
- \( A_{B1} \) = area of bedroom 1
- \( A_{B2} \) = area of bedroom 2
- \( A_{LR} \) = area of living room
- \( A_H \) = area of hallway
- \( A_T \) = total area = \( A_{B1} + A_{B2} + A_{LR} + A_H \)
- \( LSR \) = living space ratio

Strictly in terms of area usage, Floor Plan 1 is the better choice because it yields a higher LSR. In this case 90% of Floor Plan 1 is in the rooms, compared to only 80% in Floor Plan 2.

If noise was a factor and the designer wanted to limit the amount of shared wall space between the Bedrooms and the Living Room Equation 4.6 could be used.
Chapter 4

Modular Approach to Home Design

\[
\frac{CW_{LR,B1} + CW_{LR,B2}}{BW_T} = NDF
\]  \hspace{1cm} \text{Equation 4.6}

Where:

- \(CW_{LR,B1}\) = common wall between the living room and bedroom 1
- \(CW_{LR,B2}\) = common wall between the living room and bedroom 2
- \(BW_T\) = total bedroom wall length
- \(NDF\) = noise disturbance factor

Floor Plan 1 has an \(NDF = 0.25\), while Floor Plan 2 has an \(NDF = 0\). Compromises between area usage and common walls can easily be found for this simplified example. When scaling up to a full-sized house, the principles remain the same; it is only the complexity of the problem that changes.

Table 4.11 reports the LSR results for the eight previously explored floor plans. The LSR for this assessment counts bedrooms, studies (if applicable), the family room, the dining room and all open-plan spaces as living space, while hallway, laundry, kitchen and bathrooms will not.

For a base comparison the 10 module set, arranged with no negative space (thus no open-plan spaces and no hallways), presents an LSR = 0.626 when the four smallest modules are used for bathrooms and laundry, and one second-largest module is used as the kitchen. Equation 4.7 presents this calculation:

\[
\frac{A_L}{A_T} = \frac{2 \times 15.18 + 12.18 + 2 \times 9.5}{2 \times (15.18 + 12.18 + 9.5 + 7.14 + 5.1)} = \frac{61.54}{98.2} = 0.626 \hspace{1cm} \text{Equation 4.7}
\]
Compared with the base value of 0.626, all of these plans yield superior LSR values, which illustrate the potential of negative-space design because often a high proportion of the added space was usable. The notion of usable space is important to the housing market (an extra large garage may make the house look bigger on paper, but it doesn’t impact organization within the home, so too with exterior dining areas).

With the exception of Refined Plan 3, each plan refinement increased the area of the home as well as the LSR. Refined Plan 3 increased the area, but decreased the LSR. This result may serve as an indicator that the refinement process needs to continue, or a particular solution was desired and valued over a slight LSR reduction.

The same principles used for the LSR can be applied to an investigation into the proportion of common family space, or entertaining space, in order to cater to different lifestyles.

Table 4.12 presents the NDF tabulation for the plans. The NDF presented simplifies and approximates various acoustical considerations. By finding ‘exposed’ bedroom walls and dividing by the total bedroom wall length, the percentage of walls dividing potentially noisy areas from bedrooms is found, with this measure, the smaller the number, the more isolated the bedrooms are, which is desired. The results primarily illustrate the varied outcomes given the same set of modules.
With respect to NDF, the initial Design Plan 1 performed the best. The path of refinement provided increased area, boundary ratio and living space ratio performance while sacrificing bedroom isolation. The other plans changed only marginally, both increasing and decreasing.

Given the three above parameters, optimization along single lines is a straightforward process. Increasing the complexity of the optimization to a two or three parameter problem would drastically affect the pursuit of an optimized plan. Additionally, real-world optimization along these lines could conceivably include many more parameters, each ranging from quite simple to very complex.

For many parameters, expressions of performance, such as with the LRS in this example, can be mathematically simplified to promote efficiency and eschew ineffectual refinement loops. The difficulty arises when instructing the computer how to balance good performance in one area with poor performance in another. The goals sought largely dictate the final form of the decision-making matrix that is ultimately applied to a series of possible solutions.

This final step of computer automated optimization and planning is an emerging field. Advancements that have applicability to housing have often been made in areas such as circuit design and factory layout optimization. The methods discussed in Section 2.7 illustrate the varied approaches being developed. The crucial hurdle has been
programming preference to guide design refinements. Because of this, several programs have opted for a crude rejection filter to allow for human interaction to select and discern good from slightly better. In the future homeowners may interact with design programs in much the same way as they interact with architects and engineers now.

This chapter has examined the potential for modular systems to provide adequate planning flexibility for the Australian housing market. This is important because housing options will allow a modular system to be competitive in the market and ultimately supply homeowners what they expect from a house.

From an investigation into the current practices by several builders, it has been established that the standards met by most houses are common to all builders. These standards, both in terms of sizes and layout regimes, offer a strong model for new system specifications. From this, the modular system displayed adequate potential for the purpose of encompassing a range of accepted housing plans with a handful of different modules. This allows for the economic production of modular houses in a factory setting.

Further, techniques and methods were touched on that could be employed to bring sophisticated optimization tools to the task of home design. From layout programs to traditional optimizations of resource and material, computer design can play a strong role in the increased sustainability of the housing market.
Chapter 5
Environmental Performance

5.1 Introduction

During the literature review several interpretations of the term ‘sustainability’ as could be applied to domestic construction were encountered. By drawing on these outlooks and goals, as well as the current methods utilized by the residential housing market, a program of environmental improvement began to take shape. It was also discussed that although the present state of technology puts nearly any goal within grasp; however economics, industry practices and infrastructure may limit the realistic extent of expected outcomes. In addition, ‘perceptions’ of PMHS limit the impact of such frameworks.

This chapter assesses the constraints of two of those outcomes, namely waste and embodied energy reduction within the high-volume residential construction market. As there are numerous steps that can be undertaken to achieve either of these goals, this chapter aims to illustrate the achievability of positive outcomes. The objective is to evaluate the ability of modular systems to realize gains over current practice in these areas.

By looking at the standards currently achieved and assessing the potential for modular systems to better their performance, an indication of outcome improvement should begin to emerge.

5.2 Sustainable Housing

Previously ‘sustainability’ was discussed and explored as a concept, as a goal and as a process of improvement (Section 2.6). From the wide range of presented ideas, sustainable housing can be defined as a design and construction process whose aims are to provide high quality housing in such a way as to reduce the environmental burden they represent.
From the literature, outcomes that are both achievable with various housing systems and would provide the greatest benefit to the environment were identified. Figure 5.1 revisits the diagram previously presented in Chapter 3. The three key areas that the system seeks to address: Embodied Energy, Waste Reduction and Efficient Material Use.

![Figure 5.1- Three-pronged environmental sustainability goal](image)

Embodied Energy is the required energy to produce a product. Houses require production and transportation energy inputs to process raw materials into a final product. As energy consumption continues to increase the importance of efficient energy use grows more important. Operational energy requirement reductions are a key element of this issue, but significant amounts of energy are consumed prior to building completion, and this is an area where efficiency can be improved. It is also important to note that addressing the operational perspective exclusively can result in net decrease of energy efficiency; a particular example is the use of high-intensity insulation to prevent heat loss, where the environment must provide more energy to produce the insulation than it would to offset the heat loss.

Waste Reduction: Natural resource use is a critical issue in some sectors, and could be in others in the future. The realization of waste reduction can be achieved in two ways.

- Improved Material Use Efficiency – this aspect deals with generating a smaller percentage of material unused by construction which is important both in terms of environmental burden but can also reduce embodied energy intensity.
* Improved Material Reuse – concerns material waste redirected from landfill for use in other projects as well as aspects of deconstruction and reuse at the end of a structure’s life-cycle.

Efficient Material Use: While waste reduction is important, it is more beneficial to the environment to simply use fewer raw materials in the first place.

Material waste reduction and use can be thought of as the input and output of material on a construction site. Figure 5.2 is a flow chart illustrating how, in these terms, progress is envisioned to be made.

![Diagram of Environmental Inputs and Outputs of Home Construction](image)

**Figure 5.2:** Environmental Inputs and Outputs of Home Construction

The focus of this project is on the processes above the horizontal line, as opposed to many current approaches addressing issues below. Figure 5.2 above treats waste and efficient material use as separate things. Waste is identified as an occupational output, while efficient material use is concerned with material as an input (wasteful input to phrase it differently). This distinction is important in that exclusive focus on recycling waste material so not improve the situation of resource removal from the environment.
The following sections expand upon these relationships and how the practices governing the quantities involved may be improved or in some cases replaced in an effort to more finely tune home construction towards reduced environmental impact.

5.3 Embodied Energy

Energy consciousness is playing an increased role in Australian society today. As media reports (Hodge, 2005; Duncan 2005) and television reports indicate, greater emphasis is being placed on the efficient operation of the home and society in general (both in terms of energy and in other areas such as water as mentioned previously). Low-flow shower heads and more efficient toilets are being introduced and awareness is steadily being raised. Behavioural changes are also taking place, especially with regard to water savings (watering at night, washing cars with buckets, etc.). Efficient light bulbs in homes and the increased prevalence of smart lighting system in office buildings (with sensors to reduce unused light) are also influencing consumer energy consumption.

Within this emerging culture of environmental awareness, typified by responses to increased greenhouse gas emissions and energy consumption (Paterson, 2005), one area that is often overlooked by the general population as well as learned people is embodied energy.

As previously mentioned embodied energy is the measure of the total amount of energy, both direct and indirect, that goes into producing a product (Crawford, 2005). Assessments of this nature, whose scope traces inputs along the entire length of the supply chain, from raw materials on down, are important to give a greater understanding of how complex production process are and provide a more accurate view of the true impact production and consumption can be.

5.3.1 Embodied Energy Measurement

The concept of embodied energy highlights a very informative way in which processes can be examined for efficiency and whole-of-life impact. However
methods and goals employed to give measures of embodied energy are varied and allow for a wide range of results for even the simplest of products.

With current discussions around global warming, the topic of CO$_2$ emissions has become a topic of great focus and importance. Studies have often examined the resulting CO$_2$ emissions in conjunction with energy requirements (Buchanan and Honey, 1994; Suzuki, Oka and Okada, 1995). These studies have been investigating the improvement of air-quality impact by identifying materials that represent reduced CO$_2$ emissions. Timber has unsurprisingly performed consistently better than other materials such as steel or concrete. As with all aspects of environmental impact however, the whole picture is much more complex. It is noted that neither current reforestation nor common building practices are well suited to push the use of timber to the extreme for the benefit of air-quality.

A popular method of evaluating embodied energy is by measuring the thermal energy represented by quantities of materials. Reddy and Jagadish (2003) investigated the energy consumed by the production of several basic construction materials in India. Table 5.1 illustrates the wide range of embodied energies that materials can posses.

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>Embodied Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement</td>
<td>5.85</td>
</tr>
<tr>
<td>Lime</td>
<td>5.63</td>
</tr>
<tr>
<td>LP Cements</td>
<td>2.33</td>
</tr>
<tr>
<td>Steel</td>
<td>42.00</td>
</tr>
<tr>
<td>Aluminium</td>
<td>236.80</td>
</tr>
<tr>
<td>Glass</td>
<td>25.80</td>
</tr>
</tbody>
</table>

Table 5.1- Embodied Energy of common construction materials in India (Reddy and Jagadish, 2003)

5.3.2 Embodied Energy Values

As embodied energy values factor in processing methods as well as transportation of materials, etc. there is always a variation depending on locality as well as other factors. Presented below, in conjunction with Table 5.1 above, are values from both
the US and Australia of embodied energy of some common construction materials. From these values the hierarchy of intensities will be apparent.

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>Embodied Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium – Sheet</td>
<td>180</td>
</tr>
<tr>
<td>Copper – Cable</td>
<td>115</td>
</tr>
<tr>
<td>Plastics – Polystyrene</td>
<td>110</td>
</tr>
<tr>
<td>Glass – Clear Float</td>
<td>90</td>
</tr>
<tr>
<td>Paint</td>
<td>55</td>
</tr>
<tr>
<td>Steel – Reinforcement</td>
<td>40</td>
</tr>
<tr>
<td>Ceramics – Porcelain</td>
<td>25</td>
</tr>
<tr>
<td>Timber – Particle Board</td>
<td>20</td>
</tr>
<tr>
<td>Clay Products – Bricks</td>
<td>6</td>
</tr>
<tr>
<td>Timber – Hardwood</td>
<td>5</td>
</tr>
<tr>
<td>Plaster – Gypsum</td>
<td>4</td>
</tr>
<tr>
<td>Fibreglass Insulation</td>
<td>3</td>
</tr>
<tr>
<td>Concrete – 20 MPa</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.2– Embodied Energy of common construction materials in Australia (CSIRO, 2004)

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>Embodied Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>170</td>
</tr>
<tr>
<td>Synthetic rubber</td>
<td>110</td>
</tr>
<tr>
<td>Copper</td>
<td>100</td>
</tr>
<tr>
<td>Plastics - general</td>
<td>90</td>
</tr>
<tr>
<td>PVC</td>
<td>80</td>
</tr>
<tr>
<td>Acrylic paint</td>
<td>61.5</td>
</tr>
<tr>
<td>Galvanised steel</td>
<td>38</td>
</tr>
<tr>
<td>Hardboard</td>
<td>24.2</td>
</tr>
<tr>
<td>Imported dimension granite</td>
<td>13.9</td>
</tr>
<tr>
<td>Glass</td>
<td>12.7</td>
</tr>
<tr>
<td>MDF</td>
<td>11.3</td>
</tr>
<tr>
<td>Glue-laminated timber</td>
<td>11</td>
</tr>
<tr>
<td>Laminated veneer lumber</td>
<td>11</td>
</tr>
<tr>
<td>Plywood</td>
<td>10.4</td>
</tr>
</tbody>
</table>
Table 5.3- Embodied Energy of common construction materials in Australia (Lawson, 1996)

<table>
<thead>
<tr>
<th>Type of Material</th>
<th>Embodied Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>227</td>
</tr>
<tr>
<td>Carpet – Synthetic</td>
<td>148</td>
</tr>
<tr>
<td>Polystyrene Insulation</td>
<td>117</td>
</tr>
<tr>
<td>Linoleum</td>
<td>116</td>
</tr>
<tr>
<td>Paint</td>
<td>93.3</td>
</tr>
<tr>
<td>Copper</td>
<td>70.6</td>
</tr>
<tr>
<td>PVC</td>
<td>70</td>
</tr>
<tr>
<td>Zinc</td>
<td>51</td>
</tr>
<tr>
<td>Steel</td>
<td>32</td>
</tr>
<tr>
<td>Fibreglass Insulation</td>
<td>30.3</td>
</tr>
<tr>
<td>Mineral Wool Insulation</td>
<td>14.6</td>
</tr>
<tr>
<td>Plywood</td>
<td>10.4</td>
</tr>
<tr>
<td>Asphalt Shingles</td>
<td>9</td>
</tr>
<tr>
<td>Particleboard</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 5.3- Embodied Energy of common construction materials in Australia (Lawson, 1996)
Chapter 5

Environmental Performance

<table>
<thead>
<tr>
<th>Material</th>
<th>EE (Kibert, 2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose Insulation</td>
<td>3.3</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>3.1</td>
</tr>
<tr>
<td>Lumber</td>
<td>2.5</td>
</tr>
<tr>
<td>Brick</td>
<td>2.5</td>
</tr>
<tr>
<td>Concrete – 30 MPa</td>
<td>1.3</td>
</tr>
<tr>
<td>Aggregate</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 5.4 - Embodied Energy of common construction materials in the USA (Kibert, 2005)

The above tables show the general magnitude of embodied energy for various materials; they also illustrate the variation that can occur due to location, measuring time and methods, etc. It is important to remember that each value is given per unit weight. This is an important factor as the volume of material per unit weight can vary greatly between, say, aluminium and steel.

Table 5.5 illustrates the similar yet non-identical values for a few materials from each of the above tables.

<table>
<thead>
<tr>
<th>Material</th>
<th>CSIRO</th>
<th>Lawson</th>
<th>Kibert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>180</td>
<td>170</td>
<td>227</td>
</tr>
<tr>
<td>Steel</td>
<td>40</td>
<td>38</td>
<td>32</td>
</tr>
<tr>
<td>Bricks</td>
<td>6</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Concrete</td>
<td>2</td>
<td>1.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 5.5 - Side-by-side comparison of a few EE measurements

It is important to remember that the measurements by each party are separated not only by time and location (CSIRO and Lawson in Australia, Kibert in the USA), but that the exact product measured were not identical (CSIRO measured 20 MPa concrete, Lawson in-situ concrete and Kibert 30 MPa concrete). This highlights a fundamental difficulty in making true accurate assessments about embodied energy, that discrepancies noted in measurement can be as much a part of industrial changes as they are measurement practices. That being said however, it can be taken away that these figures help provide a reasonably consistent context for future measurements.
Both Kibert (2005) and CSIRO (2004) acknowledge the positive benefit that recycling can have on the embodied energy of a product. Kibert (2005) notes that recycled aluminium only represents 8.1 MJ/kg, nearly 96% less than the 227 MJ/kg noted for new aluminium. CSIRO reports nearly 95% savings on aluminium. However, not all products yield quite such dramatic results. Kibert finds that recycled steel represents a 73% savings, and CSIRO finds glass at only 20%.

According to CSIRO (2004), the average embodied energy for Australian homes lies between 4.5 GJ/m² and 5.5 GJ/m². For a home of 200 m² (slightly less than the current average), at 5 GJ/m², upon completion will represent 1000 GJ of energy.

![Embodied Energy against Operational Energy](image)

**Figure 5.3- Embodied Energy against Operational Energy (based on Milne, 2004)**

Figure 5.3 illustrates the relationship between a dwelling’s embodied energy and three operational rates. Each operational rate (high, normal and low) show the cumulative energy used to run a household (lighting, power, heating, etc.). The value at a given time represents the amount of energy that has been used to run the home during to that point in time. The slope of the embodied energy line accounts for maintenance and renovation to the structure over its life-cycle.

Each operational rate is evaluated based mainly on thermal efficiency and power requirements (lighting, appliances, etc.). It should be noted that these values can vary widely with climate, construction type, lifestyle, and temperature control method.
• High – 66 GJ/year – may use inefficient heating or cooling systems, low insulation, high power consumption lifestyle (multiple televisions, computers, inefficient lighting, etc.)

• Normal – 55 GJ/year – average performance for temperature control efficiency and power consumption

• Low – 44 GJ/year – efficient insulation or temperature control systems, high efficiency lighting (perhaps increased natural lighting)

For houses lasting 100 years, of the total energy used for construction and operation, between 15% and 20% of it resides within the building. If 5 million homes are built in the next century at the current levels, the amount of energy consumed will be around 39,000,000 TJ, of which 5,850,000 to 7,800,000 TJ will reside in the homes.

Research has been done to identify the proportional contributions to embodied energy for single dwelling homes (Ting, 2006). Figure 5.4 provides results from the analysis of a two-storey single dwelling home in Victoria using the Bill of Embodied Energy [BEE] program. BEE is used to estimate both the cost and embodied energy of construction projects for evaluative and optimization purposes. The house was 320 m\(^2\) including the garage and was a four bedroom home built to typical STBC standards. The home was concluded to embody roughly 1310 GJ of energy at the time of completion. Per unit area this comes to 4.1 GJ/m\(^2\).
Chapter 5  
Environmental Performance

As illustrated, the predominate component of the embodied energy is the external walls, due to their external finishes (brick, etc.) as well as their extra insulation and material not required on interior structures. This distribution encourages the use of modular systems as they heavily target external walls, thus yielding potential for a large impact when factored for the number of new homes produced in Australia.

Traditionally the focus has been on reducing the operational rates on which houses are run. Methods include efficient light bulbs, improved insulation and temperature control systems, more energy efficient appliances, etc. These actions are all very worthwhile; they do and will continue to have a significant impact on the rate of energy consumption. However, ABS (2002) noted that Australians used an average

---

**Figure 5.4**- Embodied energy breakdown by housing component (Ting, 2006)
of 20 GJ per person in 1999. It was also estimated that “current residential energy efficiency measures are projected to only slow the rate at which our residential energy consumption increases”. This observation has recently highlighted the importance of the embodied energy component of the equation has gained in prominence. The goal being to not only reduce the slope of the rate lines shown in Figure 5.3, but to effectively reduce the intercept of the embodied energy line; knowing that factoring it over the large number of homes to be built in the future will translate into a measurable and worthwhile result.

5.3.3 Embodied Energy Reduction

The methods available to builders seeking to reduce the embodied energy of home construction are numerous and tend toward organizational approaches as opposed to specific technological ‘silver bullets’, i.e. processes that will automatically reduce the amount of energy required for a particular process. However the use of new products and technologies can have a positive impact, both on embodied energy and material considerations (discussed in Section 5.4). Products such as precast fake-brick panels can effect construction time, energy requirements, and overall material demands.

Several of the world’s leading sustainable building rating guides, LEED (USA), BREEM (UK) and GreenStar (Australia), include and encourage steps that can be taken to improve the operational and embodied energy component of housing design and construction.

As illustrated above, the use of recycled materials is one of the best ways to reduce embodied energy. Other methods include optimization of transportation schedules, as well as optimized processing and handling procedures. There is a limit to the amount of impact a builder can have however, thus it is important for manufacturers to do what they can as well. Builders as well as the government both can play a driving role in the steps manufacturers and processors will take to improve their energy consumption results.
5.4 Material Waste

Waste collection is an important part of the operation of any residential area. Weekly garbage collections, recycling, perhaps garden waste programs, these are all integral to the comfortable running of a municipality. Proper depositing of waste is an important task in any walk of life, especially in industrial contexts where the amount of waste can be very large, or potentially hazardous. Disposal procedures for construction materials are carefully controlled and evaluated, particularly with respect to hazardous waste, but also with respect to improve site aesthetics and reduce public disturbance (especially in city construction).

Further, societal consciousness of the impact of physical waste, from the introduction of widespread recycling programs to social commentary in the media, is growing. The construction of houses is not typically an area people consider as a source of landfill material, but it is; and in light of the projected number of homes to be built over the next several years, it is an area where gains can have a real impact. In addition to the material aspect of impact, embodied energy intensity is affected by material waste and the transportation that goes into its removal.

5.4.1 Waste Amounts

In order to effectively approach the issue of waste reduction and understanding of the materials and volumes involved is important. With a grasp of the amount of material at issue, the efficiency of any particular solution can be evaluated. This is significant as one of the current governing factors is economic efficiency, and this measure will certainly play a central role in any potential solutions.

Forsythe et al (2000) determined that on average the construction of a single home (neglecting excavation and demolition) generates approximately 15.8 kg/m$^2$ of waste, as calculated against gross floor area. At that rate, for houses averaging 227 m$^2$, that comes to roughly 3500 kg of material.

For some perspective, at 2300 kg/m$^3$, that comes to 1.5 m$^3$ of concrete, or roughly 6.2 m$^3$ of wood at 560 kg/m$^3$. At the projected level of 221,000 home-construction starts from spring 2006 to fall 2008, which would generate 770 thousand tonnes of material.
Friedrich Schmidt-Bleek coined the term *ecological rucksack* as a measure of the amount of material that must be moved to produce a specific resource (Kibert, 2005). In much the same way embodied energy provides a more accurate assessment of energy consumption, examining the ecological rucksack demonstrates the importance of reuse and recycling as much as possible. Table 5.6 gives the amount of material (in kg) that must be displaced to produce 1 kg of the product.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ecological Rucksack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>85</td>
</tr>
<tr>
<td>Recycled Aluminium</td>
<td>4</td>
</tr>
<tr>
<td>Steel</td>
<td>21</td>
</tr>
<tr>
<td>Recycled Steel</td>
<td>5</td>
</tr>
<tr>
<td>Platinum</td>
<td>350,000</td>
</tr>
<tr>
<td>Gold</td>
<td>540,000</td>
</tr>
<tr>
<td>Diamond</td>
<td>35,000,000</td>
</tr>
</tbody>
</table>

Table 5.6- Ecological rucksack for selected materials (Kibert, 2005)

Allowances must be made for the irregularity of resource acquisition in terms of location and method of resource extraction. This concept offers a context for the notion of environmental disturbance as a result of material use. From this graph it can be shown that recycled aluminium requires the movement of 94% less earth material as opposed to new aluminium. This environmental impact can be affects embodied energy as well as the natural landscape from which the resource is taken.

The ecological rucksack provides another method of evaluating the ultimate environmental impact of construction. Decision parameters may well include these types of analysis in order to provide the most representative evaluation of designs and practices.

### 5.4.2 Options and Solutions

The generation of waste on the work site is not particularly a product of gross neglect or any specific fault of the labourers or foremen. The simple fact is that every little
bit adds up: little bits of wood, those extra bricks ordered just to be safe, and that bit of packaging, etc. The industry has found that, on a per site basis, it is just not in their economic best interest to attend to all of these little waste sources, to save time for their workers, a large bin is provided, waste is deposited, and at the end of the build it is hauled away.

This picture is not to say that nobody cares about waste and that there are not programs in place to take some steps, but simply that it would be impractical to do much more within the current system.

When there are incentives and benefits and the scale of the operation makes greater attention to detail worth while, a large impact may result.

**WasteWise Construction Program**

WasteWise (DEH, 2001) was a program run between 1995 and 2001. It was a partnership between the Australian government and several voluntary construction companies with the goal of reducing the amount of material waste going to landfill. While the projects focused on were commercial and not residential in nature, the methods used could be applied to any construction job.

The following tables summarize some of the results obtained in each of the two phases of the program. Following the tables is some discussion on how the methods used can be applied to a residential construction, both currently and by using modular systems.
### Table 5.7- WasteWise Phase I achievements

<table>
<thead>
<tr>
<th>Company</th>
<th>Achievements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bovis Lend Lease Pty Ltd</td>
<td>98% of waste material recycled from State Office Block site, Sydney</td>
</tr>
<tr>
<td></td>
<td>90% of steel and concrete waste sent to recycling centres in 1997</td>
</tr>
<tr>
<td>Multiplex</td>
<td>60% site waste recycled from Homebush Bay Olympic Stadium in 1997</td>
</tr>
<tr>
<td></td>
<td>Implemented concrete re-use system, crushing and reusing 32,000 m$^3$ of concrete</td>
</tr>
<tr>
<td>John Holland</td>
<td>Reused or recycled 760,000 kg of waste in one year</td>
</tr>
<tr>
<td>Fletcher Construction</td>
<td>43% waste reused or recycled from Dandenong Police and Court Buildings</td>
</tr>
<tr>
<td></td>
<td>Waste reduction techniques developed through WasteWise used internationally</td>
</tr>
<tr>
<td>Barclay Mowlem</td>
<td>55% timber framework recovered and recycled at the Vantage Apartment site</td>
</tr>
</tbody>
</table>

After the initial successes of WasteWise Phase I, more entities were eager to participate in Phase II. Phase II was not just an extension of Phase I in that there were construction companies improving their waste performance, but there were also professional and oversight organizations involved to improve their practices and to further educate the industry and their members.
Table 5.8 provides a brief summary of a few of the outcomes and achievements experiences by some of the participants of Phase II in 1999.

| The Australian Institute of Building |  
| Added Waste Minimisation Code of Practice to policy statements |  
| Chapters included waste minimisation seminars for continuing development |  
| Barclay Mowlem Construction Limited |  
| Implemented waste separation techniques on all construction sites |  
| Developed and implemented a comprehensive environmental management system |  
| Imposed waste minimisation requirements on subcontractors |  
| Bovis Lend Lease Pty Ltd |  
| Diverted 75% (254,000 m³ of 337,000 m³) of waste from landfill |  
| Practiced waste avoidance in addition to above reuse and recycling |  
| Housing Industry Association Limited |  
| Partnerships Advancing the Housing Industry program for waste and energy |  
| Instituted waste management training and education seminars |  
| John Holland Group Pty Ltd |  
| 86.8% by weight (76.6% by volume) of waste diverted from landfill |  
| Rail division diverted 100% of 80 tonnes from landfill |  
| Multiplex |  
| Focused on reducing waste, returning waste to supplier and recycling separation |  
| Conscientious ordering to reduce on-site modification and thus waste |  
| Imposed waste minimisation requirements on subcontractors |  

Table 5.8- WasteWise Phase II, 1999 achievements

Phase II in 2000 and 2001 found many of the companies adopt or refine similar strategies in an effort to continue their outstanding results. In 2000 John Holland diverted 78% (by volume) of its total generated waste from landfill; Multiplex achieved 73%. Similar results were reported during 2001 as well.

Several of the methods used by the participants of the WasteWise program to reduce cost and waste can be applied directly to modular housing construction. The Multiplex Citibank project in Sydney offers excellent examples of several of these
principals. The 54 storey high-rise construction involved first the demolition of the on-site building prior to construction. 98% of the demolished material was recycled. Demolition is not usually part of suburban construction, but the methods used during construction were equally successful. Three key strategies were employed to reduce construction waste:

- Waste “designed out” through the use of prefabricated panelling and sandstone facades.
- Plasterboard ordered and delivered pre-cut, reducing off-cut waste by 70%, thereby reducing plasterboard costs by 40%.
- Material delivery packaging eliminated and other reusable elements (paint tins, palettes, crates, etc.) were returned to suppliers or recycled.

Designing out waste is an approach where materials are ordered pre-cut or shaped to avoid such work being completed on site. Such an approach is well suited to modular production. Factory production allows per-unit costs to be reduced through bulk orders and shipments. The efficiency for a manufacturer to initially produce a properly sized component is increased through the use of identical modules provided a range of different plans; thereby improving optimization. Conscientious design and supply can also have a positive effect on the cost of a product. Additionally, bulk factory supply can foster packaging return programs as the transportation of such items can be streamlined from a single production facility more easily than from numerous individual sites.

All of these steps were made possible through the use of waste management plans developed in conjunction with subcontractors, promoting an efficient and holistic method for environmental responsibility. Waste management also has an impact on the overall energy intensity of a project. The energy to produce and transport waste material from a home is still linked to the production of the home; the end result of waste is material with a higher resultant embodied energy.

One of the main potentials for prefabricated housing, regardless of the materials or construction methods used, is the centralization of waste production. The economics
and logistics of carrying out waste management plans are greatly simplified when 
waste generation occurs at one factory, not 10, 15, 40 sites around a metropolitan area. 
The feasibility of returning 100 kg of material from each of 40 different sites is 
unacceptable for both cost and environmental reasons. Cost for the price of the fuel 
and the time it takes to move that amount of material around, and environmentally for 
all the driving that needs to take place. However organizing the return of 4000 kg of 
material from one location is much more straightforward.

The efficiency of material use can also increase in some instances with a centralized 
production operation through self-reuse. Off-cut from one production step may be 
used in-house in another step. The impracticality of employing the off-cut on an 
individual site may prevent that for temporal (step 8 produces material perfect for step 
2) or economic reasons; but these issues can be diminished or eliminated in an 
organized factory setting.

Quantifying effects with the ecological rucksack measure and others such as 
embodied energy help to guide and influence decision making, both for corporations 
and governments; but one of the most valuable uses is in the education of the public. 
Water resources have recently enjoyed increased education programs, and most 
readings of the situation demonstrate that the education is having a positive impact in 
both attitude and behaviour.
Chapter 6
Structural Validation and Optimization

6.1 Introduction

The suitability of modular systems to produce traditional Australian house designs while still retaining their re-configurability was treated in Chapter 4. The environmental benefits of modular development’s organizational structure were discussed in Chapter 5. Figure 3.1 presented three key elements, the last of which is discussed in the following chapter: structural engineering of PMHS.

The aim of this chapter is concerned with the validation of the PMHS approach with regard to structural issues, specific design falls outside the scope of this project. Two areas of investigation will be addressed to achieve this aim. First a module will be assessed against current Australian standards to verify the potential for modules to adequately resist expected loading both from occupation and from transportation. Second the technique of Evolutionary Structural Optimization [ESO] (Xie and Steven, 1997) will be applied to a module to investigate the potential for module improvement in terms of structural material efficiency.

6.2 Australian Housing Standards and Conditions

Home construction is a well understood and carefully controlled activity. Numerous codes and guidelines have been written and rewritten to ensure quality and safety for each and every homeowner. Specifications cover nearly every facet of home design and construction, far too many to address within the scope of this project. While compliance with all relevant codes is crucial, here the investigation will be limited to a narrow portion of structural design requirements. Specifically the resistance of expected loading conditions applied to the module during transportation and resident occupation.
For the purposes of this investigation, the loading conditions explored will consist of vertical and horizontal loadings acting upon an individual module during occupancy as well as potential forces applied during transportation. These measures of performance will give an indication of the suitability for modular applications in the housing sector.

Loading criteria are determined by the likelihood that a structure will experience a given loading condition during its life-cycle. The most important loading classification is ‘dead load’. Dead loads are forces that result from the structure itself. In this single storey investigation, the dead load is comprised of the walls themselves and the roof. Dead loads indicate that there is a 100% that the build structure will be forced to resist the loads. In order to ensure safety, loading factors are used to give a margin of safety to the design.

The second key loading class are live loads. Live loads result from non-structural forces that may be applied. Occupants and furniture are predominately the two considerations with respect to houses. Live loads are more unpredictable than dead loads and so factors are again employed to account for this to ensure a safe structure.

Other common loading classifications are wind, snow and earthquakes. Both dead and live loads in addition to snow loads are typically regarded as vertical loads, whereas wind and earthquake loadings are typically horizontal in action (though wind can have a significant vertical effect).

6.2.1 Vertical Loading

Vertical loads are typically applied to a structure by gravity (weight of roof, upper floors, snow build-up, etc.). Another consideration to vertical loading conditions is the effects of wind. Wind can both push down on a structure as well as create a suction force pulling up. This suction force can be dramatic and devastating to a structure in rare cases (typically highly cyclonic events). For this investigation however, suction forces are neglected as the roofing design considered is not a lightweight classification. Table 6.1 below illustrates a few generic roofing packages and their respective mass per unit area from Australian Standards International [ASI].
Table 6.1- Mass of typical roof constructions (ASI, 2002)

<table>
<thead>
<tr>
<th>Mass of roof (kg/m²)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Steel sheet roofing 0.50 mm thick and battens</td>
</tr>
<tr>
<td>20</td>
<td>Metal sheet tiles or medium gauge steel sheet roofing, battens, 12 mm softwood ceiling lining, sarking and lightweight insulation</td>
</tr>
<tr>
<td>30</td>
<td>Steel sheet roofing 0.75 mm thick, 13 mm plaster ceiling, roof and ceiling battens, sarking and lightweight insulation</td>
</tr>
<tr>
<td>40</td>
<td>Steel sheet roofing 0.75 mm thick, battens, graded purlins and high density fibreboard ceiling lining</td>
</tr>
<tr>
<td>60</td>
<td>Terracotta or concrete tiles and battens</td>
</tr>
<tr>
<td>75</td>
<td>Terracotta or concrete tiles, roofing and ceiling battens, 10 mm plasterboard, sarking and insulation</td>
</tr>
<tr>
<td>90</td>
<td>Terracotta or concrete tiles, purlins, roofing and ceiling battens, 19 mm hardwood ceiling lining, sarking and insulation</td>
</tr>
</tbody>
</table>

The range of different roofing options gives an indication of how much potential exists in the area of material optimization. Targeting roofing practices, including the changed structural component, may be an important companion to this investigation of wall-systems.

To resist the vertical loads imposed by gravity, the wall must be able to support the weight both out-right but also be able to resist toppling. In the case of traditional framing, each stud may be able to resist the load applied to it, but a series of balanced studs is very unstable and thus very dangerous. Figure 6.1 illustrates typically framed room showing the vertical studs as well as the horizontal top plate, bottom plate and noggings (intermediate lateral support). These supports prevent tipping and in high-load cases (typically encountered in larger steel structures) the buckling of the vertical members.
6.2.2 Horizontal Loading

Horizontal loads on houses come primarily from wind and in some places earthquakes. A horizontal force is one that attempts to slide, collapse, tip-over a structure. As wind forces are difficult to predict, different locations are classed based on their typical wind conditions. These wind conditions are based on the most intense weather conditions likely to be encountered, from non-cyclone areas where the maximum wind comes from thunderstorms, to severe tropical cyclone areas at high risk to encounter devastating winds (ASI, 1998).

For the purposes of this project, earthquake loading conditions will be neglected for simplicity and time limitations.

Horizontal loads are resisted by lateral bracing (such as noggins are illustrated above in Figure 6.1, or cross bracing if required). This bracing prevents failure by collapse. The connections of a wall to the foundation and the other walls (in this capacity described as shear walls) provide resistance to sliding and tipping of the structure. For this investigation, concrete is going to be analysed. Given concrete’s density, it is assumed that sliding and tipping are counter acted by the friction and weight, respectively, of the structure. Should friction and weight not provide the necessary resistance; there are numerous methods to structurally enhance the joining of walls to foundations. In light of these solutions, for this investigation it will be assumed that weight and friction do provide the necessary resistance.
6.3 Structural Analysis of a Module Wall

The wall will be analysed for its performance in resisting both vertical and horizontal loads. The intended outcome of this analysis is to observe the behaviour changes when holes are placed in the structure. Full structural design in conformance with the relevant building codes is beyond the scope of this performance, but can be reasonably straightforward for standard construction practices. Complexities increase when optimizing structures as is dealt with in Section 6.4.

As mentioned previously, the module to be analysed is modelled as a concrete structure. Analysing concrete provides two advantages over analysing a timber frame model: firstly concrete performance is topical as it has been used as a modular material (“Modular Precast”, 2005), and secondly the analysis will provide an indication of the performance of possible future continuum constructions. Continuum constructions are built with one uniformly (or nearly so) material configuration (such as a concrete slab or wall, or steel plates). Frames, such as stud walls, behave differently and exhibit different failure modes. Also, a uniform concrete structure simplifies ESO analysis so focus may be placed on the process taking place.

The wall analysed is 2700 mm in height, 4000 mm in width and 120 mm thick. The concrete used for this analysis in SAP2000 had a density of $2356 \text{ kg/m}^3$ and had a compressive strength of 25 MPa. Figure 6.2 shows the von Mises stresses (discussed in Section 6.4.1) resulting from vertical and horizontal loads (originating from the right side of the wall).
With the forces action down and to the left, a stress build-up in the lower left corner is expected; and is indeed clearly visible in the figure. Figure 6.3 shows the same loading conditions acting on a wall with similar properties but with a doorway placed in the structure.
Figure 6.4 presents the same wall with the same magnitude of horizontal loads acting from the left towards the right. In each doorway case stress build-up can be seen in each lower corner away from the force application against the doorway and the opposite edge of the wall. It is worth noting that a large portion of the material on the other side of the opening from the load is less-stressed than it was previously without the doorway and the uniformity of stress distribution along the top of the wall is interrupted by the doorway. These behaviours illustrate the uneven use of material load-bearing capacity. Optimization of this behaviour provides a potential avenue for material reduction, thereby allowing for material and energy intensity reduction per module.

### 6.4 Evolutionary Structural Optimization

One of the primary objectives of investigating modular housing is to assess its ability to drive sustainable innovation. In Chapter 5 the point was made that material waste is an issue of concern within the domestic construction market as this area has both impact both on natural resources and embodied energy. Additionally it was discussed that increasing the efficiency of material use is one method to address this issue.
Evolutionary Structural Optimization [ESO] is a powerful approach that allows for the optimization of structural elements in terms of the material used. The approach uses a combination of Finite Element Analysis [FEA] and iterative element removal to optimize a shape through a step-by-step evolutionary process.

### 6.4.1 ESO Theory

FEA is an analysis method where an element is analysed as a composite of many small elements, each with their own stress characteristics. The advantage in FEA stems from the picture that can be achieved, through the use of computers, of the manner in which the element is resisting and supporting the loading. ESO stems from the observation that “more often than not it is found that part of the material is under-stressed compared to the rest of the structure” (Xie, 1997, p.13). Combining the ability to detect inefficiencies and the goal of improving upon said found inefficiencies, ESO results.

After the initial FEA analysis specific under-stressed elements can be identified and selected for removal. Once the elements have been removed, the structure has changed, and an analysis is carried out again. This process is then repeated on the newly shaped structure several times over, continually removing under-stressed elements, progressing towards an increasingly efficient use of material to support a given load.

Each step of the iterative process compares the stress of each individual element to the overall maximum stress experienced by the structure. Xie and Steven (1997) use the von Mises stress for this purpose. The von Mises stress is a measure of an element’s stressed state by factoring the stresses from several different directions, as defined by Equation 6.1:

\[
\sigma_{vm} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\tau_{xy}^2}
\]  
\text{Equation 6.1}
Where $\sigma_x$ is the normal stress in the x direction and $\sigma_y$ is the normal stresses in the y direction and $\tau_{xy}$ is the shear stress. The von Mises stress is initially evaluated for each element of the structure, with the greatest value defined as $\sigma_{\text{max}}^{\text{vm}}$.

Once the maximum value has been defined, the stress level of each element is then evaluated by Equation 6.2 (Xie and Steven, 1997b):

$$\frac{\sigma_e^{\text{vm}}}{\sigma_{\text{max}}^{\text{vm}}} < RR_i$$  \hspace{1cm} \text{Equation 6.2}

Where $\sigma_e^{\text{vm}}$ is the von Mises stress for each element $e$, and $RR_i$ is the current rejection ratio, with $i$ representing the evolutionary rate. After each iterative step, all elements which satisfy Equation 6.2 are deleted from the model. For example: if the rejection ratio is 0.1, and the maximum stress is 9, then all elements with a stress less than 0.9 would be removed; i.e. for a rejection ratio 10%, any element stressed to less than 10% of that of the maximum stressed element is removed. The rejection ratio is defining ‘under-stressed’.

The rejection ratio starts small, and once all of the elements that fall under it have been removed, it increases to progressively cull the inefficient material. There may be several passes of stress analysis and removal for each ratio value, as the stress values of the elements will change as material is removed. Once Equation 6.2 ceases to remove material, then the evolutionary rate increases and the rejection ratio value increases to remove a greater amount of material. The evolutionary rate steps up the rejection ratio a set amount, depending on the size of the problem and the rejection ratio limit set.

A limit is set on $RR_i$ to preserve the integrity of the structure. This limit depends on the structure, the level of conservative design, ability to accurately model the expected conditions, etc. The absolute ideal optimization would have $RR_i = 1$, where all elements are maximally loaded, but the resulting stress structure only appears in a few special cases (Xie and Steven, 1997).
6.4.2 ESO Analysis

The following section presents a simple example of optimization upon a single module using the ESO approach. This analysis will provide familiarity with the method as well as demonstrate the potential applicability to the development of increasingly environmentally sustainable housing modules.

6.4.2.1 Design Area Specification

The first step in the optimization of a structure is to model the structure’s dimensions. This involves modelling a design area that encompasses the expected (or desired) design area. It is not necessary for all of the material modelled to be a candidate for removal. Non-design areas play an important role in the analysis and optimization of complicated or composite structures. Once the area is specified, the constraints and loading conditions can be set.

For the purpose of this investigation, the module modelled conforms to the information provided in Table 6.2, Figure 6.5 shows the model used. This arrangement was used to investigate how the different relationships between window and door placement would affect the optimization process and final optimized shape.
<table>
<thead>
<tr>
<th>Component</th>
<th>Geometric Description (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Width</td>
<td>4000</td>
</tr>
<tr>
<td>Interior Length</td>
<td>3000</td>
</tr>
<tr>
<td>Wall Height</td>
<td>2700</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>120</td>
</tr>
<tr>
<td>Wall 1 Opening</td>
<td>Window W8 1810 x 2057 at 690 off ground</td>
</tr>
<tr>
<td>Wall 2 Openings</td>
<td>Door A 900 x 2200</td>
</tr>
<tr>
<td>Wall 3 Opening</td>
<td>Door B 900 x 2200</td>
</tr>
<tr>
<td>Wall 4 Openings</td>
<td>Door C 900 x 2000</td>
</tr>
<tr>
<td></td>
<td>Window W5 1200 x 1400 at 1000 off ground</td>
</tr>
<tr>
<td></td>
<td>Door D 900 x 2200</td>
</tr>
</tbody>
</table>

**Table 6.2- Module geometric specifications**

**Figure 6.5-** Geometric model of sample module for ESO

### 6.4.2.2 Model Loads and Constraints

For the ESO model, the doors and windows have been modelled not as holes but as non-designable sections that do not offer load bearing capacity. This was done so as to have surfaces to apply loads to; just as typical windows catch wind but don’t help support the wall.
Chapter 6

Structural Validation and Optimization

The constraints largely include the supports to the structure. In the case of a housing module, the support is provided by the base slab as mentioned previously. This will not only provide the vertical support necessary, but also the resistance to slipping that is required, either through fastening to the slab, or in the case of heavy constructions in low-wind area, friction. As such, the module is modelled as having numerous pin connections along the base of the walls. Pin connections prevent movement, both vertical and horizontal (just as friction against a solid base would) but they do not resist rotational forces. This means that a single wall pined at the bottom could not be lifted or slid, but it could be tipped over, this is important in how the horizontal forces are modelled.

The loading conditions are very important. The shape that the final optimization takes is dependent on the loading conditions, both magnitude and direction. This highlights one of the limitations of ESO. Highly optimized elements tend to lose their ability to resist forces they were not optimized for. For this reason, housing design cannot be absolutely optimal because the capability of modelling the exact loading conditions that the structure will encounter is severely limited, the prime example is wind direction and magnitude. For this reason conservative design based upon a range of expected loading conditions will be produced. These results will exhibit the potential of increased efficiency in housing design, not illustrate the full capabilities of ESO.

Finally the material properties must be defined. The stresses and amount of required material to support a given load with timber will be very different from concrete. Similar design areas and loading conditions analysed against different material can produce very different designs, illustrating the power of ESO to optimize problems guided solely on the individual problem’s performance.

The load cases were developed from four separate loading conditions, one vertical mass from the roof, the self-weight of the structure, and two horizontal scenarios.

As a single storey structure, the only vertical dead load comes from the roof. From Table 6.1 above, a mass of 75 kg/m² was used in the roofing calculation (AS 1684.2-1999, 2002). In taking into account the pitch of the roof (here set as 22°) a value of 83 kg/m² per m² of floor area was used. This value takes into account the slope of the
roof, the roofing materials as well as the roof’s structural elements. As mentioned previously, this roofing system models a fairly heavy when compared to some of the light-weight options. This was chosen as often the light-weight solutions are more expensive, it improves the frictional support of the walls-on-slab, and is more representative of the current market.

Because a standard roof was designed for, the possibility of suction due to the wind (the wind trying pulling the house off the ground) was treated as very remote. Should the house be destined for a high-wind or storm area, this condition would be thoroughly checked and the suitability verified.

For the following examples a 1.2 kPa wind load was applied to the walls. Design forces from wind vary on building configuration (length and width proportions) as well as roof design (gable vs. hip orientations, a hip being when roof slopes into the wind).

The concrete was modelled as having a compressive strength of 25 MPa and a density of 2300 kg/m$^3$. The density was important to determine the weight of the structure itself for self-weight loading. The values used are generic and do not represent the latest in concrete quality either in terms of strength or weight. Future investigations may look at high-strength and/or light-weight concrete or other materials to yield the most efficient and environmental results. These values allow for the simple demonstration presented here.

6.4.2.3 Finite Element Model

Once the geometric model has been built in the computer, the finite element mesh can be generated. The size of the mesh determines the accuracy achieved. A fine mesh allows for more precise calculations and refinement, but it also requires more processing power. Figure 6.6a shows the FEA mesh, while Figure 6.6b shows a close up of the upper left corner of the foreground door to better illustrate the mesh and its non-uniformity.
The total number of elements in the design is 12,553. Though it was not done in this investigation, a common FEA technique is to run a coarse analysis with large elements to determine key areas of interest and then refine the mesh in those areas, giving precision where it’s needed, but not dramatically increasing processing time by evaluating less crucial areas.
Two different models were made for the analysis: long wall designable and short wall designable (Figure 6.6a above shows the long wall designable model, while Figure 6.7 below shows the short wall designable).

The difference in the modules is the filling in of the non-designable holes (doors and windows) so they can be loaded. The gaps are left empty in the designable portions to simulate non-load bearing sections. With this approach, there is no consideration for the weight of the window on the wall underneath it; this is one of the details that would be included in production module design and testing, but it has been neglected here for simplicity and illustration of the ESO process.

For the module with short designable walls (Figure 6.7), the optimization occurs only on the short walls. This approach assumes that the horizontal force is being transferred from the long wall and being resisted by the short walls, in addition to the vertical force resulting from the roof. This approach assumes wind from only one direction. For this reason, both directions are analysed so ensure each direction is stable. The examples here simplify the investigation for illustrative purposes. As these modules are used in conjunction with others, specifics of connection and
organization are important to the overall performance of the system. Further work is required to evaluate the performance of many modules together.

### 6.4.2.4 Analysis and Optimization Procedure

With the elements generated and the loads and constraints determined, several more parameters must be set. The remaining parameters dictate the specifics of the optimization. The parameters required (left justified below) and the settings for the first example (right justified below) are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum iteration number</td>
<td>30</td>
</tr>
<tr>
<td>Maximum volume removal rate</td>
<td>0.750</td>
</tr>
<tr>
<td>Maximum rejection ratio</td>
<td>0.250</td>
</tr>
<tr>
<td>Initial rejection ratio</td>
<td>9.0000004E-02</td>
</tr>
<tr>
<td>Evolutionary rate</td>
<td>9.9999998E-03</td>
</tr>
<tr>
<td>Minimum volume removal rate per iteration</td>
<td>4.9999999E-03</td>
</tr>
<tr>
<td>Maximum volume remove rate per iteration</td>
<td>2.9999999E-02</td>
</tr>
<tr>
<td>Total number of elements in full design</td>
<td>12553</td>
</tr>
<tr>
<td>Criteria</td>
<td>von Mises</td>
</tr>
<tr>
<td>Element stress</td>
<td>Average of nodes</td>
</tr>
</tbody>
</table>

The iteration number is the number of times the program will increase the rejection ratio, the initial rejection ratio and the rejection ratio increase per iteration (evolutionary rate) is also defined. The maximum volume removal rate defines how much of the structure can be removed. While theoretical optimization could remove significant portions of material, for practical purposes the computer should stop removing material after a certain point, thus the purpose dictates this value. Additionally parameters are set for the volume removal per iteration step.

The criteria describes the stress theory that is used to evaluate the rejection ratio requirement, as mentioned in Section 6.4.1 this application is considering the von Mises stresses. The element stress parameter describes how the stress of the element is calculated. In this case the element stress is going to equal the average found from the nodes comprising the element. Finally the optimization method is defined. There are two main methods: topological and shape. Shape optimization limits the program to material removal along the edges of the designable area. Topological optimization (used here) allows for any designable material to be removed (effectively allowing for holes in the structure).
Each iteration produces stress information for each element, a few lines of which look like this:

<table>
<thead>
<tr>
<th>ELEMENT PROPERTIES &amp; STRESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

As discussed above, the stress for each element is evaluated against the maximum stress calculated as per the rejection ratio setting. The ‘Evolution’ column indicates what action is taken. A ‘0’ means the element should remain in the design, a ‘-1’ denotes an element that fails the rejection ratio criteria and is removed:

<table>
<thead>
<tr>
<th>ELEMENT PROPERTIES &amp; STRESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>9439</td>
</tr>
<tr>
<td>9440</td>
</tr>
<tr>
<td>9441</td>
</tr>
<tr>
<td>9442</td>
</tr>
<tr>
<td>9443</td>
</tr>
</tbody>
</table>

Additionally there is a ‘1’ designation for the addition of elements, but that was not explored in this investigation. At the end of each iteration a summary is produced (the following from iteration number 9):

<table>
<thead>
<tr>
<th>SUMMARY OF EVOLUTION ------</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements in full design</td>
</tr>
<tr>
<td>Number of designable elements in full design</td>
</tr>
<tr>
<td>Number of designable elements in current design</td>
</tr>
<tr>
<td>Number of elements removed in this iteration</td>
</tr>
<tr>
<td>Number of elements added in this iteration</td>
</tr>
<tr>
<td>Number of the total void elements</td>
</tr>
<tr>
<td>Current Rejection Ratio</td>
</tr>
</tbody>
</table>

As the iteration steps continue, the number of void elements (removed elements) increases, improving the efficiency of the structure by reducing the number of elements used to support the given load. The environmental application comes into focus when each of those elements represents resource material and embodied energy that is being removed not just from a single structure, but from a product used to build thousands of homes.
6.4.2.5 Optimization Results

For each design criteria (long and short walls designable) a final result was determined by carrying out the optimization over 30 iterations. Figures 6.8 to 6.11 show the progression of the optimization of the long walls (horizontal forces acting on the left short wall towards the right).

Due to the horizontal loads, the resulting structure in Figure 6.11 shows elements that closely resemble cross-bracing. The final structure had 1173 elements removed. Figure 6.12 shows the number of elements removed per iteration (bottom line) and the running total of how many elements had been removed from the structure.
Figure 6.12 - Total and per-iteration element removal

Figure 6.13 shows a closer look at the per-iteration removal trend line along with the progression of the rejection ratio.

Figure 6.13 - Rejection ratio and element removal

Figure 6.13 shows the rejection ratio (right axis scale and step-increasing trend line) as the number of elements removed per iteration (left axis). It can be seen that at each rejection ratio increase, the number of elements removed increases (most dramatically
around iteration 9 and 10). This is expected as the criteria for ‘under-stressed’ is relaxed at each step up of the rejection ratio.

Figures 6.14 to 6.17 show the results for the short wall optimizations (horizontal forces action on the lower long wall towards the upper long wall). In the door wall, the bracing structures begin to form again, unsurprising given the horizontal loading on the structure. As this module exerts no force on the material under the window opening, the removal of that material is expected. Future implementations of optimization will need to consider the combined structures of several modules in order to more accurately investigate the structural behaviour of the home design, but such considerations were outside the scope of this work.

In each design case (long and short walls) the material directly along the door on the other side from the force application has been removed. This is not surprising given the stress contours illustrated in Figures 6.2, 6.3 and 6.4 previously. The number of iterations for this design was 35. The summary of the short wall optimization is as follows:
Chapter 6

Structural Validation and Optimization

SUMMARY OF EVOLUTION -----

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements in full design</td>
<td>13357</td>
</tr>
<tr>
<td>Number of designable elements in full design</td>
<td>4379</td>
</tr>
<tr>
<td>Number of designable elements in current design</td>
<td>3134</td>
</tr>
<tr>
<td>Number of elements removed in this iteration</td>
<td>15</td>
</tr>
<tr>
<td>Number of elements added in this iteration</td>
<td>0</td>
</tr>
<tr>
<td>Number of the total void elements</td>
<td>1260</td>
</tr>
<tr>
<td>Current Rejection Ratio</td>
<td>0.2100000</td>
</tr>
</tbody>
</table>

Note that due to the smaller design area, there are fewer designable elements for this optimization as for the long walls (4279 vs. 5906 for the long walls); however because the rejection ratio went higher because of the increased iteration number (0.21 vs. 0.13 for long walls) a greater number of elements were voided (1260 vs. 1173).

The analyses presented above were carried out upon a module with pre-placed door and window openings. Figures 6.18 to 6.21 (Figures 6.18 and 6.19 show the long wall progression, Figures 6.20 and 6.21 the short wall) below show the optimization of the same sized module as above, with the same loading, the only difference being the absence of pre-placed openings within the walls.

Figure 6.18- Box optimization 1

Figure 6.19- Box Optimization 2

Figure 6.20- Box optimization 3

Figure 6.21- Box Optimization 4
The key feature of the above analysis is the predominately symmetrical shapes taken by the walls. This arrangement is unsurprising considering the majority of the loading is symmetrically applied in the downward direction. The slight variations in the two halves of each wall are a result of the horizontal wind load; the variation is so slight because of the relatively small magnitude of the load.

Finally, the same approach was used as for Figures 6.18 to 6.21, except the weight of the walls themselves was neglected. Until construction in zero- or low-gravity environments begins, this has little practical application beyond a purely aesthetic generation. However it helps to illustrate the effect the weight of the structure, even on single storey walls, can have.

Without the effect of gravity on the wall, the initial braced arch structure in Figure 6.22 opens up dramatically to Figure 6.23. As in Figures 6.18 to 6.21, there are slight discrepancies in the symmetry of the designs due to the asymmetric loading resulting from the horizontal wind force applied to the structure.
6.4.2.6 Optimization Evaluation

The new designs demonstrate a reduction of material without sacrificing their ability to sustain the placed loads. In spite of the simplification, this process shows strong potential to assist in the further reduction of material demands of modular construction. Further study is needed to find the most worthwhile application of this technique to the process of final module design. The numerous configurations of floor plans necessitate a comprehensive understanding of the loading conditions before optimization can become its most effective.

There is another potential application of ESO towards material reduction not illustrated here. ESO, in addition to removing material, can also evaluate elements for thinning as opposed to removal. Results may look very similar to the results presented above, except removed elements above would be made thinner than their initial thickness. This reduces weight and material demands (both with resource and energy requirements) while perhaps maintaining insulation properties or improving production efficiency. Further work is required to apply this facet of ESO to modular construction to demonstrate the full potential of these benefits.

ESO and similar techniques are beginning to be used for building design. Ohmori et al. (2005) discuss Extended ESO, where the two new ideas are shape control based on contour lines (2D) and contour surfaces (3D) and bi-directional evolution. These extensions to ESO alter the dynamics and control of structural design through an evolutionary process. Organic architectural aims and efficient structural goals can both simultaneously be addressed with this technique.

ESO must be used conscientiously however, as the more efficient a structure becomes, the more specialized to its loading conditions (illustrated in Figures 6.3 and 6.4). This specialization is undesirable because it presents a potential weakness to changing load conditions (often typified by wind loading). However, by remaining aware of this fact, designs can make improvements to the structural efficiency of the modules, and therefore positively benefit the environmental impact of the system.
Given the forces encountered by single-storey houses, structural considerations are not likely to govern design. Structural checks must be made to ensure safety and quality, but optimization with regard to material and weight reduction appears to be the key element for consideration towards final designs. The range of materials available for the wall construction provides a number of possibilities to investigate. Concrete, foam-core panels, wood...great gains seem achievable through careful planning and consideration of the many design considerations.
Chapter 7

Conclusions and Recommendations

7.1 Introduction

The aim of this work was to investigate the potential for prefabricated modular housing systems (PFMH) to provide improved sustainability outcomes to the Australian high-volume home builders market. The overarching outcome of this study is that modular systems can influence the volume builders market in the direction of improved sustainability without significant changes to their trade practices or the financial viability of their business operations.

This study focused on single storey, high-volume construction which currently utilizes timber framed, brick veneered construction with plaster board lining on interior surfaces. The modular system investigated here was limited to individual rectangular shape modules, replacing building envelope and the internal walls; without addressing the foundation or the roofing systems. The investigation evaluated the feasibility of modular systems providing an alternative to the current construction method described above. The study also proposes a framework within which, through a rating mechanism, continuous product innovation and development can be driven towards improved sustainable outcomes. It emphasises environmental benefits that may result from the adoption of such a system, especially when greater control of the construction waste and lower embodied energy requirements can be achieved.

7.2 Conclusions

The Australian housing market comprises a significant (over 50%) portion of the Australian construction industry (as discussed in Section 2.2) and in effect contributes proportionate greenhouse emissions generated by the Australian construction industry. The repetitive nature of housing units indicates that even a marginal improvement in the efficiency of this sector will provide measurable results, both in terms of monetary performance and environmental impacts. This is the fundamental
driver of this research proposal and illustrates the significant potential this work embodies. This goal is set to be achieved through investigating PMHS within topological and geometric constraints currently inherent in the volume builders’ product range. It is demonstrated that PMHS is a viable solution for addressing some gaps existing in the current practice, subject to planning flexibility issues and negative perceptions of PMHS being adequately addressed and/or eliminated.

Energy consumption within the housing sector life cycle comprised of the embodied energy (pre and post occupancy - construction, demolition and recycling) and operational energy (during occupancy) components. Significant environmental benefits may be achieved through PMHS construction - occurring within a centralised controlled environment – minimising construction waste, optimising material use, reducing trade personnel travel etc. It is also apparent through product and process refinement, accreditation and reward mechanism that continuous and consistent enhancements are achievable.

It has been demonstrated that both topological and geometric planning functions can be automated and their results optimized (Section 2.6). This is not necessarily a common practice within the volume builders market or housing sector in general. The procedures examined here are based on those used for spatial optimization for apartments and industrial machinery layout and placement. These developments have not been driven specifically by housing applications, and as such current results do not demonstrate the potential applications that may one day become common place in the housing construction industry. The suitability of modular organization to these automated layout systems demonstrates that modular applications are well suited to deployment where optimization parameters are highly regarded, as they are in the case of environmental sustainability concerns.

The automation and topological investigations presented have been based on current practice and market solutions to home design. The rationalized modules are based on current product ranges; demonstrating that a limited number of rationalised prefabricated modules can replicate popular volume builder product ranges with marginal standardization to their geometric design.
Chapter 7 Conclusions and Recommendations

The topological and geometric capabilities of the PMHS are of key importance to the validation of a modular approach. Chapter 4 focuses on these capabilities and the findings and plans presented (primarily in Section 4.9) demonstrate that through conscientious design planning requirements can be met; validating modular systems with regard to the planning flexibility required for high-volume construction needs in Australia. As planning conventions differ across Australia it is beneficial that modular approaches are comprised of a large number of unique module configurations to best suit the local conditions. Automation and configuration of such a procedure is evidenced by the wide range of modular solutions currently available. Flexibility along geographic lines is highly beneficial to any large-scale market.

In addition to the demonstrated planning capabilities and the sustainability outcomes of the PMHS, the proposed method to become an attractive solution both to the volume builders market as well as to the consumers presents two apparent challenges. They are the changing of the negative perception of PMHS as temporary and/or cheap housing and the ability to accommodate individual preference. Solutions to these two challenges would determine the time and effort required for PMHS to acquire its fair market share. Further research is therefore required to seek answers especially through a choice of external façade appearances and interior decorations to enhance the image and individuality.

Shifts in operational aims discussed above foster a movement towards PMHS as an innovative solution to accumulating sustainable housing stock. It is known that the housing market is a perception and culturally driven market place. Evolutionary approaches seem to have a better chance of acceptance by a wider community than a revolutionary approach. The methodology of investigating current volume builders’ product ranges to standardise the geometric proportioning of the modules stemmed from this view. It is encouraging, as demonstrated, that the current geometric and topological relationships within the volume builders single storey product range can be easily replicated using few standardised modules, which not only makes the proposal feasible but also practicable and attractive within the trade practices.

Environmental sustainability is concerned with a wide range of issues in the residential construction context. The two issues focused on in this investigation were
embodied energy and waste reduction. Both of these areas are well targeted by modular systems because of the importance walls (especially exterior) play in the home’s performance. Given that over 50% (Figure 5.4) of embodied energy of a typical domestic building resides within the building envelope and the internal partition walls, even marginal improvements to material usage either through structural optimisation, automated fabrication or the introduction of low embodied energy materials, can make a speedy impact. Improvement in these areas is measurably impacted through process organization and planning (illustrated by the results WasteWise was able to achieve, Section 5.4.2) and structural and material design. There are typically six trades that interface in completing the building envelope and all these trade personnel have to commute to and from the site. Significant improvements can be achieved by co-ordinating and streamlining these activities at one central fabrication yard. Modular systems provide alternative approaches to these areas offering a new path improving trade practices. Through modules being pre-fabricated under controlled factory environments and then transported to site, significant impacts on material optimisation and product improvements are likely to be achieved.

The decision making framework proposed in Chapter 3 encompasses planning, evaluation of sustainability, accreditation, and implementation of modular housing proposal. The key objectives of this proposed framework is the continuous product innovation which is feasible within a controlled environment of fabrication, transport and installation.

The increased prevalence of environmental rating tools (GreenStar, LEED, etc.) illustrates greater acceptance and understanding of environmental design goals. The framework highlights the importance of integrated planning, a highly emphasized approach in modular design. The next step is the integration of rating tools to design and certification processes. This progression will encourage holistic design practices that have been shown to improve efficiency and the potential to achieve desired outcomes by the designers.

The structural design of modules is one area where new techniques and material applications can play a primary role in achieving sustainability outcomes. As
illustrated using Evolutionary Structural Optimization technique, significant advances can be made minimizing the volume of material, consequently minimizing the embodied energy. It is also important to investigate new materials and processes which minimize interaction between different trades, improve thermal insulation, reducing trade interface issues minimising dispute resolution, and testing for sustainable performance prior to leaving the fabrication phase. Further, modular systems are ideally suited to optimization along these lines in that standard components are used as the base for the numerous designs. By focusing resources on the improvement of the star rating for home design, adoption and employment of those optimization efforts is that much easier.

7.3 Recommendations for Future Work

As a researcher, undertaking this study has provided me with insights into the various aspects of pre-fabricated modular housing systems that require further attention. Detailed investigation into these aspects in order to improve the outcomes is not feasible within the time frame of a master’s degree and therefore is not incorporated within the scope of this study. The aspects discussed here are geared towards enhancing the proposed concept including the possibility of automation of the process, enhancement and detailing aspects of the engineering design and sustainable performance measurement of such a system.

- The most impacting future work, which can be taken as a priority item, is to investigate and develop a business case and assess the industry response.
- Improving and expanding the presented rating framework into a fully realized decision support tool, incorporating multi-disciplinary factors as well as existing regulatory schemes
- Automate topological and geometric design of modular systems, incorporating further design concerns (foundation, roofing, etc.), while maintaining sustainable performance optimization as a primary goal
- Improve optimization of modular solutions through the use of lightweight, high-insulation materials with low embodied energies; looking increasingly to
4th generation materials such as fibreglass, structural plastics, foams and advanced light weight aerated concrete products
References


References


