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TOWARDS PREFABRICATED SUSTAINABLE HOUSING – AN INTRODUCTION
Mark B Luther

Summary of Actions Towards Sustainable Outcomes

Environmental Issues/Principal Impacts
- The world is heading toward greater urbanisation, and in Australia current housing supply is not keeping up with demand.
- Housing unaffordability is also becoming a major concern in Australia.
- Insitu housing construction, which is the dominant construction method, is highly labour intensive, has variable quality and produces significant amounts of waste.
- The inefficiencies of insitu construction also results in higher costs.

Basic Strategies
In many design situations, boundaries and constraints limit the application of cutting EDGe actions. In these circumstances, designers should at least consider the following:
- Pre-fabricated architecture can deliver buildings that have high order and diverse design, while offering the additional benefits of waste reduction, renewable systems integration and optimal performance.
- Fabricating housing off-site in controlled factory environments allows for greater quality control, and potential efficiencies which have become common place in car and other manufacturing industries.

Cutting EDGe Strategies
- Applying database technology to housing construction will create a 'kit-of-parts', which will achieve the efficiency of standardised manufacture, while allowing for a multitude of varied building designs to be achieved.
- Automating factory construction for housing via the use of CAD-CAM technology, could produce rapid prototyping, and allow for ‘one-off’ designs to be manufactured efficiently.

Synergies and References
- Environment Design Guide
  – CAS 18: Fairweather Homes – Selected Case Studies Victoria (November 1999)
Prefabricated building systems are once again gaining popularity. The new prefabricated paradigm offers the integration of several approaches previously ignored: automated manufacturing, integrated building services and environmental sustainable principles. Consistency, predictable environmental control, modular flexibility, quick assembly and affordability are promising features of modern manufactured construction. Though the concept of prefabricated building is not new, this type of construction may be the only hope in obtaining a truly sustainable architecture for our future.

This paper attempts to define and evaluate several prefabricated building systems, ranging from a ‘kit-of-parts’ to fully assembled ‘volumetric’ modules. It aims to categorise various manufactured types among a vast amount of information, and to observe their attributes regarding materials, flexibility, structural integrity, delivery and constructability. This paper suggests that pre-fabricated architecture can deliver high order design and diversity within the framework of waste reduction, renewable systems integration and optimal performance.

**Keywords:**
sustainable building, modular design, pre-fabrication, renewables

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**Figure 1  Stadthaus apartment building in London is a fully timber prefabricated building**

Stadthaus is the world’s tallest modern wooden building at nine stories, and was designed and constructed by Waugh Thisleton Architects. The building is constructed using large Cross Laminated Timber solid panels which are used in every aspect of construction including the stair core and elevator shafts. The timber panels took four carpenters 27 days to erect, and the whole building was complete in 49 weeks. When compared to an identical steel and concrete building this construction method offers a 400 per cent reduction in weight, 70 per cent reduction in the foundation, and a shorter construction period, which led to cost savings as well as environmental benefits.

(Image Courtesy of Will Pryce)
1.0 INTRODUCTION

The dominance of the one-off housing prototype, as we now know it, cannot continue. It is hypothesised that the development of mass-produced, environmentally benign housing is one of the critical factors in the transition to global sustainability. Such housing will need to be constructed from renewable and/or recycled materials, be thermally conditioned using minimal or no energy from non-renewable sources, and be affordable. Conventional housing construction can be characterised as skilled-labour intensive, dependent upon on-site construction, using non-recyclable materials, having minimal prefabrication, is costly, results in variable quality, and is time-consuming. These houses are often constructed from a variety of materials, which are energy-intensive to produce, resulting in a structure with high-embodied energy content.

2.0 WHY PREFABRICATION

2.1 Housing Need in Australia

The demand for affordable architecture has arisen from the immediate dwelling and shelter needs of a society that can no longer sustain the existing paradigm. In Australia alone, housing costs exceed the ‘severely unaffordable range’ based upon per capita income as shown in Table 1. Land prices over the last few years have well exceeded the cost of the dwelling. Each year there is a shortfall of over 40,000 housing units in Australia (HIA, 2008). Relief and crisis dwellings are ever-increasing in demand, as well as the need for additional housing due to population growth. The economic costs of housing capital have come to a crossroad with those of affordability.

At present, the energy and material resource impacts of contemporary dwellings are enormous in regards to natural resources, manufacturing, community infrastructure support and operation. Infrastructure, such as power plants and water services are next in line to becoming unaffordable for governments to support. There is a convergence in housing need for both the developing and industrialised countries, that requires new solutions that go beyond conventional building.

2.2 Disadvantages of Current Construction Methods

Typical mass housing construction in industrialised countries like Australia can be characterised by on-site construction, use of traditional materials and limited design variation. While the use of pre-fabrication such as roof trusses and some wall framing has been adopted by the mass housing market, construction mainly takes place on site by various skilled tradespeople such as bricklayers, carpenters, plumbers etc. This process is costly, requires skilled labour, results in variable quality and is time consuming.

Costly – 50 per cent productivity, or less, is common to building processes where a project requires specialised on-site fabrication and is highly non-productive as opposed to other industries where more than 90 per cent productivity exists when fabrication is conducted in a controlled production facility (Digitales Bauen, 2008).

Variable quality – the quality and reliability of on-site construction can vary tremendously. This performance variation is often witnessed within the building envelope where houses rated with 6-7 Star for thermal efficiency are tested to be as ‘leaky’ for air-movement (and thus thermal energy inefficient) as a 2.5-3 Star house (Luther, M, 2007). Prefabricated and pre-tested components are more reliable in their actual performance than conventional prototype building.

Time consuming – the amount of time spent to bring a project to its lock-up stage under conventional methods can be up to 6 times greater than modular off-site prefabricated projects. The installation of services presents the largest portion of time. Not only is this time wasteful but economically unaffordable.

High environmental life-cycle impacts – conventional construction yields high embodied energy processes, does not lend itself well to deconstruction and thus leads to a tremendous amount of on-site waste, and potentially the waste of the whole building at end of life.

Achieving material efficiency with flexibility can be accommodated only if buildings are constructed in a modular component (that is a volumetric component) or from a ‘kit-of-parts’. The concept of modular prefabrication considers standardisation to maximise the efficiency of manufactured material size and is reuse, and therefore waste is minimised and potentially recycled. (Refer to the appendix for further reading on waste).

<table>
<thead>
<tr>
<th>Country (city size considered)</th>
<th>Affordability Index*</th>
<th>Median House Price</th>
<th>Median Household Income</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia (Population 50,000+)</td>
<td>6.3</td>
<td>A $357,407</td>
<td>A $57,078</td>
</tr>
<tr>
<td>Canada (Population 100,000+)</td>
<td>3.7</td>
<td>CAN $212,398</td>
<td>CAN $57,682</td>
</tr>
<tr>
<td>Ireland (Population 50,000+)</td>
<td>5.3</td>
<td>£306,220</td>
<td>£57,960</td>
</tr>
<tr>
<td>New Zealand (Population 75,000+)</td>
<td>5.7</td>
<td>NZ $316,113</td>
<td>NZ $55,125</td>
</tr>
<tr>
<td>United Kingdom (Population 150,000+)</td>
<td>5.5</td>
<td>£145,300</td>
<td>£26,181</td>
</tr>
<tr>
<td>United States (Population 400,000+)</td>
<td>3.6</td>
<td>US $188,699</td>
<td>US $52,706</td>
</tr>
</tbody>
</table>

Affordability Index* - ‘slightly unaffordable’ >3.0, ‘seriously unaffordable’ >4.51, ‘severely unaffordable’ >5.1
(Source: Demographia International Housing Affordability Survey, 2009)

Table 1 Housing Affordability
Typical houses are constructed almost exclusively from conventional building materials, namely concrete, aluminium, steel, brick and timber, which are energy-intensive to produce, and thus Australia’s existing housing has high embodied energy content (Newton, 2001). (Refer to the appendix for further reading on embodied energy).

Environmental footprint – In Australia, current housing construction practice is unsustainable in terms of the energy required for production of the materials used as well as required for the operation of the resultant dwellings. The ecological footprint of the average Australian is approximately four times the level that is globally supportable (Simpson et al., 2000). Note that the environmental ‘footprint’ of housing is influenced by their size which is compared against the number of people accommodated by each. As well the reduction of excessive labour, selection of materials which can be recycled, potential ease of deconstruction, and improved operational performance – all lead to a lower energy consuming building. Materials that are naturally resourced with minimal processing, provide for a minimised environmental footprint.

Regardless of the individual variations, house construction has changed little in the last 150 years, as homes are still constructed on-site, with predominantly manual labour, using largely conventional wood construction. In spite of what our perception might be, the twenty largest home building firms comprise less than 18 per cent of our annual house production (HIA, 2008). This indicates a huge diversity of players within the housing market, and resulting in procurement and supply chain processes that are quite scattered. When compared to an automated manufactured product such as an automobile or a kitchen appliance, there is much room for improvement.

2.3 Considering Housing Sustainability

Housing has become less affordable for the next generation of homebuyers (Age, 2006) and household sizes have been steadily declining for decades (Haberkorn et al., 2004). Yet, their floor area measured per occupant, has increased. In the last decade and as a result of recent economic climate as well as increasing property demand, land costs have exceeded housing costs in most cases 2:1 or 3:1, inversely proportional to their distance from a city centre. Scenarios of constrained choice, inappropriate housing options and continued heavy environmental impact are envisaged (AHURI, 2006). An Australian Housing and Urban Research Institute (AHURI) study identifies a set of objectives for policy development. These included:

Diversity – housing forms that are flexible and accommodate the different needs and uses of society

Affordability – provision of dwellings that are appropriate for all incomes

Sustainability – provision of housing that has a minimal impact on the environment.

The author believes that a true solution towards affordability and sustainability in building comprises a combination of three essential criteria: automated manufacturing, integrated building services and environmental sustainable principles as shown in Figure 2. These three criteria need to be integrated, over time, through efficient manufacturing processes, design and planning.

3.0 MOVING TOWARDS MANUFACTURED HOUSING

3.1 Toward Industrialisation

Before the breakthrough of the assembly line, Ford Motors built cars like all the other manufacturers – one at a time. The chassis stayed in one spot and didn’t move until the car was finished. Stock runners literally ran around the factory fetching parts. These handmade automobiles required many hours of costly skilled labour and kept prices high. Harpers Weekly in January 1910 wrote: “The man who can successfully solve the problem and produce a car that will be entirely sufficient mechanically, and whose price will be within reach of millions who cannot yet afford automobiles, will not only grow rich but will be considered a public benefactor”. Henry Ford wanted to be that man (Capen, Cash, Morgans, et. al., 2002).

A breakthrough in the assembly processes occurred in April 1913 when a production engineer tried a new way to put together a flywheel magneto. The operation was divided into twenty-nine separate steps. Each employee was instructed to place only one part in the assembly process before pushing the flywheel onto the next person. Previously the part took a single person 20 minutes to assemble, while it took 29 men after a perfected process five minutes to assemble. Gradually, this strategy was passed into engine assembly and other parts.
By October 1913 the concept of moving the work to the man reach its zenith. On this historic day the Ford company rigged a rudimentary assembly line whereby a chassis was pulled slowly across the factory floor by rope. Parts, components and 140 assemblers were stationed at different intervals along the 45m line. As the winch literally dragged the chassis across the floor, workers attached parts to the car. Rather than 12.5 hours it took five hours to construct a single car. Constant revision improved the time it took to make a single car to 93 minutes in 1914. By 1916 Ford Motor had produced over eight times more Model-T cars than it did in in 1912.

It is exactly this concept that needs to be introduced into the automated manufacturing of housing. Sir Michael Latham's, Constructing the Team of 1994 identified a necessity to overcome the industry's 'adversarial' and 'fragmented' nature through enhanced supply-chain partnering and collaboration (Latham, 1994).

### 3.2 The Industrial Revolution

Industrial innovation has come in waves according to O’Brian, Wakefield and Beliveau (2000). The following is a summary of their suggested three revolutions:

**The first revolution** – This occurred in the 18th century involving great advances in the industrialisation of agriculture and the invention of the steam engine, which was used in the textile industry.

**The second revolution** – This took place around the turn of the 20th century and was characterised by new technologies like steel manufacturing, the chemical industry, electricity and transportation (i.e. the automobile and aviation). With the advent of machines and repetition for mass production, workers resisted change because it replaced traditional, craft-based production processes with standardisation. Though by the 1960’s, western production methodologies and manufacturing principles lacked the ability to meet the changing needs of the matured marketplace.

**The third revolution** – The Japanese took many of the western principles and introduced quality, efficiency and customer value into the manufacturing vocabulary. These exist and define the modular pre-fabricated manufactured housing of the present Japanese market. In doing so the Japanese developed broad organisational strategies such as the ‘team approach’, ‘just-in-time’, design for manufacture and assembly to reduce production costs, improved productivity, quality, and the elimination of waste. These principles became synonymous with today’s modern industrial terminology, such as: ‘lean manufacturing’, ‘supply chain management’, and ‘innovation risk management’. (O’Brien, Wakefield and Beliveau, 2000)

Lean construction is, the continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream and the pursuit of perfection in a construction project. Using machines and repetition for mass production are characteristics commonly associated with industrialised manufacturing of a particular product. This industrialised manufacturing process is intended to improve production by replacing the traditional, crafts-based production process with standardisation, machine-based production process giving a consistent affordable quality product.

Japan is at the forefront of construction technology and development, especially in the areas of robotics and computer control systems. Robotics such as automatic floor finishes, reinforcement fabrication
machines, painting robots, welding robots, unmanned forklifts and giant manipulator arms. In spite of their capabilities, these robots can not be fully utilised by the construction process without a total reorganisation of current building practice to integrate robotic construction.

3.3 Benefits of Automated Manufacturing

The stakeholders in an automated manufactured building process are diversified. The task at hand requires a cooperative team. A competition in England provides an example where a ‘Design for Manufacture’ challenged the housing industry to build high quality well designed sustainable homes at a construction cost of £60k (Dept. for Communities and Local Government, 2006). Several of the outcomes yielded:

- team-working acknowledged the value of different skills that can complement each other and enhance the end product
- architects engaged with the supply chain side on the opportunities and constraints of working with different materials and build systems
- construction costs were controlled while improving quality
- improved energy performance and less environmental waste were identified could occur at less cost.

Table 2 suggests the various stakeholders of automated building and that within the various groups, similar benefits and goals are sought.

On the other hand there are several counter arguments which can be related to the points mentioned in Table 2 which may view prefabricated manufacturing in a negative context. Such a study was conducted in a thesis project comparing UK housing manufacturing against the Japanese prefabricated building methods by William Johnson (2007). In this case, a Strengths-Weakness-Opportunities-Threats or SWOT analysis

<table>
<thead>
<tr>
<th>Owner</th>
<th>Architect/Engineer</th>
<th>Manufacturer</th>
<th>Government</th>
<th>University &amp; TAFE</th>
<th>Builders</th>
</tr>
</thead>
<tbody>
<tr>
<td>affordability</td>
<td>organised building services</td>
<td>material optimisation</td>
<td>meeting housing demands</td>
<td>engagement with local industry</td>
<td>greater simplification of assembly</td>
</tr>
<tr>
<td>fast delivery</td>
<td>modularisation</td>
<td>structural integrity</td>
<td>providing affordability</td>
<td>manufacturing process R&amp;D</td>
<td>cost benefits</td>
</tr>
<tr>
<td>improved quality</td>
<td>engineered building envelope</td>
<td>labour efficiency</td>
<td>regional employment</td>
<td>product innovation &amp; development</td>
<td>speed of assembly</td>
</tr>
<tr>
<td>lower energy bills</td>
<td>manufactured quality</td>
<td>reduced material handling</td>
<td>showing leadership in a new industry</td>
<td>develop research potential of Higher Degree Research students</td>
<td>lightweight handling</td>
</tr>
<tr>
<td>improved IEQ (Indoor Environmental Quality)</td>
<td>lightweight system</td>
<td>24 hour operation</td>
<td>exportability of product &amp; skills workforce skill development</td>
<td>skills and training</td>
<td>compatibility of components</td>
</tr>
<tr>
<td>sustainable materials</td>
<td>improved strength to weight ratio</td>
<td>less assembly time</td>
<td>spin-off industry</td>
<td>Aust. Research Council research grants</td>
<td>reduced source supplier</td>
</tr>
<tr>
<td>integrated renewable energy systems</td>
<td>minimised waste</td>
<td>lean manufacturing</td>
<td>replication of factories provides employment</td>
<td>product design innovation</td>
<td>reliability of components</td>
</tr>
<tr>
<td>superior fire protection</td>
<td>better environmental &amp; energy rating</td>
<td>improved quality</td>
<td>innovation</td>
<td>materials research</td>
<td>predictability of delivery</td>
</tr>
<tr>
<td>increased guarantees</td>
<td>greater repetition of components</td>
<td>quick and easy change over</td>
<td>meeting GHG environmental targets</td>
<td>modular design research</td>
<td>reduced environmental impacts</td>
</tr>
<tr>
<td>reduced environmental impact</td>
<td>superior fire rating</td>
<td>inventory control</td>
<td></td>
<td>construction innovation</td>
<td>improved OH&amp;S</td>
</tr>
<tr>
<td>reduced air leakage (increased thermal efficiency)</td>
<td>improved acoustics</td>
<td>flexibility of manufacturing</td>
<td></td>
<td>automation research</td>
<td>traceable products</td>
</tr>
<tr>
<td>greater piece-of-mind</td>
<td>reduced air leakage</td>
<td>greater output</td>
<td></td>
<td>national recognition</td>
<td>offer greater quality assurance</td>
</tr>
</tbody>
</table>

Table 2 Opportunities and Benefits of Industrialised and Automated Housing

(Source: courtesy of Mulithouse ©)
was made between the UK and Japanese building methods. The author has taken that study and revised it to consider present Australian building methods and compared them against the potential of Modern Methods of Construction (MMC) in Table 3.

4.0 MODULAR PREFabricated BUILDING

Modular design is not new. The 1920's to the early 1960's were full of inventors and innovations for modular construction and its on-site delivery. The 'Turning Point of Building' (Wachsmann, 1961) was an indication that such constructs would be the predecessor over conventional building processes as we know them today. Relocatable school buildings represent one of the most popular forms of 'modular' prefabricated construction today in Australia. Yet, the processes by which such buildings are manufactured, is a far cry from applying present technological advancements. There are significant opportunities to advance the entire modular design and procurement process. This is not only possible through the building structure and its materials, but more so through its specification, database programming, logistics, assembly and services technology. These opportunities require research at the pre-design as well as the prototype level. Such an investigation is also in need of an organised research structure inclusive of economic, environmental, and social benefits of modular dwellings.

4.1 A Brief Background

In order to obtain a better sense of what prefabricated buildings can offer, in the context of our present global situation, it is best to provide a review of the past; and the reasons that these attempts have not been successful and hence the lessons that can be learned. The objective is to acknowledge the established principles of prefabrication in the context of modularity. Many pioneering designers considered ‘modularity’ as a key component of prefabrication. Designers such as Le Corbusier, Buckminster Fuller, Jean Prouve, Konrad Wachsmann, Fritz Haller, et al., all embraced various principles and interpretations of modular design.

The modular or ‘prefab revival’ is indebted to its past and must overcome several of its established phobias in order to advance and gain acceptance in today’s marketplace.

The beginning of industrialized building can be dated to 1851 when the architect Sir Joseph Paxton designed and exhibition building for London which became famous as ‘Crystal Palace’. The glass panel provided the module of this building system. Everything else was designed according to its dimension. The innovations on the Crystal Palace were a huge step forward for the building industry which unfortunately did not maintain its momentum. If the building industry had developed and embraced technology as it did the aircraft or car industry, for example, we would all live in highly technologically sophisticated houses today. However, there is a huge discrepancy in the development between building and other industries. (Horden, 2001).

As Richard Horden states: “change in building construction technologies, in most countries, is generally slow and rarely noticeable. When people think of a house, they are influenced by what already exists. The sense of familiarity is greater than the desire of experiment. Most people are looking for a home which is not the same as a product. They haven’t accepted the idea of a home being modular or prefabricated For an office block or an airport this concept is perhaps more acceptable” (Horden, 2001).

Failures in modular building have resulted from a vicious co-dependency on public acceptance, volume production, and distribution infrastructure. None of these attributes can successfully exist without the presence of the others. The public was looking for cost reduction and availability, while such reductions, in turn, depended upon mass production, and high public demand, offering little flexibility. Today the robotic and pre-programmed processes of building can offer ‘one-offs’ and unique diversity (Bock, 2006). While modularity remains a key component of such building systems, the limits of ‘modules’ have been redefined to utilise pre-fabrication as an economic advantage. Yet, often the processes by which prefabricated buildings are manufactured, is a far cry from applying present technologies such as computer rapid prototyping, parametric modelling, production line manufacturing and database technology:

<table>
<thead>
<tr>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affordability, quality, energy, waste reduction, environmental reduction. Quantity of product, on-time delivery</td>
<td>Perception of singular non-flexible product, minimal diversity, selective material &amp; tooling for it.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunity</th>
<th>Threat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin-off business, skill training, exportability, innovation in products, designs &amp; manufacturing</td>
<td>Non-flexibility in machine use and tooling. Mono use of material selection and cost increases. Government regulations and codes to new innovations and systems.</td>
</tr>
</tbody>
</table>

Table 3 A SWOT analysis of modern methods of construction for Australia
**Rapid prototyping** – is using computer-aided technology to allow ‘one-offs’ to be manufactured efficiently through CAD-CAM routing and machining for 2-D or 3-D objects.

**Database technology** – implies the cataloguing of parts or components, their relationship and location with other components and their availability as well as cost and logistics to be identified.

**Parametric modelling** – involves the dimensions of an object or entity to be scaled or changed accordingly to a set of rules or parameters (e.g. a door size opening changes width and height but the door handle and hinges do not change size).

Modular prefabrication offers significant opportunities to advance the entire manufacturing process, building design, structural components, materials application, and most importantly the integration of renewable energy and building services technology.

The shortfall in the ‘inventors’ of the past was that each developed their own individual system, which remained constrained, dogmatic and limited to the designs of its inventor, and thus, flexibility and an invitation to design by ‘others’ was excluded, due to the method of the system.

### 4.2 Categorising Modular Prefabricated Systems

Modular design is based on the dimensions of a building component defining the ‘module’, used as a unit of measurement or standard which determines the proportions of the remaining construction. The Japanese Tatami mat, for example is based on the proportions of the human body. All other dimensions of that building system evolved around the mat size, resulting in a systematic architecture, scaled and proportioned according to the unit of the human being one person lying or two people sitting.

In order to develop a strategy to evaluating as well as designing future modular and pre-fabricated systems it may be useful to try and provide a ‘classification of modular systems’. It may be difficult to segregate modular ‘types’ from an actual design solution, but they can help in defining distinctive characteristics of modular prefabricated design. Figure 4 outlines an evaluation of modular design in terms of prefabrication or on-site construction for either of the modular systems:

- skeletal
- panel/skin
- cellular types.

Solutions to modular and pre-fabrication need to be approached in a more systematic way to that of conventional construction. This new thinking requires more preconstruction planning and less planning in the construction phase. Modular and pre-fabrication design should consider:

- Systems that are composed of separate components (modules) that can be connected or integrated together.
- Systems that allow components to be added or replaced without affecting the rest of the system.
- Systems that can create spaces of differing scale through repetition of components.
- A ‘modular architecture’ easily allows the addition or subtraction of components and can enhance the flexibility of usage and maintenance of a built structure.

![Figure 4: A categorisation of modular pre-fabrication systems and construction methods](image)

*New considerations which modular construction can integrate into the other construction stages.

(Source: Luther, Morechini, and Pallot, 2007)
4.3 Modular Building Categories

Panel Systems
A panel system is defined here as:
- construction based on a single integrated unit
- external cladding, structure, insulation, internal lining, fenestration and design for ventilation may be included in the unit, making it diverse and unique
- a system which may span floor to ceiling (wall panel) or floor to roof
- a system which can minimise the building elements as well as provide an integrated structural stability

Panels can comprise the entire envelope and structure such as seen in the Tropical House by Jean Prouvé. Prouvé designed the Tropical House as a prototype for inexpensive, readily assembled housing that could be easily transported to France’s African colonies in the 40’s. Fabricated in Prouvé’s French workshops, the components were completed and flown disassembled to Africa. The house sits on a simple one-meter grid system with fork-shaped portico support of bent steel. All but the largest structural elements are aluminium. No piece is longer than 3.96m (13 feet), which corresponds to the capacity of the rolling machine, or heavier than 100kg (220 pounds), for easy handling by two men.

Figure 5 Contemporary Structural Insulated Panel (SIP) construction

(Image courtesy of Kingspan)

4.4 Modular Design Systems

Beyond the three categories of panel, skeletal, cellular, a further breakdown into four different modular design system types can be defined as noted in Figure 4. These describe the manner in which the modular building unit is constructed

Element or Component System
An element or component system is:
- based on a single modular component
- can be easily constructed or assembled into a system
- can produce a skeletal or panel building typology

Kit-of-Parts
A ‘kit-of-parts’ system is:
- a set of variable components packed together which make up a building.
- which can be assembled on-site or delivered as a prefabricated system
The problems with this particular ‘design system’ can be that only one solution of assembly exists. A ‘kit of parts’ should benefit by offering flexibility in modular components. The Toyota Motor Corporation is offering prefabricated housing where consumers can assemble their ‘dream home’ from over 350,000 single parts. Computer-aided design and manufacturing will produce around 2,000 components which in turn make approximately 300 functional modules (Bock, 2006). Below is an example of a cellular (volumetric) type of modular unit, based on a ‘kit of parts’ design system.

**Fill-In Systems**

A ‘fill-in’ system could be defined as:

- elements spanning between two structurally complete units.
- any combination of modular pre-fabricated systems: panel, skeletal or cellular units

**Complete Units**

A ‘complete unit’ might be defined as:

- a cellular shell ready for fitout (e.g. ‘Spacebox’ @ www.hollandcomposites.nl)
- a module which can consist of pre-assembled panels and services (e.g. bathroom/toilet pods)
- a composite system fulfilling both structural and envelope needs (e.g. a concrete pods which are stackable without relying on additional structure).

**4.5 Construction stages**

The final portion of Figure 4 relates to how we consider the construction stages of modular pre-fabricated design: the foundation system, sub-floor, building envelope or roof. It may be that each of these stages is comprised from various prefabrication building categories (i.e. floors as panels, walls as a ‘kit of parts’ and a ceiling/roof structure which is a delivered to site as a complete unit).

What has been missing from modular prefabrication is a better organisation of service integration for plumbing, electrical connections, and ducting. Such
essential components of construction need to become the backbone of modular prefabricated systems if they are going to be successful.

Further investigation into renewable energy systems, storage and their control are an additional, yet to be integrated part, of contemporary sustainable design and construction. ‘Plug-in’ renewable energy systems have a well placed future in prefabricated modular design. Most importantly, the idea that services and renewable energy systems are an essential part of the construction stage planning in prefabricated design is acknowledged.

5.0 CONCLUSION

This paper has provides an organised approach to understanding the diversified types of prefabricated modular building. The author is not stating that the proposed method of investigation is the definitive on modular prefabricated building diagnostics, but rather a possible approach. This paper suggests how manufactured modular prefabricated systems can hold the key to providing sustainable housing needs for Australia. Although it does not necessarily prove the case for the three proposed criteria to achieve sustainable housing: automated manufacturing, integrated building services and environmental sustainable principles, it sets the scene that such criteria would have a reasonable impact.

Another important aspect, not covered in great depth in this paper is that of cost. Any newly introduced system is basically bound to cost more until it is manufactured in greater quality and becomes the norm. However, several studies of cost reduction have been studied elsewhere. Sir Michael Latham’s, Constructing the Team of 1994 mentioned above identified a necessity to overcome the industry’s ‘adversarial’ and ‘fragmented’ nature through enhanced supply-chain partnering and collaboration, proposing a 30 per cent reduction target for construction costs by the year 2000 (Latham, 1994). Others have indicated a 20-25 per cent cost reduction as achievable.

The need for environmentally sustainable housing with improved building service integration is urgent. In developing countries, the requirement is to house both growing squatter settlements, as well as those who have benefited from recent economic booms. In industrialised countries, there is a need for an alternative to the current resource and energy-intensive housing. The author anticipates to write a paper which will address automated manufacturing processes and integrating building services and environmental sustainability in greater detail.

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