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Revisiting Prefabricated Building Systems for the Future

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Abstract: Prefabricated building systems are becoming popular again, promising more than just affordable architecture. The new paradigm offers consistency, predictable environmental control, modular flexibility, and quick assembly. Above all, this type of construction may be the only promise in obtaining a sustainable architecture for our future. The language of prefabricated building is not new and offers varied solutions ranging from a 'kit-of-parts' to fully assembled modules.

This paper attempts to diagnose and evaluate prefabricated modular building systems. It aims to categorise various modular systems and to observe their attributes regarding materials, flexibility, structural integrity, delivery and constructability. Finally, the 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.

1.0 INTRODUCTION:

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. Relief and crisis dwellings are ever-increasing in demand, as well as those due to population growth. The economic costs of housing capital have come at crossroads with those of affordability. Land prices over the last few years have well exceeded the cost of the dwelling. Solutions to these problems are of course multi-faceted. Land will be leased while the capital development rests with an owner. The capital development will become an investment, an entity of resale, reuse and recyclability.

At present, energy and material resource impacts of dwellings are enormous in regards to natural resources, manufacturing, community infrastructure support and operation. With an anticipated dwelling boom over the next 5-10 years: $950 million expected in the Northern Territory, Australia and $50 million on relocatables in Victoria alone, as well as a moratorium on housing development in Broome (due to the lack of infra-structure), the need for a solution is inevitable. Power plants and water services are next in line to becoming unaffordable for governments to support.

This foreseen crisis however, has been single handedly dealt with through a multitude of innovative product manufacturers throughout Australia. Among such products are progressive solutions to renewable energy, water purification systems, autonomous and low-energy lighting, innovative ventilation and air conditioning, and endless newly fabricated building materials. These manufacturers are optimistic, yet, face an unknown marketplace for their specific product. One of the primary issues is that there is no integration between the different products which requires further design development. This also requires testing efficiency and performance evaluation of the various design solutions.

Therefore the problem rests with our current approach to building design and its process of construction, development and research towards the end product as a living unit. Furthermore, the feedback loop of performance and outcomes is next to non-existent. In situ testing, for energy use, comfort, (thermal, lighting and acoustic), health, structural integrity, etc. are beyond the research scope of many projects.

2.0 BACKGROUND

Modular design is not new. The 1920's to the early 60'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' construction today. 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, its structure, building materials and services technology. These opportunities require research at the pre-design as well as the prototype stages. This assignment is also in need of an organized research structure inclusive of economic, environmental, and social benefits of modular dwellings.

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. The objective is to acknowledge the established principles of
prefabrication in the context of modularity. Many pioneers considered ‘modularity’ as a key component of prefabrication. Le Corbusier, Jean Prouve, Konrad Wachsmann, Fritz Haller, 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.

3.0 A DEFINITION OF MODULAR BUILDING

Modular design is based on the dimensions of a building component defining the ‘module’, used as a unit of measurement or standard which as a result 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; one person lying or two people sitting.

The beginning of industrialized building can be dated to 1851 when Paxton created his Crystal Palace. The glass panel is 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 actually 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).

3.1 Modular Construction Benefits

Prefabricated design can be applied to both on site as well as modular construction methods; however, modular prefabrication is the preferred and more efficient method as it takes on similar principles of repetition and standardisation. The advantages of modular prefabricated construction methods are:

- Low Cost
- Easy and Compact Shipping Methods
- Time Efficiency in Product Delivery
- Increase of quality control through organized machine-based manufacturing
- Increased standard of OH&S (Occupational Health & Safety) manufacturing
- Reduction of Unforeseen Risks
- Easy Assembling of Parts
- Predictable Environmental Conditions and Services
- Tremendous material waste reduction

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 and the aspect of pre-fabrication is an economic advantage.

4.0 EVALUATING MODULAR DESIGN SYSTEMS

Solutions to modular and pre-fabrication design need to be considered and approached as design problems. 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.

4.1 Modular Categories

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’. In fact, it may be difficult to segregate these categories from an actual design solution, but they can help in defining distinctive characteristics of modular prefabricated design. Figure 1 outlines an evaluation of modular design in terms of prefabrication or on-site construction for either of the modular systems: skeletal, panel / skin and cellular types.
At first, we consider that a modular system can be prefabricated or constructed on site. Since we are engaged in the paradigm of pre-fabricated construction we might explore whether pre-fabrication itself can be categorized into particular types. In our analysis, a panel/skin, skeletal or cellular type of modular unit is determined to be a distinctive category of prefabricated building. These prefabricated systems are units that can be constructed by one or more modular systems. In this case, elements or components, a kit-of-parts, a fill-in or an assembled complete unit constitute modular design systems. Next, we define the possible construction stages and how modular pre-fabricated systems can become or are a part of this in their design. These construction stages are categorized as: foundation, sub-floor, envelope, roof, services and energy sources. The last two stages, 'service' and 'energy source' are intended as independent stages or products that could be delivered as pre-fabricated units or become a part of the other building stages.

The boundaries between the 'of modular building categories', and the 'modular design systems' are quite flexible such that, as shown in the following two examples, a panel as well as a skeletal type of modular unit can be part of a design system such as a kit of parts.

A panel system is defined here as:
- the 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 or roof panel.
- a system which can minimize the building elements as well as provide an integrated structural stability.

Panels can comprise the entire envelope and structure (see Figure 2) such as in the Tropical House by Jean Prouve. Prouve designed the Tropical House as a prototype for inexpensive, readily assembled housing that could be easily transported to France's African colonies. Fabricated in Prouve's French workshops, the components were completed and flown disassembled to Africa in the cargo hold of an airplane. 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 13 feet, which corresponds to the capacity of the rolling machine, or heavier than 220 pounds, for easy handling by two men.

The house volume is defined as multiples of the basic modular component the "wall panel" which integrates a full prefabricated envelope system; structure, external cladding, internal lining, solar penetration, ventilation and insulation. The lightweight (aluminium and insulation) panels may act as a secondary element to the main structure or as doors, walls and windows.

Figure 1: A Categorisation of Modular Pre-fabrication Systems and Construction Methods
A **skeletal** system is defined as:

- individual components assembled to provide a structural frame, foundation or structural system.
- a system which acts as an independent element to which envelope elements are attached.

Inter-connection or integration can occur between the skeletal system and other mechanical services.

![Figure 2: The Tropical House by Jean Prouve](image)

Built in 1980 - 1982 in Swindon England, the Renault Centre by Foster Associates stands as an example of modular system building (Figure 3). The concept uses an umbrella structure as a "modular unit" to span the required distance (a bay dimension of 24 meters). The system consists of self-sustaining modules capable of grouping in a variety of configurations and responds to the demand of the site and its internal use, to requirements of flexibility, speed of construction and low cost. This allows incremental bi-directional growth for future change or expansion with minimum interruption to the current function of building.

A **cellular** system is defined as:

- Components which form entire singular spaces, that combine together, create a building or are prefabricated as an entire cellular building.
- Envelope, interior, mechanical and structural systems can be incorporated within a single unit. Delivered to the site as one unit (see Figure 4).
4.2 Modular Design Systems

After defining the 'Categories of Modular Units' we move on to considering their fabrication through 'Modular Design Systems' which are broken down into four groups (see Figure 1). These describe the manner in which the modular building unit is constructed.

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

Figure 5 is an example of a modular design system based on a single 'component' the FedEx envelope. The material tradename is 'Tyvek', which is made from 25% post-consumer recycled materials, is water resistant, and can be used as a modular building. The system is highly flexible, like LEGO blocks.

A *kit-of-parts* system is:
* a set of variable components packed together which make up a building.
* can be assembled on-site or delivered as a pre-fabricated system.

The problem with this particular 'design system' may 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).

Figure 6 below is an example of a cellular type of modular unit, based on a "Kit of Parts" design system.
A 'fill-in' system could be defined as:
- one spanning between two structurally complete units.
- a combination of modular pre-fabricated systems: panel, skeletal or cellular units
- simply a 'fill-in' to make up the void or open space.

Figure 7 is a mobile medical unit project which is an example of a cellular type unit based upon a shipping container applying a 'fill in'.

A 'complete unit' might be defined as:
- a preassembled cellular module ready for use
- a module which can consist of pre-fabricated panels and services.
- a system made up from the others fulfilling both structural and envelope needs.

Figure 8 shows an example of a mobile medical unit project, a cellular type, but this time based on a 'complete unit' design system as an inflatable bubble.

The final portion of Figure 1 relates to how we consider the construction stages of modular pre-fabricated design. The stages consist of considerations for prefabrication such as the foundation system, sub-floor, building envelope or roof. An example of such system designs is provided in the structural and drainage integration by the architect Fritz Haller (Figure 9) and the organization of prefabricated heating and water supply units (Figure 10). 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. Finally, the idea that services are an essential part of the construction stage in prefabricated design is acknowledged.
5.0 THE NEXT PREFABRICATED SYSTEMS: A SOLUTION

We need to rethink the way we make things, especially our architecture. A total re-engineering of building materials, their manufacturing processes, construction and operation requires redesign, waste reduction and transformation into energy producing products and building. A sustainable future of architecture demands research into renewable, adaptive, recyclable and environmental building components. This design needs to offer the composition of modular flexible space and versatility. Our next architecture will require innovative engineering of building services together with progressive design, applying the knowledge of material chemical composition, detailed construction assembly and the implementation of renewable energy and water systems.

Modular prefabricated building requires a new paradigm to make it work and coexist with present demands of affordability and reassuring sustainability. This paper is only a small step in trying to revisit and convince the designer that there may be a future in architecture with prefabricated systems and that we need to be open minded about what they can offer.

One of the primary intentions of revisiting modular building systems is to explore the past, discover possible patterns and solutions and reconsider what might be missing. Within this context we might consider a new approach or purpose for prefabricated modular building and what it could offer. An example is provided in Figure 11, which focuses on modular medical relief structures, and this approach is extended into the building life and transportability of the unit. Depicting the permanent, temporary and transient conditions of the modular prefabricated unit directly relates to its construction category or type, its application of modular systems, its material selection, and construction method.

![Figure 9: Structural System with Drainage Pipes (F. Haller)](image)

![Figure 10: Plumbing Network as a Single Element or System (courtesy of Digitales Bauen)](image)

**Figure 11:** An Example of Applying the Modular Systems to Medical Relief Centers
It is therefore useful to perform an analytical diagnosis of modular designs in an attempt to find opportunities to improve them. One of the major opportunities for modular designs is their application of RARE (renewable, adaptive, recyclable, and environmental) architecture principals integrated into the design. As stated by (Luther Altomonte & Coulson 2006), "it could be expected that our buildings become energy resources, instead of energy consumers". Modular often translates to individual units, allowing easier integration of services (i.e. heating and cooling) control in comparison with conventional building. Prefabricated design provides a good opportunity to take on the R.A.R.E. principles because it supports the idea of integrated design at all stages in a project and offers the possibility to combine multiple systems and services. The focus is on flexibility, of design, of adaptation, of space and aesthetics. By identifying and classifying modular design we open up a larger playing field and therefore more variations. Modular design has not been as accessible in the past due to high costs and code restrictions. However today modular designs are becoming more intelligent as our sophistication of materials, energy systems and building services improve. The new paradigm for modular design is to understand its classifications, taking onboard our developed technologies, using renewable and adaptive principals to rectify livable space and through testing, combining and refining modular architecture it can be readdressed within a new light, one that may be more successful than the past.

6.0 CONCLUSION

This paper has attempted to organize and provide an analytical method in the design evaluation of prefabricated modular building. The necessity for such is apparent to students who are presented with abundant examples on the topic with no particular design objectives, direction or construction methodology. The authors are not stating that the proposed method of investigation is the definitive on modular prefabricated building diagnostics, but rather a start to a possible approach. Teaching ourselves about the topic of modularity and prefabrication prompted a desire to find an organization of it. We wanted to ‘discover’ how it could be explained and taught to others.

This research lead to a better understanding of the subject matter and provides inference on how to evaluate new modular prefabricated systems designed by others. It has also provided insight towards an approach in designing our own modular systems as well as providing critical analysis of our limits in a particular design. If we can categorize and put things temporarily into silos, only to be able to take them out again as need be, we are better off than designing in a atmosphere of unknown chaos.

The recognition of integrating innovative building services and renewable energy sources into modular prefabricated design is a huge step towards sustainable living unit production. If we can organize our designs with a checklist of optimum flexibility through prefabrication and modularity we may finally be on the road towards an effective architecture.

REFERENCES