SUSTAINABLE PREFAB HOUSES: CHALLENGING CONVENTIONS IN DESIGN, CONSTRUCTION AND OCCUPATION

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Abstract: The Australian volume housebuilding industry has been reluctant to adopt more sustainable or innovative alternatives to well-established construction methods such as brick veneer (Dalton 2013:14). Furthermore, new dwellings have, on average, increased in size, instead of being designed to make more intelligent and effective use of space and resources (ABS 2010; Clune 2012). To date, architects and academic researchers have had little influence in this market, and instead focussed on cost-certainty with limited scope for experimentation and innovation (Dalton 2013:30&59). In order to overcome such barriers, the LP13 project was set up as a collaboration between the Applied Design Research Lab at the University of Sydney and the Industry Partner, who is a manufacturer and supplier of Structural Insulated Panels (SIPs) for large housebuilders. The project attempts to integrate a SIP system into a quality, sustainable and affordable prototype prefabricated house that would challenge conventions in design, construction and occupation of current offerings in the volume house building market. Design solutions were developed to appeal to and impact on this outwardly conservative market. The aim was to innovate by building on the existing SIP building system already on offer and to integrate it into an optimised overall solution that addresses issues of design quality, affordability and energy-efficiency holistically. The project makes improvements that address technical and construction issues (for example by optimising energy efficiency and speed of construction) as well as configuration (through layout and customisation options for the houses). The collaborative design approach of the project involved manufacturers, designers, engineers, expert consultants and house builders.

Keywords: Housing, Sustainable Design, Prefabrication, Energy Efficiency, Mass Customisation
1 Introduction

This paper will describe the research process and results from the LP13 project at the Innovation in Applied Design (IAD) Lab at the University of Sydney. The LP13 project was born out of an ARC linkage grant, set up by IAD Lab director, Prof. Mathew Aitchison, in order to research the design and construction of quality, sustainable and affordable pre-made housing in Australia, using an integrated and holistic approach.¹

The industry partner was a manufacturer of Structural Insulated Panels (SIPs) with Expanded polystyrene (EPS) core and Magnesium Oxide (MgO) boards externally. The advantages of this product are high R-values, high levels of airtightness, low levels of Volatile Organic Compounds (VOCs) from the MgO, which is also mildew resistant and highly durable. The industry partner’s interest in this project was to demonstrate that their SIPs can be used to build more efficient, sustainable and affordable housing through the design and building of a pilot project house.

Working with industry on applied research projects with real building outcomes carries its own risks - the same risks faced within the commercial realities of the industry itself. These include: uncertainty around financing and partnering; complicated decision-making processes that go outside the control of the research team; tight timelines; and, complex communication issues. Cumulatively, these factors come to bear in ways that “pure” research projects are less exposed to. Nevertheless, the purpose of applied research is to test ideas and strategies, not in the rarefied conditions of the Lab or university, but the terminal environment where the final product will be designed, built and used. This process, which might appear confusing and disjointed, still holds many valuable lessons that are shared in this paper.

2 Project References

The industry partner had previously worked in areas of innovation of housing design and some of these ideas also influenced the LP13 project. One example is a collaboration of Frazer Paxton Architects on called the ‘Grow Your Own Home’ project. This was a modular house that could expand over time, so a family could add on extra modules as needed (Fig. 1). Members from the industry team had also previously been involved with disaster relief housing in Haiti where they worked with local communities on the design of prefabricated house types that would best suit their needs.

![Figure 1: ‘Grow Your Own Home’ project by the Industry Partner and Fraser Paxton Architects](Source: Correspondence from the industry partner)
As part of the literature and references review, other projects were studied where universities or research organizations collaborated with industry and consultants on creating sustainable prototype projects. Two examples are the sustainable retrofit project HouseZero, a collaboration between Harvard University and Snohetta (Snohetta 2017) and also the Illawarra Flame house by the Sustainable Research Building Centre at the University of Wollongong (SBRE 2017). In terms of research method, the relevance for LP13 is the holistic approach; both of these reference projects involved incremental improvements on various aspects of the building, in order to achieve the overall aims of designing and building a more sustainable home.

Another prototype house that influenced the approach taken was the Lighthouse in the UK, constructed in 2007 on the BRE Innovation Park in Watford and designed by Sheppard Robson Architects (Fig.2) (Shepard Robson 2007). This project also uses a SIP system (by Kingspan) and incorporates design and technical innovations in terms of layout, efficient building fabric, ventilation and renewable energy generation, in order to achieve the highest code for Sustainable Homes in the UK – a rating of 6.

In terms of design innovation, two reference research projects are particularly relevant: Diego Ramirez-Lovering’s work on housing flexibility (Ramirez-Lovering 2012) (Fig.4), and Damian Madigan’s work on infill housing in established suburbs (Madigan 2017). Both projects challenged housing design conventions by rethinking the way familiar housing typologies can be planned and used. This was particularly relevant for the floorplan layouts of the LP13 project.
3 Briefing and Problem Definition

The initial project aims were developed through collaborative briefing workshops with the industry partner to better meet their needs and business goals. The complexity of the research question and aims required an approach that addressed multifaceted aspects of the problem, which became apparent in the initial briefing meetings. Issues raised included: an integrated design approach with the engineers; understanding how this product fits into the market (specifically the affordable housing market); flexibility in architectural expression; meeting high sustainability targets; refining product engineering; and, initially, the goal of building a completed prototype house (Fig. 4).

In the volume house building market, two areas in particular stood out to us with significant scope for innovation and improvement. Firstly, energy-efficiency standards in low-cost volume house building in Australia are notoriously poor (Fig. 5). The example image shows a suburban house in Gawler (SA) under construction to basic specifications. Although incomplete, the construction already shows significant weak points in the thermal envelope, for example: aluminum window frames without thermal breaks, single glazing and gaps in the timber framing where it will be difficult in practice to install effective insulation.
Secondly, floorplans often prioritise quantity over quality of space and usability (McMansion syndrome) (Ramirez-Lovering 2012:45-46). Through the initial workshops and benchmarking research, the LP13 project objectives were further refined to develop a prototype house designed with the Industry Partner’s SIP product at an affordable price point but without the usual trade-offs in design quality and energy efficiency. This project therefore attempted to meet higher sustainability targets and offer a smarter design and layout than typical for affordable volume house building.

The project aims were refined in more concrete financial terms by carrying out a survey of competitors in the market of volume housing, pre-fabricated and sustainable houses (Fig.6). One of the cheapest houses on the market were project homes by Statesman Homes in South Australia with a base price of $735 per m² (construction cost). Modular prefabricated homes from Ecoliv cost around $2500 per m². Highly energy-efficient prefabricated offerings from Archiblox are priced around $3500 to $5000 per m². While the comparison based on m² prices is difficult given exclusions and inclusions, which were also reviewed, this benchmarking of m²-costs was a useful exercise to understand where the project would sit in the market. The goal in this project was to be affordable but not necessarily to develop solutions that are even cheaper to build than low-cost (but also low-quality) housing that is already on the market. Instead, the aim was to develop solutions that offer other benefits at a similar price point and that support affordability in the long run in terms of running cost and enhanced usability.
In addition to assessing how the project fits into the market, a survey was undertaken of the regulatory context of affordable and social housing in Australia. This survey was useful so that potential regulatory barriers could be identified – aspects of which may need to be challenged if they contradict the project aims – and to allow the design to be compliant for as broad an application as possible. Multiple sites were under consideration at this stage of the project, so codes and regulations were mapped out that would affect the way affordable housing is designed and built across four states that were surveyed (Fig. 7). This survey suggested that NSW has the most stringent design guidelines for affordable housing and was therefore used as the basis for the first design iterations.

**Figure 6:** The breadth of the market: Homes by Statesman, Ecoliv and Archiblox.

The kinds of areas regulated in the surveyed design codes were: site planning, interior layout, building construction and finishes, as well as energy-efficiency and sustainability. In this cross comparison, the Livable Housing Design guidelines (LHA 2017) and the NSW FACS Design Standards provided the most concrete guidance (FACS 2017).
design that takes these into account should therefore be as versatile as possible within the affordable housing market across Australia. The overall size of the houses and spaces was one of the key aspects in these guidelines. The challenge was to fit the larger size rooms of the houses designed to a Livable 'platinum' standard within the confines of what was considered an acceptable maximum overall dwelling size.

4 Design Development

In terms of design, the research employed an iterative process, which can be broadly outlined in four main steps: Step 1 was to develop a prototype concept design. Step 2 was to refine this design through energy-use simulation and input from our engineering research partners. Step 3 was the development of specifications, as well as external envelope detailing and design options. Step 4, the final step, was to build a full size, actual house to demonstrated these principles in built form. For reasons outside the control of the research team, this prototyping was cancelled. Nevertheless, the findings of steps 1-3 hold great value for future work.

The LP13 prototype design developed in steps 1-3 challenges volume suburban housing by providing an alternative solution that offers improvements in three areas in particular: a) increased adaptability and flexibility; b) improved thermal efficiency; and c) customization to site and user preferences. The iterative process and considerations that underpinned the development of this design solution will be discussed in the following key steps.

4.1 Step 1 – Prototype Concept Design

The site dimensions of 12.5 x 30m were based on the industry partner target market and on suburban housing that their volume house builder clients build. The first step was to test the floor area standards from the above guidelines by applying them to a three-bed house floor plan layout. Several plan options were developed: a compact option, an L-shaped plan type, as well as two long and narrow plan types (Fig. 8). All these options satisfied the functional requirements, but they did not sufficiently challenge the floor plan arrangements that can be found in other volume house building.

![Figure 8: Initial test floor plans](image-url)
In response to this first design test, strategies were introduced to challenge aspects of volume house building that had been identified as problematic earlier. In particular, adaptability and flexibility could be used as cost-effective ways to make the proposed homes more user-friendly and affordable in the long run. The comprehensive survey of flexible design tactics by Tatjana Schneider and Jeremy Till was used as a key reference (Schneider and Till 2007) (Fig.9) and three strategies were identified in particular that were useful for the LP13 project:

1.) Functionally neutral and reconfigurable spaces that could change use over time
2.) Slack space that could be appropriated, particularly outdoor space
3.) Structural design that supports flexibility

These strategies informed a new series of concept sketches and design iterations, developed in workshops by the architectural team. These new design concepts of elastic volumes move away from an ‘Existenz Minimum’ (bare essentials) approach to affordable housing. The floorplan is less compact than the previous versions but it makes use of the low-cost wall system to offer an overall more generous spatial experience. This revised design concept offers a number of advantages that a basic, compact form could not provide (Fig.10):

1.) Functionally neutral and re-configurable. Each volume is large enough to accommodate either 2 bedrooms, a Living/Dining/Kitchen area, a small Granny flat or a home office and kitchen.
2.) Slack space & expandability. The volumes are spaced apart to create slack space that can be used for storage, terraces or laundry, for example, which suits an ‘outdoor’ lifestyle, or which could be filled in by an extension at a later date if required.
3.) Structural flexibility. The external walls of each volume would be built with the Industry Partner’s SIP system and would be structural. The internal walls would not be structural and could therefore be reconfigured.
4.) Thermal envelope hierarchy. This arrangement of volumes enclosed by SIP walls creates thermal zones that could potentially be heated and cooled separately.
5.) ‘Elastic’ volumes. The concept could be adapted to sites of different widths.
The application and testing of these principles can be seen in a series of draft floorplans (Fig.11).

Figure 10: Diagrams of design concepts
This first sketch design was further refined to align with complying development rules within NSW, because at the time, this was the most likely location for the prototype (NSW 2008). The revised designs could achieve planning approval swiftly for a potential site in NSW and it would also be likely to be closer to the expectations in other states. Six different floor plan options emerged out of this compliance check and its potential implications on the layout (Fig.12). A key alteration was prompted by the requirement of a carport or garage to be set back 1.5m from the front façade of the building. The first option was chosen as the preferred design because the plan successfully retained the courtyard slack space and also incorporated the required garage.

Figure 11: Floor plan options

Figure 12: NSW Complying development floor plans
The aforementioned Livable House Design guidelines were re-applied to this preferred floor plan layout. Option one shows the initial configuration with a garage as a 3-bedroom house (Fig.13). However, as circumstances change, the garage could be converted into an extra bedroom and bathroom (Fig.14). Eventually the eastern portion of the building could be converted into a self-contained ‘granny’ flat for extended family or a source of income for the main household (Fig.15). The final layout therefore incorporates the advantages of a more flexible house plan that can accommodate changes in household circumstances.

![Figure 13: Option One: Three bedroom plus garage](image)

![Figure 14: Option Two: four bedrooms](image)

![Figure 15: Option Three: Two bedroom plus granny flat](image)
4.2 Step 2 – Energy-Use Simulation and Engineering

Apart from challenging conventions in housing floor plans, another important aspect was achievable energy-efficiency in relation to the targeted price point. A first step was to identify the standards and guidelines that were used for rating energy-efficiency for housing in Australia. The most common is the NatHERS rating. For NSW, Basix is a key rating tool also used for code compliance. Furthermore, the passive house standard was used as a more ambitious benchmark to assess the LP13 project against, taking into account aspects such as airtightness and thermal bridging that are not as relevant for these other rating tools.

To make sure that the consequences of these different standards and guidelines were translated into the construction, their impact on the specifications was documented. These would influence parts of the design including: site works, construction materials, insulation, windows, doors, power, ventilation, water, sanitary, joinery, metalwork and finishes. Some aspects of the guidelines and standards contradicted each other and also conflicted with the project aims. For example, the NSW FACS guideline explicitly states that there should be no double glazing in affordable and social housing designs, although it can improve energy efficiency (FACS 2017). In the spirit of the project, such conflicts were addressed as part of the challenge to rethink affordable housing.

In order to rate the house design and achieve the energy-efficiency target, a survey of energy assessment tools was undertaken to identify those appropriate for the LP13 project. The tools identified were the Firstrate5 tool as a quick way to evaluate design options for NatHERS. Sefaira was used as a more general tool to estimate the overall energy use of various design iterations. The PHPP package and DesignPH tool would be used for assessing building performance in relation to the passive house standard. Another energy assessment tool which was considered was Design Builder. Furthermore, one of the engineering PhD students, Gerardo Soret, supported the project by providing thermal bridging analysis, which will be further outlined below.

For the NatHERS assessment, a series of tests were run to optimize the design for a potential site in Adelaide (then, the most likely as a location for the Step 4 prototype build) and later for a site near Sydney (Fig.16). A 6-star rating would be sufficient to achieve BCA compliance. With the right orientation, however, an initial test showed that an 8-star rating could be achievable when incorporating the Industry Partner’s SIPs wall system, a waffle pod ground floor slab, R4 insulation in the ceiling and double glazed UPVC windows.¹

¹ Note for final paper presentation: we intend to calculate the added cost for these specifications over a basic NatHERS pass. These should be available for the presentation in January.
The Sefaira tool provided a better breakdown of where additional improvements could be achieved and where most of the heat loss happens (Fig. 17). Areas of improvement, according to this assessment, would be additional floor insulation and also increased airtightness. Sefaira was also used for an initial assessment of how much roof area for Photovoltaics (PV) would be needed to achieve a zero-energy home, as a potentially enhanced version of the low-cost house prototype. Although it exceeds the scope of this paper, a passive house assessment is underway and will be published in a forthcoming paper in collaboration with Dr. Carlos Jimenez-Bescos.
4.3 Step 3 – Detail Specifications and External Envelope

A key objective of the research was to improve the efficiency of the panel product (Fig.18). The cutting SIPs on site, for example, not only reduces the efficiency of construction by creating waste and adding time and Labour cost, but it also makes it harder to control the consistency of the thermal envelope and increases chances of air leakage and thermal bridging. Several solutions were investigated. To facilitate BCA compliance, a secondary timber support structure was introduced as a structural spline, which also improved fire performance. Although the panels are structurally self-supporting without the timber studs, in the event of fire, the EPS core could melt and the structure of the whole system could be compromised.
Throughout the design development and benchmarking research, the two engineering PhD candidates at the University of Queensland, Gerardo Soret Cantero and Aaron Bolanos Cuevas, researched the thermal, fire and structural performance of the Industry Partner’s SIP system. Soret calculated the thermal performance of a previous system which used laminated MgO splines between the SIPs. The system performed well in terms of thermal mass, but poorly in terms of thermal bridging and also constructability (Soret 2015, 2017). A further thermal analysis simulation of the new SIP wall system showed that the overall R-value would be markedly reduced by the introduction of timber studs versus a pure SIP system (Fig.19). The final version of the prototype structure should therefore be designed to reduce the timber framing as much as possible and replace the studs with SIP splines where possible, without compromising the structure.

Cuevas tested how the EPS responded to various levels of heat. The main recommendation from this test was that the entire perimeter of the SIPs would need to

Figure 18: SIP project by the Industry Partner’s - Adelaide Hills

Figure 19: Industry Partner’s SIP – Thermal bridging analysis
be encapsulated to protect the EPS core from direct exposure to fire. Fire and/or excessive heat could comprise the structure of the system once the EPS melts.²

As part of collaborating with engineering experts, the building’s construction details were to be developed to ensure their methods of encapsulation and potentially alternative methods for framing were applied. One of the key construction details was the roof system. While the wall system had gone through various iterations of detailing, the interface with the roof and type of roof system was less well developed. These details would be crucial for energy efficiency, buildability and cost. After discussions and a survey of common roof systems used for cost-efficient housing, three potential options were identified. The first was a traditional steel roof system with rafters. The second option was a truss roof, with the main part of the insulation at ceiling level and a ventilated attic. The third option was a SIP roof with rafters below to achieve the required spans. (Fig. 20).

Figure 20: Roof construction system options

These roof construction system options informed an external envelope design studies matrix that was used as a design development and benchmarking tool (Fig. 21). Part of the project brief was to target a volume house building market, rather than an exclusive ‘high-end architecture’ market. It was therefore important not to impose architectural tastes but to offer options and design flexibility to suit different user preferences. The matrix demonstrated that the same floor plan could be used with different roof types to achieve vastly different architectural expressions. The hip roof was a favoured option because of its mass-market architectural appeal and cost-certainty. Others preferred a skillion or gable roof version, with a more contemporary design appeal. By tabling the various options, it was easier to go through an evaluation process to identify the one that best meets the project aims.

² Cuevas currently continues his PhD research on the structural integrity of a system with a focus on achieving a system that relies on as little timber framing as possible, taking account of both fire and structural loads.
5 Conclusions

This industry-linked research has challenged assumptions and conventions of what could be achievable in affordable house building, in terms of energy-efficiency and design quality. Overall, this project is a promising starting point rather than an endpoint. It has also served to find leading research in the field and incorporate these lessons in new ways. These lessons, and the finding of this study, can be transferred into further work in this area and can make a contribution in transforming Australia’s housing for a more sustainable future.

The designs, that were developed for an affordable housing market, demonstrated that a high level of energy efficiency can be achieved with cost-effective construction specifications. The additional measures required, such as double glazing and R4 ceiling insulation, can change the house design from a bare pass to an 8-star NatHERS rating and are not as prohibitively expensive as assumed. In the design and benchmarking process, it has also become clear that achieving strict standards, like the passive house standard for our example sites in Adelaide and Sydney, has less to do with expensive specifications and is more about considered planning and construction.

Furthermore, the designs developed challenge floor plan conventions in volume house building. The project showed that innovative planning of the houses can make a significant difference for long-term usability and flexibility. These aspects are particularly important for a smart and sustainable housing future, where the mono-functional suburban house may no longer be achievable for most. The findings of this project suggest that volume house building can do more than be designed for and serve the average family model of 2 parents and 2 children. This ideal model only applies to a limited number of households and houses will need to be able to adapt to other scenarios when required throughout the householders’ lifetime. The proposed prototype
design provides an alternative solution to suburban housing that is potentially adaptable to different sites and user preferences, more flexible in its long-term use, and offers improved thermal efficiency.

Future research avenues could include: cost-benefit calculations and comparisons to traditionally built volume housing offerings; comparative energy-efficiency simulations; optimised construction detailing; design studies of adapting the concepts to another site; and, the ultimate test of constructing a prototype house.

References


