Towards Sustainable Modular Housing: A Case Study of Thermal Performance Optimisation for Australia

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ABSTRACT

The need for affordable housing is a growing issue requiring sincere and urgent attention globally. With increasing focus on climate change and other environmental issues our housing must be environmentally sustainable too. We also need housing in remote areas where conventional construction is both cost and resource inefficient. Prefabrication offers great opportunities for both sustainability and affordability and hence is emerging as an attractive alternative to conventional on-site construction.

In this context, the CRC for Low Carbon Living in Australia has been engaged to develop designs for sustainable and affordable modular homes. The early optimisation was undertaken using AccuRate Sustainability – Australia's national benchmark software tool for rating the thermal performance of residential designs. An iterative process was employed where the rating software was used as a design and analytical tool to generate optimised designs for various orientations and climate zones throughout Australia. This paper explores the process of improving the performance of an existing design and developing a thermally optimised new design, and presents some of the early results of this optimisation.

The results show significant improvements in the thermal performance when compared to the existing design, but more importantly, the combined engineering and design research efforts developed general design principles that seemed to work well for most of the climates and orientations studied. This research contributes to the debate on integrative design process and its significance for sustainable built environment in general; it also ascertains the path forward for a more comprehensive approach to net zero energy and self-reliant modular housing – the eventual aim of the project.

INTRODUCTION

The need for adequate affordable housing is now considered a major issue in both industrialised and emerging countries (St Andrews Centre for Housing Research et al., 2014). With increasing focus on climate change mitigation and adaptation along with other environmental concerns these housing solutions need to be environmentally sustainable too. Both in Australia and overseas prefabricated housing solutions have been identified and are being proposed as an important path that can deliver both sustainable and affordable housing (Quale, 2012; The Greens, 2013). There is also a significant need for adequate solutions for remote area housing (regional communities, mining towns, emergency shelters, etc.) where conventional on-site construction is both costly and resource inefficient. Off-site construction or prefabrication in such situations becomes an especially attractive alternative.

In this context a multidisciplinary research team at the Cooperative Research Centre for Low Carbon Living (CRCLCL) has been engaged by Nova Deko, a modular housing manufacturer, to develop design solutions for 'Sustainable and Affordable Living through Modular, Net Zero Energy, Transportable, and Self-Reliant Homes and Communities'(Low Carbon Living CRC, 2014). The project is currently in its second year and this paper explores the recently completed first stage of this project – improving the operational performance of an existing design – and discusses the process of developing a thermally optimised new design for sustainable modular housing as per Nova Deko's requirements.

This paper presents the findings from the early thermal performance optimization process – a combined engineering and architectural design research effort – that started with the original design called 'Samara Pod' and finished with the creation and optimization of the final improved design called 'conceptPod'. An important part of this process was the well-designed integration of various services including domestic hot water, photovoltaic (PV) system, electrical services, equipment, white goods, and rainwater harvesting. The reason for this was twofold. First, to achieve a standardised and integrated product, so the installation of the complete Pod is easier, quicker, and therefore more cost effective. Second, to apply whole systems thinking during thermal performance optimization so the final design was efficient not only operationally but also throughout its lifecycle. In order to maintain the focus on the subject matter and in response to the space limitations here, however, the research on PV and other services integration is considered out of scope for this paper. The research presented here is a work in progress and achieving a net zero energy or self-reliant status, the eventual aim of the project, will be subject to further optimisation and renewable energy, water and waste system integration.

METHODOLOGY

The research for the project began with a study of literature on theory and practice of prefabrication and then employed an ongoing collaborative and integrative design process. The optimisation was performed as an iterative process using AccuRate Sustainability, a Nationwide House Energy Rating Scheme (NatHERS) accredited software, which measures thermal performance based energy efficiency of residential designs in Australia (CSIRO, 2014). The software, from here on referred to simply as AccuRate, was tested and validated using the Internation Energy Agency BESTEST protocol and was found to be very satisfactory (Delsante, 2005). During simulation AccuRate automatically switches between mechanical air conditioning and natural ventilation modes to maintain indoor thermal comfort within parameters specified by regulatory requirements. In doing so it calculates heating and cooling demands to maintain comfort conditions over a whole year. The total annual energy load (MJ/m2) expresses the overall thermal performance in a star rating for the specified climate zone. The rating ranges between 0 and 10 starts where a 0-star indicates the building envelop practically having no effect in reducing thermal discomfort while at 10-star performance the occupants are likely to need little or no mechanical cooling or heating to maintain comfort (Ren et al., 2013).

The National Construction Code's Building Code of Australia (BCA), in the absence of any specific state level regulations, requires all new houses to meet the minimum thermal performance of 6-stars for their regulatory approvals. Considering that the subject design will anyway need to be rated for regulatory compliance and that AccuRate has robust modeling capabilities to use it as a design decision making tool the research team decided that AccuRate was a very suitable tool for this particular research. The objective was to achieve as high a start rating as possible thereby minimising the size of a PV system to offset the remaining energy requirement.

The scope for this study included five key climate zones from Australia and eight orientations for each zone. The iterative process was designed so that the pod design and its thermal performance was improved to a satisfactory level for one climate and then that optimized design was used as the base model for improvement in the following climate, and so on. The idea behind this was to test if the "good design principles” applied in one climate could serve as a good starting point for a similar climate. To apply this approach the researchers used the following climate sequence: Brisbane, Sydney, Melbourne, and Hobart, i.e., from North to South, or warm to colder climates. Finally, the climate of Darwin, which is located further north, was also tested taking Brisbane results as the base model.

The process was essentially a parametric study where three key strategies – shading, insulation and glazing – were tested and parameters, such as type, position and amount of glazing, shading and insulation, were changed individually in order to reach local and global optimums. Although this required several iterations, due to space limitations only the first and the last simulation results are presented here. Three main types of shading devices tested were fixed horizontal, fixed vertical (wing walls), and “operable shading” such as operable louvers or sails. The performance of several types of glazing options were analysed mainly based on their U-value (W/m^2K) and solar heat gain coefficient (SHGC) value. Different types and levels of insulation based on their R-values (m^2K/W) were also tested for each location. As a general principle, the level of insulation was maximized and glazing was reduced, while trying to maintain good cross ventilation and connection with the outdoors. The optimization was finalised when no further meaningful improvements in the thermal performance (measured by star rating from the AccuRate simulation) could be achieved by modifying Shading, Glazing, and Insulation.

Changes in other parameters of the design were scheduled for the next stages of the project and hence were considered external to the scope for this particular exercise. Nevertheless, design quality and aesthetics of the interior spaces and the exterior, services and technology integration, weight of the completed Pod, and non-thermal environmental concerns were always part of the consideration even if they are not elaborated on in this paper due to space limitations. In every climate the simulation was started with the orientation of the front façade with bi-fold doors at the North before testing other orientations. The exposure was kept Suburban and ground reflectance as 0.2 in all AccuRate simulations.

EXISTING DESIGN AND ITS PERFORMANCE

The study started by taking the existing design of Samara Pod as the base model for Brisbane. The house with a simple rectangular floor plan (Figure 1) is manufactured with lightweight steel framing in a wide 40 foot shipping container size. The design has been developed so that a nearly complete house would be shipped to any site. With minimum onsite assembly requirements, except when other external features such as outdoor deck and additional shading were required, the house would be ready to occupy in a matter of days after arriving on site (Figure 2). The first AccuRate simulation was based on material specifications listed in Table 1 and produced a rating of 5.1 stars with detailed results tabled in Table 2.

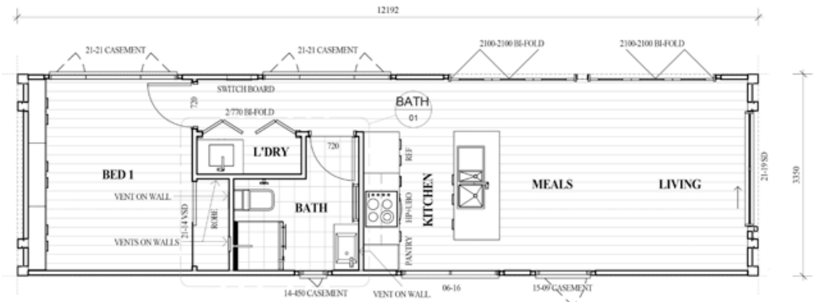

Figure 1 Floor plan of Samara Pod Base Model (Source: Nova Deko)

Figure 2 Samara Pod viewed from the North (Source: Nova Deko)

Table 1. **Specification of Samara Pod Base Model**

Element	Construction	R value (Up/Dn)
External wall	FC board/Reflective Barrier/Insulation/Plaster Board	3.38 / 3.38
Internal Wall	Plaster Board/Air Gap/ Plaster Board or FC board	0.44 / 0.44
Roof/ceiling	Steel/Ref. Barrier/Insulation/Plasterboard	4.12 / 4.35
Floor	Timber/FC board/Insulation	3.05 / 3.05
Windows	Glass/Air Gap/Glass; SHGC = 0.48; U = 3.92	0.25
Shading	As per Samara Pod (900mm North, 320mm rest)	NA
Underfloor	Enclosed 500mm height subfloor	NA

PERFORMANCE OPTIMISATION ACROSS DIFFERENT CLIMATES

Brisbane is located in a subtropical (no dry season) climate as per a modified Koppen classification (Bureau of Meteorology, 2012). The performance of the base model in Brisbane indicated disproportionate energy use in cooling. To address this issue main priority was given to reducing the amount and altering the type of glazing to reduce heat-gain. Through intense integrative design exercises a series of changes were identified and simulated. This included minor modifications to the internal layout mainly to redesign the bathroom and laundry to achieve better integration of various services. Key changes were in the building envelope for strategic placement of a mix of different types of high performance glazing (U=1.5 and SHGC=0.5 or less) especially on the East and West, and various types of shading devices especially on the North. With the help of these changes the optimised design – the conceptPod – was finally able to achieve 7.6 stars with total energy demand reduced to about 55% of the Base Model when the glazing area to floor area ratio was reduced to about 52% from the original 64%.

Table 2. Thermal Performance Improvement of conceptPod Base Model in Brisbane

Description	Heating (MJ/m^2)	Total Cooling (MJ/m^2)	Total Energy (MJ/m^2)	Rating (Stars)
Base Model conceptPod	12.3	41.0	53.3	5.1
Optimised conceptPod	10.3	19.2	29.5	7.6

As discussed earlier the conceptPod for Brisbane was taken as the Base Model for Sydney, which is located in a temperate (no dry season – warm summer) climate as per a modified Koppen classification (Bureau of Meteorology, 2012). The simulation for Sydney rated the design at 7.0 stars. Several modifications were made to the design, mainly shading and wing walls size and positions, but the best results were obtained with operable shading to the North allowing winter sun in the living areas and the bedroom, and deep shading in the form of a carport to the East. This gave a rating of 7.9 stars (Table 3).

Table 3. Thermal Performance Improvement of conceptPod Base Model in Sydney

Description	Heating (MJ/m^2)	Total Cooling (MJ/m^2)	Total Energy (MJ/m^2)	Rating (Stars)
Base Model conceptPod	12.7	17.1	29.9	7.0
Optimised conceptPod	7.8	15.2	23.0	7.9

Melbourne has a temperate (no dry season – warm summer) climate as per a modified Koppen classification (Bureau of Meteorology, 2012). When the optimized design for Sydney was tested for Melbourne, it rated at 6.9 stars, a decrease of 1 star compared with Sydney. A large number of changes in shading, glazing size and insulation were made without any significant improvement to the overall performance. It was only after converting most of the glazing into high performance glazing equivalent to top of the range double glazed windows that the rating of the Pod increased to 7.7 stars (Table 4).

Table 4. Thermal Performance Improvement of conceptPod Base Model in Melbourne

Description	Heating (MJ/m^2)	Total Cooling (MJ/m^2)	Total Energy (MJ/m^2)	Rating (Stars)
Base Model conceptPod	59.0	27.3	86.3	6.9
Optimised conceptPod	36.6	27.0	63.6	7.7

Hobart has a temperate (no dry season – mild summer) climate as per a modified Koppen classification (Bureau of Meteorology, 2012) and has a large proportion of energy use in heating spaces. Surprisingly, when the Melbourne design was simulated in the Hobart climate the obtained rating was, already higher than Melbourne, at 8.1 stars. A similar result was obtained with the base Samara Pod, which achieved a 6.0 star rating, highest so far of all tested climates. Because the obtained rating with the conceptPod was already above 8 stars, the optimization for this climate was based on obtaining the best rating possible while limiting the standard double glazing in the main windows for the living area and the bedrooms. Finally, with strategically placed high performance glazing and carefully sized and positioned operable horizontal and vertical shades the final design resulted in a rating of 7.6 stars.

Table 5. Thermal Performance Improvement of conceptPod Base Model in Hobart

Description	Heating (MJ/m^2)	Total Cooling (MJ/m^2)	Total Energy (MJ/m^2)	Rating (Stars)
Base Model conceptPod	64.0	4.6	68.6	8.1
Optimised conceptPod	82.1	7.1	89.3	7.6

Darwin is on the other end of the climate spectrum when compared to Hobart. It is located in the tropical (Savana) climate as per a modified Koppen classification (Bureau of Meteorology, 2012). Because of its proximity with the equator, the sun here can be in the South (summer) as well as in the North (winter). This meant that shading on both of these façades had to be considered very carefully. For this climate the optimized Brisbane Pod was taken as the based model. The first simulation showed a rating of 5.9 stars, the lowest rating obtained so far for any first iteration. After several changes, without much improvement, the highest rating of 7.2 stars was obtained when all Northern windows were made high performance glazing equivalent to triple glazing, insulation was maximized everywhere and 450mm fixed horizontal shading, similar to an eave, was added to all facades. However, the aesthetics of this solution remained unresolved with an intention to revisit the design and thermal performance improvement strategies employed in this climate. The maximum rating of 7.2 stars is the lowest achieved for all climates after the optimization and may be indicative of the limits of the current Pod design, its size or the small number of improvement strategies tested so far.

Table 6. Thermal Performance Improvement of conceptPod Base Model in Darwin

Description	Heating (MJ/m^2)	Total Cooling (MJ/m^2)	Total Energy (MJ/m^2)	Rating (Stars)
Base Model conceptPod	0.0	356.8	356.8	5.9
Optimised conceptPod	0.0	275.3	275.3	7.2

ORIENTATION SENSITIVITY ANALYSIS

The designs of Samara Pod and climate optimised conceptPods when simulated for all five climate zones across eight orientations they produced results as illustrated in Figure 3. The Brisbane results show that the conceptPod performs relatively well (above or close to 6 stars) for five of the eight orientations, mainly between North and East. The performance decreased markedly when the Pod was oriented to the South and West, with the West having the lowest thermal rating (4.7 stars) due, not surprisingly, to the increase in required cooling. The overall performance of the conceptPod showed improvements between 1.5 to 3.0 stars when compared to the Samara Pod. It is important to notice that the conceptPod design not only achieves a better rating, but is also more resilient to orientation changes.

Similar to Brisbane, in Sydney the conceptPod performs consistently 2 to 3 stars better than the base Samara Pod. In this case however, the performance penalty in the west and south orientation are less pronounced, with a minimum rating of 5.8 stars when facing west. This is an encouraging result as it shows a greater flexibility and resilience of the design to orientation changes. The conceptPod achieves near or above 6 stars rating across all orientations.

The results of the simulations show that orientation has lesser effect in Melbourne than in Sydney or Brisbane. This supports the hypothesis that in Melbourne the thermal performance is dominated by the R value of the envelope and quality of windows, instead of the solar gain. The Pod performs very well in all the orientations, with a minimum rating of 7.0 stars for the West orientation. This is also true for the base Samara design which obtains a more consistent performance for all orientations. The conceptPod performs consistently around 2.5 stars better than the base Samara Pod.

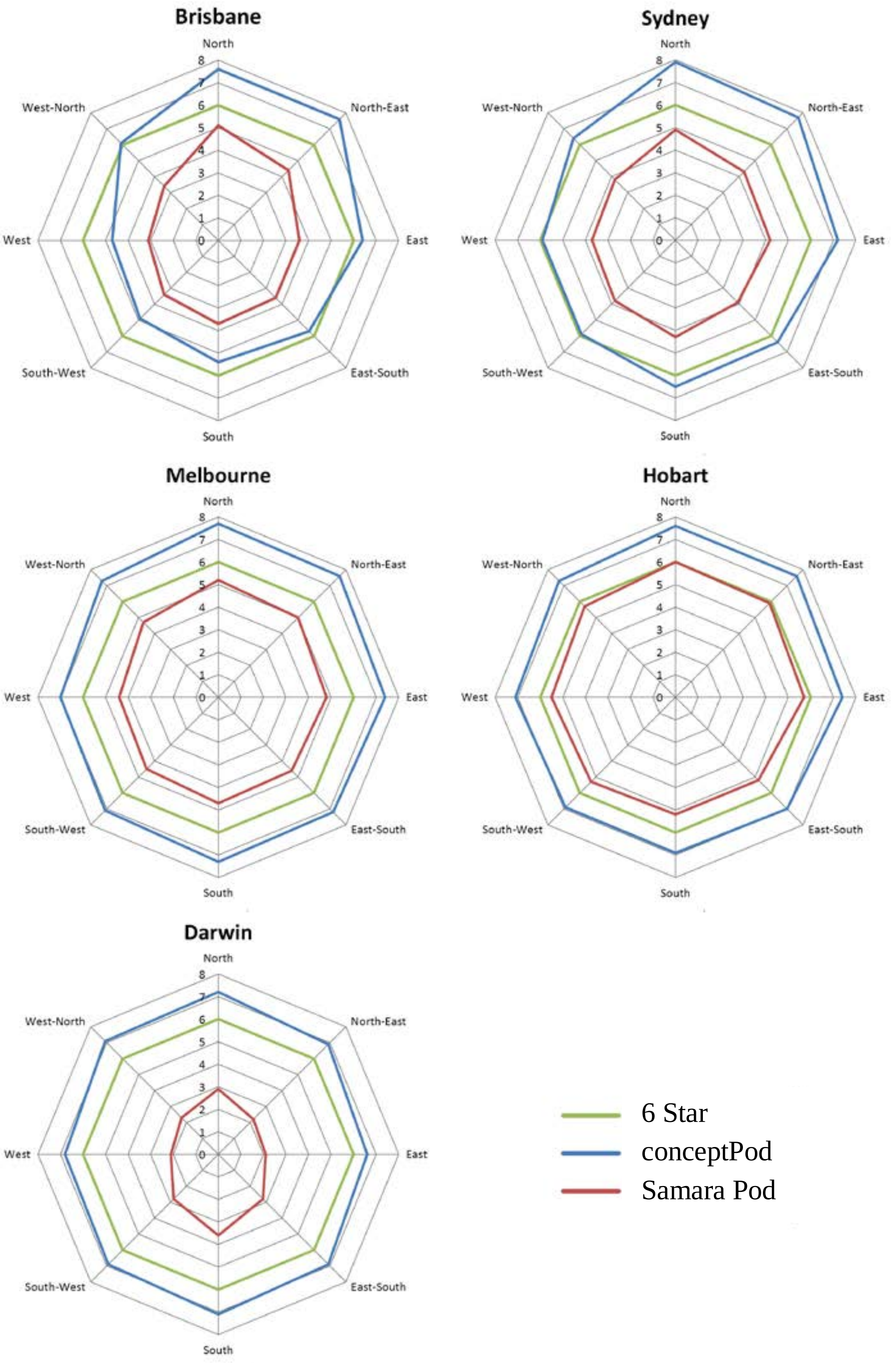

Figure 3 Orientation sensitivity analysis of Samara Pod and conceptPod

As evident in Figure-3 both the Samara Pod and the conceptPod perform very well in Hobart, although the conceptPod obtains minimum 1.5 stars more than Samara Pod across all orientations. It is worthwhile to note that, similar to Melbourne, the orientation of the Pods has less effect on the thermal performance, with only 0.8 stars and 0.7 stars of difference between the minimum and maximum rating for the Samara Pod and the conceptPod respectively. This may be due to the lesser effect of solar gain, optimised adaptive shading and highly insulated building fabric minimizing heat-loss from the Pods.

In Darwin the conceptPod performed reasonably well with performance varying between 6.6 stars as minimum on East and 7.2 stars as maximum on North (a difference of 0.6 stars). On the other hand, the base Samara Pod performed poorly, with a maximum rating of 3.6 stars when facing South, and a minimum rating of 2.1 stars for East and West orientations. This is a strong result showing the resilience and adaptability of the conceptPod design.

IMPROVED DESIGN AND ITS PERFORMANCE

All the lessons learnt from the optimization in each climate were applied to create a final design. The objective was to create a conceptPod that would work as best as possible in each climate. Even if the performance in some locations might be less than optimized, it could still have a good performance. This approach of standardisation, although counterintuitive and contrary to the notion of mass-customisation, was found to offer good manufacturing efficiencies for this particular manufacturer as it would require minimal changes in the Pod depending on the final location of the installation. In order to achieve this, further reviews of the effects of insulation levels and glazing types were carried out. It was found that two main insulation configuration (external wall/roof/floor) could be used in the Pod design depending on the location, for example, R = 4/4/2 for warm/hot climate such as Brisbane and Darwin, and R = 6/6/2 for mixed/colder climate such as Melbourne. Similar testing of glazing alternatives found that it was more effective to upgrade the main windows from double to triple glazing than to improve the insulation in the walls and roof from R4 to R6. It was also encouraging to find that the combination of triple glazing and insulation of R=6/6/2, resulted in ratings above 8 stars for Brisbane and Melbourne.

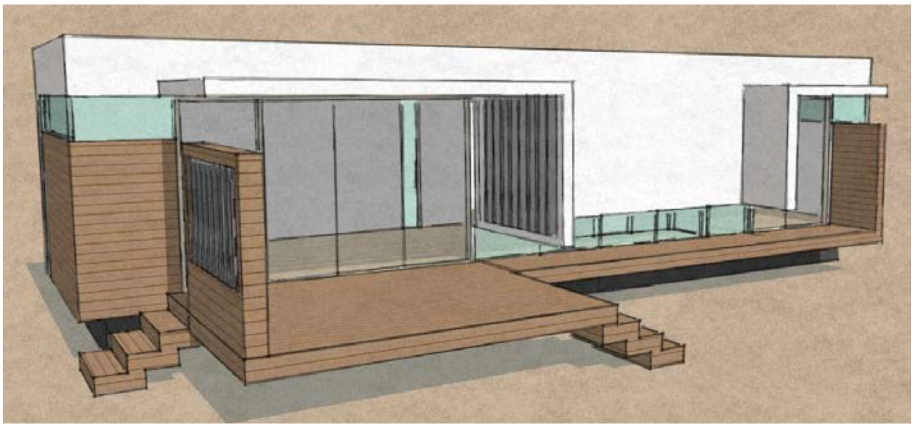

Figure 4 New integrated design of the conceptPod viewed from the North

The final conceptPod included carefully sized and located fenestrations with a mix of different types of high performance glazing. In combination with a mix of fixed and operable horizontal and vertical shading devices they simultaneously satisfied critical requirements of a good design – views, connection with the landscape, sense of spaciousness, privacy, aesthetics, and so on – and the essential aspects of a high thermal performance building – precise solar protection, passive solar heating, effective crossflow ventilation, and so on – to result in a truely integrated design.

A final set of simulations was carried out in order to assess the performance of the final conceptPod having insulation levels of R=4/4/2 and triple glazing in the main window as it was considered best option for balance between performance and cost. The simulations results are shown in Table-7. The only change in the Pod design between each location was the SHGC value of the glazing. The operable shades were designed to be easily adaptable to each climate without changing the overall design. The final results showed consistency with the earlier optimization exercise. The final conceptPod design performed well above regulatory requirements in all climates and achieved star rating up to 8.6 stars.

Table 7. Thermal Performance of Final conceptPod Design

Location	North (Stars)	East (Stars)	South (Stars)	West (Stars)	Comments
Brisbane	8.6	7.8	6.9	6.3	Glazing with SHGC = 0.3
Sydney	8.3	8.2	7.4	7.3	Glazing with SHGC = 0.3
Melbourne	7.7	7.5	7.4	7.1	Glazing with SHGC = 0.5
Hobart	8.2	8.1	7.7	7.9	Glazing with SHGC = 0.5
Darwin	6.7	6.2	6.7	6.3	Glazing with SHGC = 0.3

CONCLUSION

This study was designed to test several ideas and principles regarding the performance of the current Pod design and the limits of various strategies. The results of the final outcome show significant improvement in the thermal performance when compared to the existing design. More importantly, the combined engineering and architectural design research efforts produced an overall design that is easily adaptable for most of the climates and orientations studied. It is well-established that an optimized design for an individual climate and orientation would provide better result than a single "one size fits all" design. However, this particular optimisation process revealed that integrated design approach, with strategically embedded flexibility and economically rationalized redundancy in the type, amount and location of shading, glazing, and insulation, could result in a robust overall design outcome. This outcome – the conceptPod – showed remarkable resilience, for which the performance penalty from different locations and orientations was minimized significantly.

This research contributes to the debate on integrative design process and its significance for sustainable built environment in general; it also ascertains the path forward for a more comprehensive approach to net zero energy and self-reliant modular housing. The next phase of this research focuses on further integration of services and low carbon technologies to achieve this outcome. The lessons learned so far are being used to develope a next generation of 'greenPod', a prototype of which will be tested for a year to measure its actual performance and to compare with its predicted performance.

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