LOW CARBON LIVING CRC

RP1011 – Sustainable and affordable living through modular homes and communities

Final Report

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Acronyms

BD	Bedroom
ERV	Energy Recovery Ventilators
GWP	Global Warming Potential
GFA	Gross Floor Area
LCA	Life Cycle Assessment
LR	Living Room
OA	Outside Air
PV	Photovoltaic
RE	Renewable Energy
RH	Relative Humidity
SHGC	Solar Heat Gain Coefficient
STC	Standard Test Conditions

Executive Summary

This report presents a summary of all the findings and activities performed in the LCL-CRC research project RP1011 “Sustainable and affordable living through modular homes and communities” and represents the culmination of the project. The main objective of the project was to develop innovative designs, evaluate current and future technologies, and establish assessment processes that would both contibute to the wider research and knowledge of the project’s field and allow the projects industry partner; Nova Deko, to manufacture sustainable, net zero energy, and affordable homes and communities, based on transportable modular units (Pods).

The project started in mid 2013 and most activities finished by the end of 2015. The results of the project were provided to Nova Deko and the LCL-CRC in the form of seven reports, not including this final report.

Highlight results of the project:

- Most of the existing Nova Deko designs and models were not able to reach the required 6 star NatHERS rating.
- It was found that it was more challenging to achieve 6-star ratings for small dwellings (less than 40m^2 GFA) than for large dwellings (more than 100m^2). This is due to the way the rating tools operate and the metrics used. This put small Pod models at a particular disadvantage.
    - The cost per m^2 is usually higher in small Pods. This biases the comparison with normal, but larger, ‘kit houses’, where the potential buyers’ perception is that they receive ‘more for their money’, or, larger is better. This can have important and broad consequences for the housing market.
    - After optimization of the Samara Pod (one of the basic Pod units), it was possible to achieve 6 star NatHERS ratings with a core design (the conceptPod) for most Australian climates and Pod orientations. This important result included the optimization of insulation, shading, window size and location, use of innovative materials, cross ventilation analysis, efficient appliances, and more importantly, a new design concept (Yin Yang), among other changes.
- An inspection of the manufacturing process of the Pods highlighted that quality control issues were affecting the installation of insulation as per best practice and lack of thermal breaks. These issues resulted in thermal responsiveness problems once the Pods were installed on site. Water ingress was also identified as an issue due to detailing methods of the pods during manufacturing. Nova Deko was at that time working to rectify these issues, though a solution was yet to be found.
- Site visits also showed that the transportation of the Pods produced cracks and aesthetic damage in many of the materials, including external cladding, wall linings and floors. This required remediation treatment on site, and in some cases the replacement of damaged materials, which greatly increased the cost of installation.
- Furthermore, installation could take longer than expected due to the ‘new’ building concept. Tradespersons and contractors appeared not as experienced with transportable house installation, hence time and associated costs were higher than for a more traditionally built house. This created the necessity of a “plug and play” design.
    - On-site measurements and monitoring of a Pod installed in Tylden, Victoria (using standard Nova Deko design) showed severe problems with condensation. Thermal imaging techniques showed potential problems due to the lack of thermal breaks and general heat leakage from the building envelope, particularly from the window frames.
- A life cycle assessment (LCA) of the Samara Pod revealed that the transport of the Pod only accounts for 3% of the total GWP during the life of the Pod. This was found to be only slightly higher than the GWP transport component of a ‘normal’ house.
- The LCA also found that some of the materials used by Nova Deko increased the GWP disproportionately, hence alternative materials should be used (mainly replacing fibre cement boards). For example, the use of recycled steel would reduce the total GWP of the Pod by approximately 10%.
- All the lessons learnt from the site visits, material types, experimental data, and previous optimization results were included in a new Pod design called the greenPod. The research project team worked with Nova Deko to produce a final version of the design so it could be manufactured.
- Nova Deko was able to incorporate many of the results produced during the project in the production line for several of its models. However, at the moment of this report, the greenPod has yet to be manufactured.

It can be concluded that the project produced important advancements and knowledge in the area of transportable houses. Most notably the project illustrated that it is possible to create affordable and sustainable dwellings, although many challenges still exist, particularly in the implementation phase of this endeavour.

1 Introduction

Nova Deko is an Australian company based in Brisbane, Australia with offices and manufacturing facilities in Foshan, China. Nova Deko's original business focus was home furniture and homeware. Nova Deko saw a step to manufacturing whole houses using that furniture and homeware already manufactured in-house as a natural business progression. The concept chosen by Nova Deko was to use volumetric transportable houses i.e. houses that could be completely manufactured and finished in Foshan and then transported to a final destination anywhere in the world. In order to transport complete houses economically the seminal idea was to utilise existing worldwide shipping container transportation capabilities. This transportation strategy also produced the first important and major constraint to the further development of the modular home designs.

Nova Deko's transportable home designs use structures that have the necessary structural capacity for container shipping; that being structural fixed transport connection points as per standard shipping containers. These fixing points and associated dimensions have extremely low tolerances, hence, the main dimensions of the designs were set from the beginning by these fixing points. The only exception to these constraints was the development of a wider container (around 1.5 times wider than a normal shipping container) that could be transported using the space of two standard shipping containers.

The basic units of the Nova Deko designs were called Pods and are listed in Table 1.

Table 1 - Basic Pod units

Pod Name	**External Dimensions (L x W x H)**	**External Area**
Standard Pod	12,190 x 2,438 x 2,896	29.7 m^2
Half Standard Pod	6,058 x 2,438 x 2,896	14.7 m^2
Wide Pod	12,190 x 3,450 x 2,896	42.0 m^2
Half Wide Pod	6,058 x 3,450 x 2,896	20.9m^2

Nova Deko explored design options by building several homes based on the four basic Pods. However, they realized that there was great potential to increase the sustainability and marketability of the Pods if there was a way to make the Pods off-grid ready while maintaining a low cost, high value, approach. This seminal idea was brought to the LCL-CRC and led to the establishment of the research project RP1011 for the development of "Sustainable and affordable living through modular homes and communities".

This report represents the culmination of project **RP1011** and includes a summary of all the major findings and results of the project. The report is arranged in sections that align with the major milestones through the project, mostly in a chronological order.

Figure 1 - Existing multi Pod house design by industry partner Nova Deko.

Figure 2 - Interior of an original Samara Pod, manufactured based on the wide Pod platform.

Figure 3 - Photo of Nova Deko production line

2 Technical and Design Notes

The first major work performed in the project was the development of Technical and Design Notes. A list of all the notes is shown in Table 2 below.

Table 2 - List of Technical and Design Notes

Name	Description
Technical Note 1	Corten Steel
Technical Note 2	Cross Ventilation
Technical Note 3	Insulation
Technical Note 4	Condensation and Mould
Technical Note 5	Relation of Insulation, Window Area, and Floor Area
Design Note 1	Roof concepts

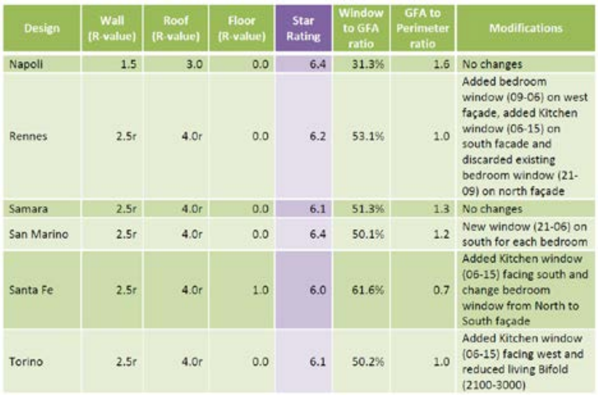
The purpose of the Technical Notes was to document known issues in prefabricated homes and explore possible solutions. This provided a starting point for discussion among the research project team.

The Design Note was part of an exploratory design exercise for improving existing solutions for the Pod's roof.

Most of the Notes were based on information from existing literature and technical material available. However, the research project team also developed original design material for the notes.

For example, in the cross ventilation note eight, existing Pod designs were reviewed in order to increase natural ventilation. This review included a redesign of the Pods, that included the relocation of windows and the addition of new windows and a modification in sizes.

In Technical Note 5 the research project team provided the first optimization of existing Pod designs (Figure 4). This set of optimizations did not take into account potential physical limitations on existing designs. It was an attempt to understand if it was possible to achieve 6 star ratings in the Brisbane climate with the minimal changes to existing designs but without construction constraints.



Design	Wall (R-value)	Roof (R-value)	Floor (R-value)	Star Rating	Window to GFA ratio	GFA to Perimeter ratio	Modifications
Napoli	1.5	3.0	0.0	6.4	31.3%	1.6	No changes
Rennes	2.5r	4.0r	0.0	6.2	53.1%	1.0	Added bedroom window (09-06) on west façade, added Kitchen window (06-15) on south facade and discarded existing bedroom window (21-09) on north façade
Samara	2.5r	4.0r	0.0	6.1	51.3%	1.3	No changes
San Marino	2.5r	4.0r	0.0	6.4	50.1%	1.2	New window (21-06) on south for each bedroom
Santa Fe	2.5r	4.0r	1.0	6.0	61.6%	0.7	Added Kitchen window (06-15) facing south and change bedroom window from North to South façade
Torino	2.5r	4.0r	0.0	6.1	50.2%	1.0	Added Kitchen window (06-15) facing west and reduced living Bifold (2100-3000)

Figure 4 - Star Rating results by improving cross ventilation and optimizing insulation levels

Finally, the Design Note provided three different roof concepts for the Pods, as shown in Figure 5.

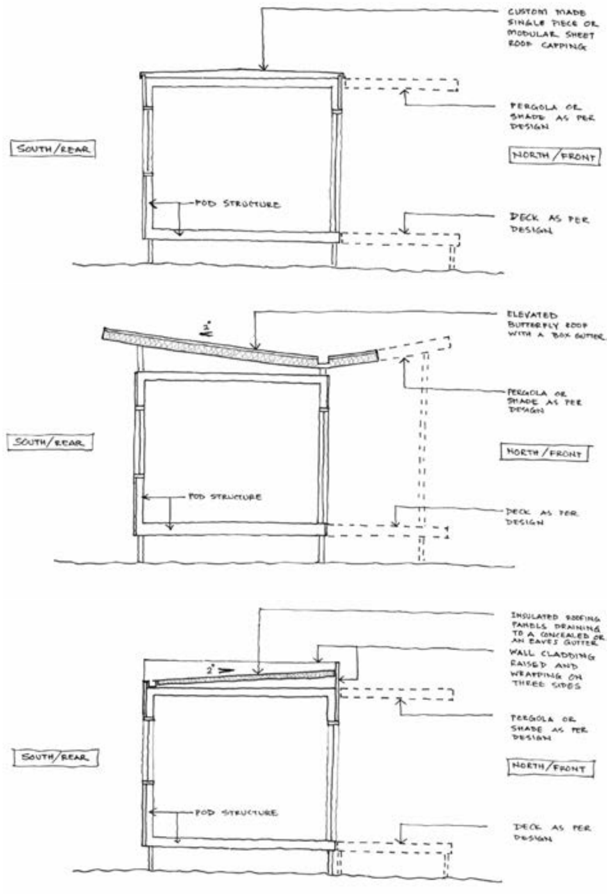


Figure 5 - Example of roof concepts developed in the Design Note 1

3 ConceptPod

This part of the project was designed to test several ideas and principles regarding the performance of the current Pod design and the limits of the potential improvements in performance by altering the Pod's specifications and the design.

In simple terms, the objective of the conceptPod design was to improve the general aesthetics and external and internal functionality of the existing Pods (see Figure 6); to improve the thermal performance of the Pods for different climates using available materials while considering financial, structural, dimensional, transporting and manufacturing restrictions; and to develop the basic work methodology to be used in the project for the continuous optimization of the Pod, which will be applied later for the design process of the greenPod.

The conceptPod is the result of the combined engineering and design research efforts applied to the existing Pod structure and materials. The results show an important improvement in the thermal performance, but, more importantly, the process produced general design principles that seem to work well for most of the climates and orientations. It is clear that optimized designs for individual climates and orientations provide better results than a single "one size fits all" design. However, it was found that by adding enough flexibility to the conceptPod design shading, rationalizing the location and size of the windows, and maximizing the benefits from insulation, the performance penalty from different locations and orientations was not as high as expected. In this sense, the design of the conceptPod proved to be resilient enough to be used in most locations and orientations, particularly if triple glazing is used in the main windows for the living area and bedroom.

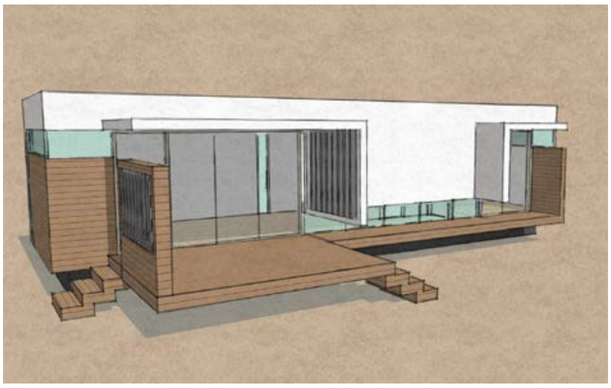


Figure 6 - The conceptPod external design (Yin Yang concept)

A crucial part of this analysis was the integration of the services and a review of the internal spaces. The idea behind integrating services like domestic hot water, PV system, electrical services, equipment, white goods, piping, water discharge, etc. is twofold.

First, achieve a "turnkey" solution, where the installation of the Pod is easier, quicker, and therefore more cost effective. This is a powerful concept as in theory the connection points of the Pod to the grid could by limited to four or five: potable water, electricity, gas, sewage, and rainwater. This integration was also the first step to off-grid Pods where it is not necessary to connect the services, or not all the services, to the grid.

Second, achieve a better control of the equipment and parts that go into the installation of the Pod. This integration will allow the inclusion of these services in the energy efficiency optimization, and also on the carbon content and ecological impact of the Pod.

At the same time, the integration of the services is tightly correlated to the interior design of the Pod. Several options of internal arrangements were studied including potential add-ons to the Pod, similar to current wardrobes that are transported inside the Pod and installed on site. Results of this process are shown in Figure 7.

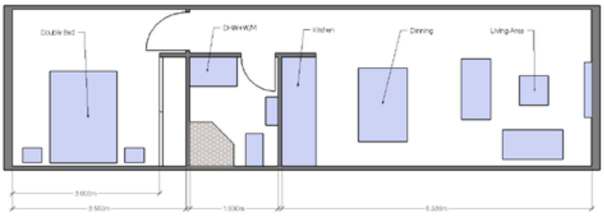


Figure 7 - Internal layout redesign

3.1Methodology

In order to optimize the thermal performance of the conceptPod it was chosen to perform iterative optimizations for one climate and use the optimized Pod on the first climate as a base model for the following climate, and so on. The idea behind this is that the "good design principles" applied in one climate could serve as a good starting point for a similar climate. To make this approach work we optimized the conceptPod using the following climate sequence: Brisbane, Sydney, Melbourne, and Hobart, i.e., from North to South, or warm to colder climates. Finally, we also approached the climate of Darwin using Brisbane results.

In each of the locations we performed a parametric study, where parameters (like R values, type of glazing, shade, etc.) were changed in order to reach local and global optimums. In this case, the optimum was found when the total amount of thermal energy (heating and cooling) required for the Pod was minimized to a point at which it cannot be improved further.

As an iterative process, there must be a starting point and an ending point. In this case, the starting point was the conceptPod using the current Samara Pod design and specifications for the Brisbane climate. The end point of the optimization in each climate is reached when no further improvements can be made on the thermal performance (measured by the star rating from the AccuRate simulation) by modifying Shading, Insulation, and Glazing.

3.2Main Results

The results obtained showed a marked improvement over existing Pods (Figure 9) and some interesting trends. First, it appears that for existing Pods the insulation on the external walls has a slightly bigger impact on the thermal performance than the roof insulation and that the level of insulation on the external walls and roof has a bigger impact than the floor insulation (assuming that the underfloor area is enclosed). Second, the gains in thermal performance of the Pod start to decrease with insulation values above R2. Third, in mild (Brisbane) and warm (Darwin) climates an R4 insulation in external walls and roof seems to be the sweet spot of insulation; higher insulation levels increase the thermal rating, but only slightly. However, in a mixed/colder climate (Melbourne) there is benefit in increasing the external walls and roof insulation to R6. This means that two main insulation configurations could be used in the Pod design, depending on the location, R = 4/4/2 and R = 6/6/2 (external wall/roof/floor).

During the optimization process it was observed that the effect of using triple glazing or similar high-quality windows (U=1.5 and SHGC=0.5 or less) was important, particularly in the difficult climates like Melbourne and Darwin. The most interesting result is that in the current design it is more effective to upgrade the main windows from double to triple glazing than improving the insulation in the walls and roof from R4 to R6. The other interesting result is that the combination of triple glazing and insulation of R=6/6/2 results in ratings above 8 stars for Brisbane and Melbourne.

Figure 8 - The conceptPod with Polycarbonate window strips

Polycarbonate windows offer a similar thermal performance to triple glazing windows and they were included in the design as a means to provide strong thermal performance with a reduced cost. The final conceptPod design has a 450 mm high horizontal Polycarbonate strip that connects 300mm wide vertical strip windows and the main triple glazed living area and bedroom windows. The living area window has a horizontal shade of 2000mm and two wing walls, also of 2000mm on each side. The bedroom window has a horizontal shading of 900mm and two wing walls on each side of also 900mm. The horizontal shade devices of the living and bedroom are operable as are the wing walls on the main deck by using either sail or louvres.

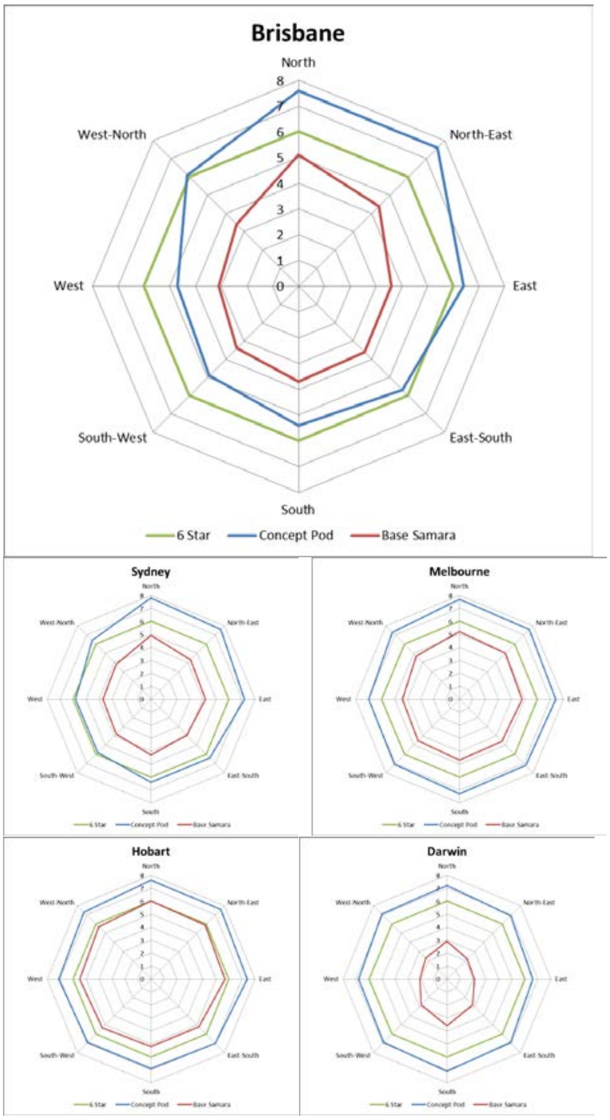


Figure 9 - Thermal performance of the Samara Pod and the conceptPod for different Australian cities

A final set of simulations was used to assess the performance of the final conceptPod design in the different climates and orientations. For the simulations, the insulation level of R=4/4/2 was used along with triple glazing in the main windows as it was considered the best option and balance between performance and cost, as per previous results. The ratings obtained in the simulations are shown in Table 3. The final results are consistent with the performance obtained during the optimization exercise, with Pods in some locations improving due to the use of triple glazing (Brisbane and Sydney) and others decreasing slightly (Darwin) in performance due to the increased dimensions of some of the Polycarbonate strip windows. In essence, the final conceptPod design is the optimized design obtained from the Melbourne climate optimization, which is the most demanding climate tested because of the extremes in temperature in the hot and cold seasons.

Table 3 - Thermal Performance Rating for the final conceptPod design

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

3.3Half pod (20 foot) conceptPod

Improving the thermal performance on the half Pod (20 foot Pod) is even more challenging than on a full Pod. Basically, all the restrictions in the 20 foot Pod are increased, as the wall space for insulation is reduced and the ratio of glass area to floor area is increased. However, the same design principles applied to the Samara Pod can still be applied to the “Santa Fe” 20 foot Pod. In this sense, the 20-foot conceptPod includes operable shading for the north façade bifold, vertical polycarbonate windows, maximized insulation as per available space, and no additional roof (Figure 10). Regarding the insulation, the external wall can only fit R2.5 insulation while available space in the roof is enough for R4.0, and for the floor the standard R2.0 was used. By using the same nomenclature as before, the insulation level for the 20-foot conceptPod can be described as R=2.5/4.0/2.0.

The results show that for Brisbane and Sydney there is not much benefit from using triple glazing for the bifold window, but there is performance advantage by using a glass with a reduced SHGC. In the case of a Pod located in Melbourne or Hobart, the U value of the triple glazed windows helps in the improvement of the thermal performance, increasing the star rating by 0.7 stars in both cases. In these locations, the use of a glass with a lower SHGC reduces the star rating, as they benefit from the extra solar heating. Although the performance of the 20 foot Pod is inferior to the conceptPod, due to the restrictions already explained above, the obtained design can achieve thermal performance in the vicinity of 6 stars for most of the locations.

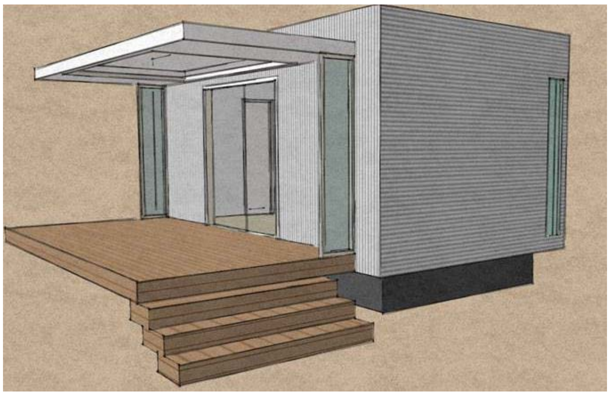


Figure 10 - Design principles of the conceptPod applied to the 20 foot Pod, front façade view.

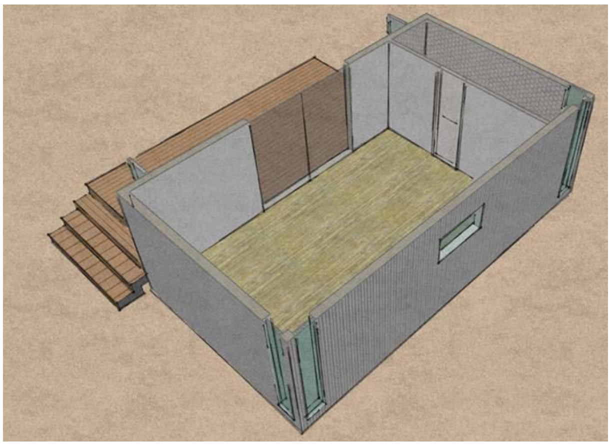


Figure 11 - Open view of the 20 foot Pod Internal layout

4 LCA of Pods

The main purpose of the LCA screening of the existing Samara Pod was to provide a rough but robust estimation of the environmental impacts in terms of global warming potential (GWP), embodied energy, and eco indicators for each stage of the Pod's life cycle: manufacturing, transport, installation, use and maintenance, and end of life. The results would then allow the project team to focus on materials or processes in order to reduce the environmental impact of the Pods.

The study included the analysis of a 'conventional' free-standing 200 sqm Australian house with four bedrooms. More detail of both houses can be found in Table 4 and the system boundaries for the LCA study in Figure 12.

Table 4 - LCA Systems definition

Samara Pod	**Conventional House**
Two people	Five people
One bedroom	Four bedroom
40 square metres	200 square metres
One storey	One storey
Walls: Steel frame, fibre cement cladding	Walls: Timber frame, brick veneer
Insulation: Glass wool bats	Insulation: Glass wool bats
Roof: corrugated steel sheet flat roof	Roof: timber truss and precast concrete tile roof
Manufactured in Foshan and shipped to site	Built on site

The functional unit selected for this study was one square metre of floor area, assuming a lifetime of 50 years and including operational energy use for heating and cooling according to the star rating of the house. It was assumed that both houses were located in Darra, Queensland. This functional unit was selected because, although it's not ideal[1], it has already been used in the literature to compare houses of different sizes and it's a common unit within the building industry and is easy to understand by end users in general.

Results from the analysis show that transportation of the Pod (including overseas shipping) only accounts for 3% of the total GWP and that materials (28%) and energy use (54%) during operation are far more important factors (see Figure 13).

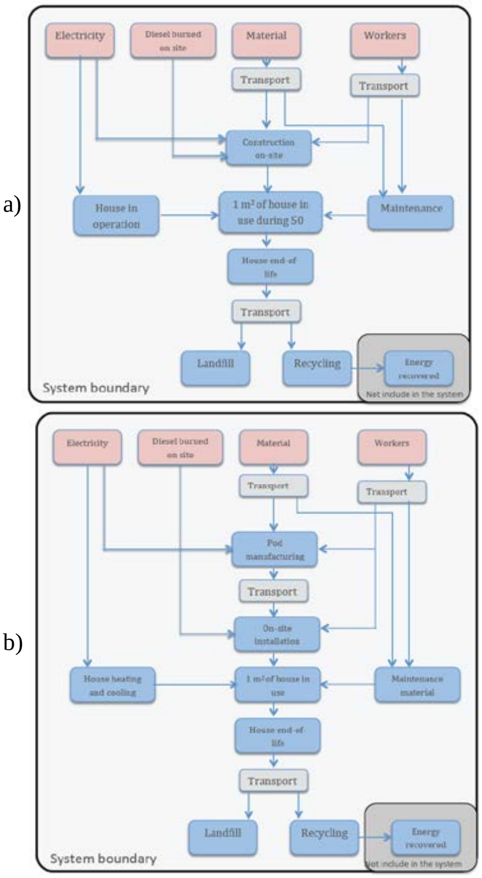


Figure 12 - System boundaries for each house; a) Conventional house and b) Nova Deko prefab Pod

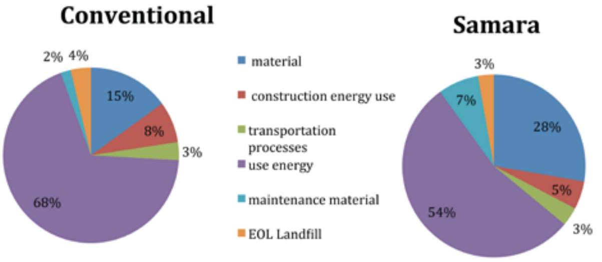


Figure 13 - Global warming potential for the Samara Pod life cycle stages

The energy use of the Pod can be reduced by increasing the thermal performance as demonstrated by the conceptPod. This required major changes in design and to a lesser degree in materials (mostly windows and insulation). However, it is possible to swap materials that have large GWP for new materials that offer the same functionally and (potentially) cost but have a reduced environmental impact.

A close inspection of the materials used in the Samara Pod shows that two materials account for most of the environmental impact, steel and fibre cement boards (Figure 14). Steel for the Pod structure is difficult to replace (although not impossible) but the best option is to optimize its use and use recycled steel. The use of recycled steel alone would

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[1] as it gives an advantage to houses of larger areas since the size of a house increases faster than the amount of material utilized.

reduce the total GWP by around 10%. Furthermore, the fibre cement boards can be replaced with lower environmental impact materials like wood or engineered wood for cladding and MgO boards for wall lining and flooring. It is expected that with careful design it would be possible to reduce the materials' GWP by up to 20%. Together with the improved thermal performance, it is estimated that a refined design like the greenPod could achieve a total GWP reduction of at least 30% with respect the SamaraPod.

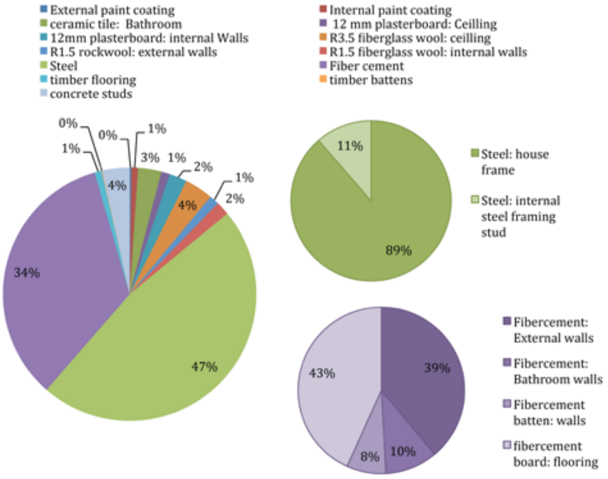

Figure 14 - Global Warming Potential of the Samara Pod materials

If we compare the environmental performance of the Samara Pod and the conventional house in terms of CO_2eq emissions per m^2 of floor area, as shown in Figure 15, we can see that the results for both houses are similar, except for the GWP of materials. It is clear from this result that the material selection for the existing Pods needs to be improved and include the use of recycling options, which could bring the results in line with conventional houses.

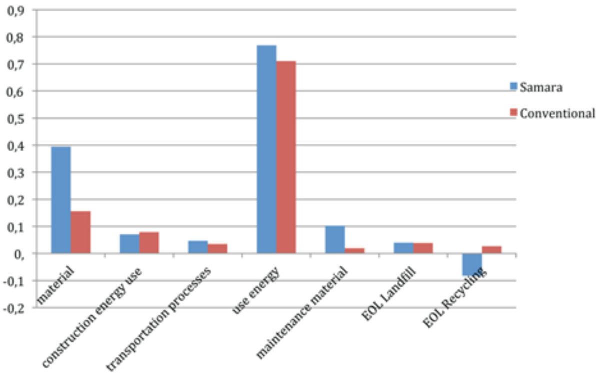

Figure 15 - GWP in tons of CO_2 eq per m^2 for each life cycle stage of the Samara Pod and the conventional house.

5 On-site testing

The project team visited a Pod installed in Tylden, Victoria, (83 kilometres north-west of the state capital, Melbourne) in order to fit the Pod with monitoring gear. During the site visit IR images, photographs, and moisture content of selected materials were obtained and the Pod was fitted with temperature and RH sensors in three locations: living room (LR), bedroom (BD) and on the porch of the Pod to measure the outside air (OA) temperature. Temperature and humidity data was recorded for almost 3 weeks, from the 14th August 2014 to the 3rd September 2014.

The team decided to analyse this particular Pod in Tylden because of condensation problems reported by the owner. The Pod, a three bedroom Valencia model, was built using a combination of two wide Pods (see Figure 16). The condensation problem created a unique opportunity for testing the performance of a Pod in the field and increase the knowledge of the research team regarding the Pod’s behaviour under cold climate conditions. This will inform the designs of future pods and help Nova Deko to avoid such issues.

Figure 16 - Floor plan of the 3 bedroom Pod in Tyldon (Valencia Model)

From the observations obtained during the site visit and the data collected from the monitoring, the team concluded that the most important sources of condensation were the lack of thermal breaks on the window frames, the pockets of cold outdoor air formed next to the windows coming from the underfloor area and the shaded sides of the Pod, and the lack of ventilation (common problem on tight buildings). All of these factors, combined with the high dew point temperature in the indoor area (see Figure 17), created high levels of condensation on window frames and glass (see Figure 18).

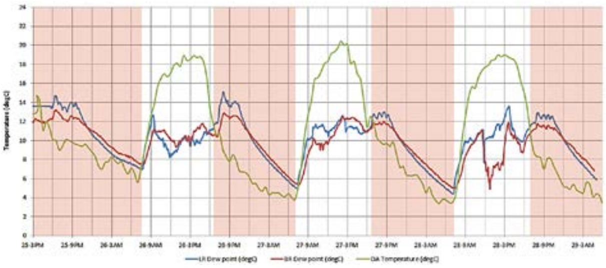

Figure 17 - Indoor and ambient temperatures logged during August 2014

An additional problem observed (and later ratified during a visit to the manufacturing facility) was the poor seal between the window frames and the walls. It was recommended to carry out a pressure test on all Pods out of the factory in order to check for seal problems and infiltration rates as a way to ensure the high quality of the product.

Some comments from the occupant also supported the hypothesis of high levels of interstitial condensation, which might be due to the non-breathable vapour barrier used in the Pods, the lack of thermal breaks within the structure and the type of insulation used on the external walls and roof.

Figure 18 - Condensation in the frame and glass on the south window of bedroom 3

It was recommended to:

- Review the vapour barrier and paints used
- Analyse the hygrothermal performance of the existing design in colder climates
- Include energy recovery ventilators (ERV) as an efficient way to increase ventilation with a minimal reduction in thermal performance
- Use underfloor insulation in all areas
- Include awnings to provide protection to the windows, which could also reduce condensation due to sky temperatures
- Use windows with thermally broken frames as current frames only achieved around 5 degrees difference between indoor and outdoor temperatures (see Figure 19).

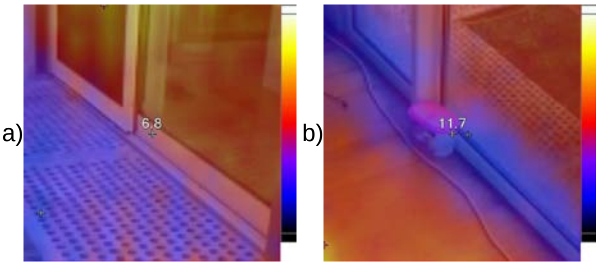

Figure 19 - Thermal images of windows on a) the exterior part of the frame and b) the interior part of the frame

6 Quality Assurance in the Manufacturing Process

Nova Deko's factory is located in the city of Foshan, China. Foshan is a well-developed city in central Guandong Province, with many manufacturing and industrial centres, historically known for the quality of its pottery and ceramics. Currently, Foshan is a powerhouse known for its products in many areas like furniture (the largest in China), household appliances, electronics, lighting, steel products, and plastic products. The Nova Deko factory is therefore well located, with many potential suppliers at a very close distance.

The current manufacturing of the Pods is not based on a conventional production line model, but on a parallel processing model. In this way, the Pods remain in the same position during all the manufacturing and finishing stages (after the basic structure has been welded and primed) so different teams can work in any of the Pods at any time if it doesn't obstruct the work of others (see for example Figure 20).

Figure 20 - Second stage of external cladding and work on internal finishes

The current manufacturing process is flexible and adjustable. It allows quick implementation of changes and improvements, which works well for Nova Deko's current needs. However, this system can also produce confusion and quality problems if quality control, documentation, and proper training protocols are not in place. Furthermore, scalability might be difficult to achieve under the current system, because of inefficient use of space, which might be a challenge in the future.

Quality assurance is one of the strongest propositions of prefabricated houses. The theory is that because the buildings are fabricated under ideal conditions the quality, from the detailing to the finishes, could be flawless, with less wastage and better overall performance. In essence, the prefab industry has the opportunity of applying the principles and experience of car manufacturing quality assurance processes to houses. However, this has been difficult to achieve in practice and many manufacturers have struggled in this area with some worthy exceptions.

Nova Deko was not different and the visit resulted in the identification of several problems with the manufacturing process and with the Pods design.

6.1 Design Issues

There were several detailing issues regarding waterproofing of the envelope and the roof. Most of the waterproofing was based on sealants which needed to fill large gaps. However, in some cases no amount of sealant is enough to waterproof the space left between the window frame and the Pod structure (see for example Figure 21). These issues could lead to serious problems once the Pod is on site and increase maintenance cost.

Figure 21 - Window frame and waterproofing detailing problem

6.2 Aesthetic Issues

There were many aesthetic issues in the Pods being manufactured. For example, the corner castings are required for lifting the Pod during transport, so they have to be accessible during the entire process. This leaves the corner castings, top and bottom, visible, even after the Pod is installed in its final location. Hence, the parts of cladding next to these castings have to be removable.

Figure 22 - Detail of the corner casting used for lifting

Another problem was the quality of some finishes, which were not up to standard for the Australian market. Poorly executed architrave corners, poor painting, and unleveled cladding were common. These sorts of problems have to be rectified on site, increasing the installation time and costs.

6.3 Quality Issues

The most important quality issues were to do with the improper installation of wall membranes and insulation. The membrane used was too delicate for the manufacturing process, creating many openings in the envelope which were left unfixed (see Figure 23). Furthermore, the membrane was installed without sealing the joints with other membrane sections or with the Pod structure, leaving large gaps.

Figure 23 - Cladding waterproofing and openings in membrane

The installation of the insulation was no better with visible gaps between the batts (Figure 24) and different types of insulation used on the same wall (Figure 25).

Figure 24 - Poor installation of the insulation

Another obvious problem is the amount of steel used in the Pod's structure. It is difficult to say which problem is the most significant in the current design but the lack of thermal breaks is probably in the top 5. Unfortunately, NatHERS does not cover this issue appropriately, and in the rating mode AccuRate does not take thermal bridging into consideration. However, it is well known that thermal bridging can reduce the effectiveness of properly installed insulation by a large percentage, so it is critical for the Pods to include thermal breaks in all the steel elements in order to have a performance that, in practice, is close to the models.

Figure 25 - Mix of insulation types used and no thermal breaks in a structure that it is mostly steel

6.4Main Recommendations

It was recommended for Nova Deko to work with suppliers and a consulting architect or a qualified building professional to devise waterproofing details for the roof, windows, and to recommend a more suitable membrane for the Pods.

It was also recommended to review the current Pod structure. It is believed by the team members that the Pod structure can be further optimised in order to use less material thus reducing weight while maintaining structural integrity and compliance with the standards.

One of the most evident issues on the Pod manufacturing was the quality assurance. It was recommended that stringent quality controls are put in place by Nova Deko, with improvements in documentation and traceability of the Pods and the implementation of tests during, and on completion of, the manufacturing process. This could be an important step for the industry as a whole, as Nova Deko could lead industry quality by providing standard tests and certifications for its houses. Some of the controls and test that could be carried out are mentioned below:

- Thermal imaging
- Vapour Test
- Infiltration Test
- Electrical Test and Certification
- Plumbing Test and Certification

Finally, it was recommended to create a specific Pod for prototyping and training purposes. The Pod could be submitted to different torture tests (fire, structural fatigue, material endurance) in order to check that required specifications are being met, and to obtain an assessment of the Pod performance under accelerated aging conditions. It could also be used for training new staff. Training and prototyping would facilitate the improvement of the overall quality of the Pods and could be used as a part of the general quality management program.

7 GreenPod

The greenPod design process was full of difficult design problems, trade-offs, and engineering optimizations that have produced a set of elements and integrated technologies that take the Pod a step forward in performance and sustainability levels, with a good chance of affordability, thanks to the integrated design approach.

The greenPod has been conceived as a natural evolution of the conceptPod work carried out previously in the project. The greenPod pushes the boundaries on some of the limitations presented in the conceptPod and therefore looks further into what is possible to design and build with existent technologies, materials, and manufacturing techniques.

Nova Deko believes that the half wide Pod has better chances of commercial success due to the easier transportation and installation process. Hence, the greenPod was designed using the current Rennes Pod as a base case, which has a footprint of 20.9m2. Being a small Pod, every detail in the design is important and has to work towards the improvement of the thermal performance of the Pod, the reduction of the energy use and environmental impact, the increase in comfort of the occupants, and the functionality and quality of the spaces.

The original Rennes Pod achieved a rating of 4.8 stars under standard test conditions (STC). Later, the Rennes Pod design was improved using the principles and results from the conceptPod, to a rating of 6.2 stars. The aim of the greenPod was to do better than the conceptPod in the following areas:

- Achieve a stronger thermal performance with a goal of 7.5 stars.

- Reduce installation time in order to reduce installation costs and complexity in assembly. This included the integration of external elements of the Pod like the supporting structures, shading, and deck.

- Integrate services like hot water systems, sewage, rainwater tanks, etc. in order to further reduce installation time of the Pod and complete the Pod as a ‘plug&play’ product.

- Integrate renewable energy sources like PV and solar hot water to reduce the dependency of the greenPod on the grid and fossil fuels.

- Improve design quality and materials used. Together with the reduction in cost and installation time it was imperative to revisit the interior design and the quality of the spaces of the greenPod. The idea behind the greenPod concept is that the interior, although small, should be comfortable and functional, with a direct connection to its surroundings in order to increase the sense of spaciousness. It was also important to develop an integrated deck, so that an outdoors room in included within the greenPod, increasing the effective area of the Pod.

- Use LCA principles to guide the design process from the beginning. The idea of achieving a lower ecological footprint is reflected in the improved thermal performance, the incorporation of renewable energy sources, and the selection of materials with lower environmental impacts.

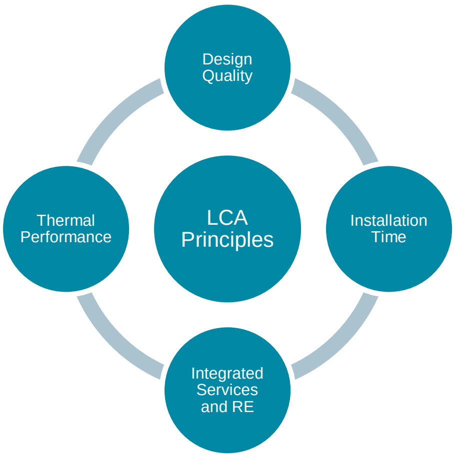

Figure 26 - greenPod guiding principles

For the design of the greenPod, we followed a similar process used for the conceptPod of iterative improvements based on thermal performance modelling results, trial and error, and integrated design. What was distinctive during this process was the inclusion of two design workshops which were the starting point of the process. The aims of the workshops were to define the guiding principles (see Figure 26) and main design ideas, the requirements for sustainability, the needs from the occupants’ point of view and from Nova Deko, and the limitations of standards, transportation, cost, weight, and materials.

With the above scope and guidelines, the research team was able to continue the design and research process, meeting regularly, to carry out small integrated design sessions focused on the different elements of the greenPod. The research team worked on the basis of providing different options to Nova Deko for the same problems to allow Nova Deko to select the option that worked best in practice.

The main results of the process are included in the following section. Not all the options developed for the greenPod are included but focuses on those that Nova Deko is trying to implement.

7.1Design

The review of the interior layout of the Rennes Pod showed that, although efficient, it could be improved by bringing all the services together on the west side of the building (see Figure 27).

This layout has two main advantages: first, it creates a big room for living, kitchen, and bedroom areas more flexible than the original layout; and second, it simplifies the integration of all the services and connection to utilities, reducing the amount of work required on site.

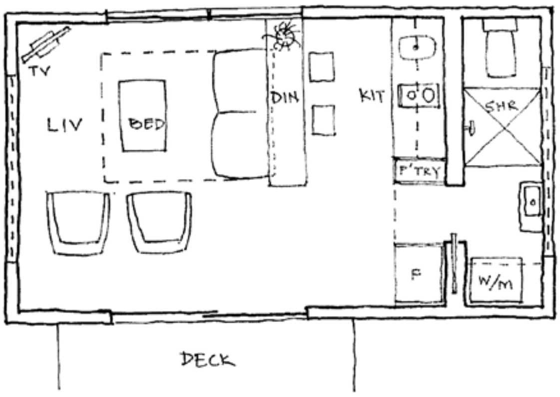

Figure 27 - Floor Plan with Sofa Bed and Bench for Dining

Windows have been placed in each of the facades in order to maximize ventilation, and the bathroom, now located in the west of the building, will ‘contain’ the west sun, further improving the thermal performance of the living area. Additionally, the bathroom can now be considered an unconditioned area (in the Rennes design it was considered an air-conditioned area as it was part of an en-suite) also reducing the energy demand of the living area and the requirements for insulation on the bathroom walls and floor (Figure 28).

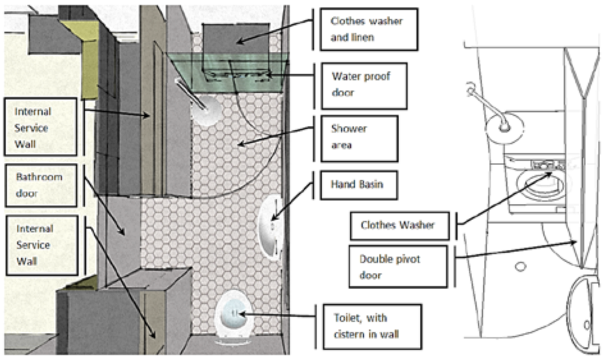

Figure 28 - Bathroom Interior design

Furthermore, the proposed layout creates a service wall between the kitchen and the bathroom that concentrates most of the pipework and cabling of the greenPod and also includes insulation in order to isolate the living area from the bathroom. This wall is also used to incorporate all the kitchen furniture and cabinetry (Figure 29).

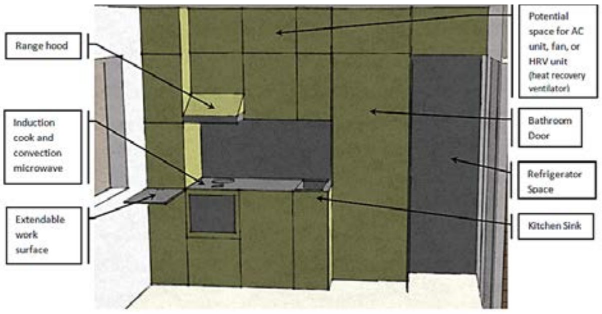

Figure 29 - Kitchen interior design

The new layout offers an optimized use of space and relation with the outdoors as the main room has better proportions than the original design.

7.2 Integration of services and RE

The integration of services and RE into the greenPod structure and systems was, as mentioned at the beginning of this report, one of the main drivers of the design process. It required a whole systems approach that in the end resulted in an integrated Pod that could produce cost reductions in manufacturing and installation on site.

The solar photovoltaic system was designed to be installed on the roof of the greenPod. With the available roof space, the maximum size of the PV system is 1kWp or 1.25 kWp, if the solar hot water collector is not installed on the roof.

Although the size of the collector is only 1kW PV the system is able to supply all of the energy required by the main services during most of the year (Figure 30), with only two months (May and June), requiring auxiliary energy either from the grid or a backup generator. The rest of the year the PV system will provide additional energy that can be used to offset grid electricity on the use of appliances and other loads.

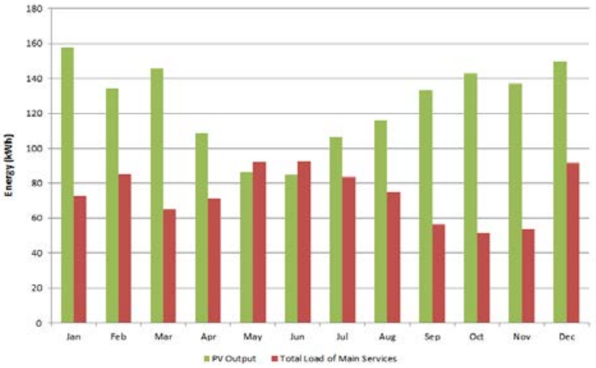

Figure 30 - PV output against main services load

Several options were considered for the hot water system. Because of its simplicity, easy integration with the greenPod, and energy efficiency, it was decided that the best option would be a roof mounted solar hot water system with electric boost, followed closely by a heat pump hot water unit.

Although a heat pump unit would require almost the same energy as the solar hot water unit (depending on climate and location), its integration in the greenPod was deemed more difficult due to the noise and vibration of the units, and the periodic maintenance required. However, they are still a desirable option and could be offered as an alternative to the solar hot water system. If this is the case, then the solar PV system could be increased by adding an extra panel (see Figure 31).

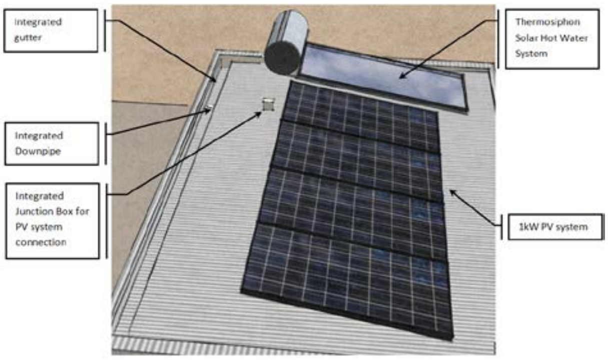

Figure 31 - Integrated RE systems, gutter, and downpipe

In most of Australia a thermosyphon system with flat plate solar collectors should be used while in freeze-prone areas an evacuated tube collector (or flat plate collector with freeze protection) is preferred. The thermosyphon roof mounted system does not require a pump and therefore requires less electricity than split systems and it is easier to integrate into the roof of the green Pod. The recommended size of the collector includes a tank of 180 litres and one solar flat plate collector with an area of 2.47m^2. A system with these characteristics was simulated for Brisbane, assuming a consumption of hot water (at 60 degrees) of 113 litres per day (1-2 person) for good results (Figure 32) as the system is able to provide all the hot water required under those conditions.

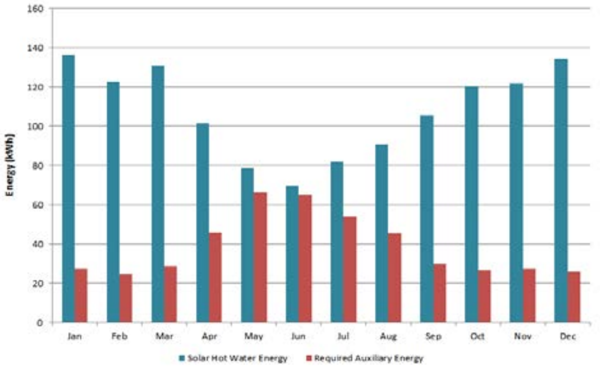

Figure 32 - Output of the solar hot water system and required auxiliary energy

The proposed sewage layout is presented in Figure 33. All the sewage discharge is concentrated in one connection point (depending on the grey water system and composting toilet), but two penetrations are required in the floor joists, in order to connect the kitchen and hand basin discharges. If a composting toilet is used the discharge arrangement is simplified as it is almost certain the discharge system could be integrated between the floor joist in the factory.

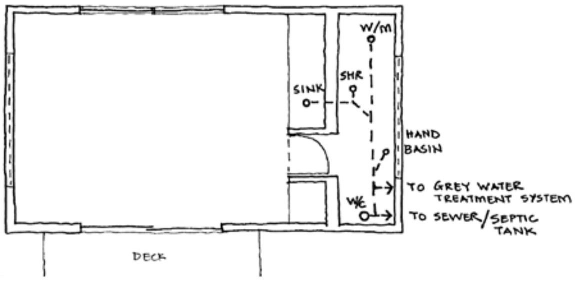

Figure 33 - Water discharge diagram

All the water supply connections and services are concentrated at the back of the greenPod (Figure 34). The layout minimizes the amount of plumbing required for the appliances and hot water system. The rainwater harvesting system is also integrated by using a gutter concealed in the roof and a downpipe located in the service wall. The downpipe will be connected once on site to the bladder rainwater tank (to be located under the Pod).

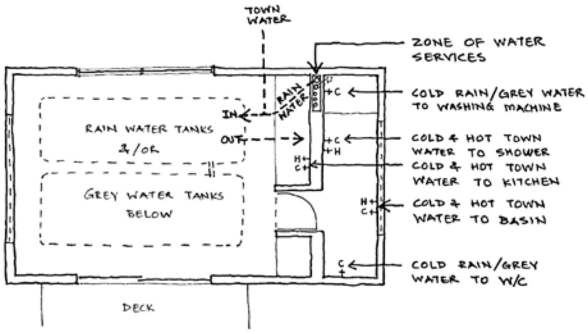

Figure 34 - Water supply diagram

Finally, the electrical services and connection point to the grid are concentrated at the front of the greenPod. The main switchboard and PV board connections are located in the cabinet on top of the refrigerator space.

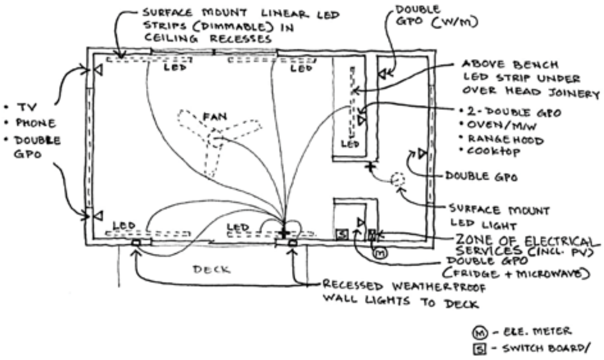

Figure 35 - Electrical services

7.3Thermal performance

Three model options were identified for the greenPod depending on the associated cost and the performance required, with the goal of achieving a rating of 8 stars.

- Option 1 – Normal windows and extra insulation: current windows used in the Pods with (U=3.92 and

SHGC=0.48) and extra insulation to cover for the underperformance of the windows.

- Option 2 – Performance windows with optimized insulation: windows with thermal break (U=2.04 and SHGC=0.36). Because of this, the insulation is optimized in order to use the least amount possible while maintaining a good performance.
- Option 3 – Performance windows and extra insulation: this option uses the best selection available for window and insulation levels. The goal of this design is to achieve as the best possible results while maintaining reasonable costs.

Thermal modelling results for each of the options is presented in Table 5. Results show that it is possible to reach an 8-star rating under standard test conditions. However, this requires an increase in the floor insulation, although it allows for insulation optimization elsewhere.

Table 5 - Summary of Thermal Performance Rating depending on window type and insulation levels

Option	Window Type	Insulation Levels							Star rating
		Living				Bathroom			
		External Wall	Roof	Floor	Internal Wall	External Wall	Roof	Floor	
Option 1	Normal	4.0	4.0	2.0	2.5	2.0	2.5	0.0	6.9
Option 2	Performance	**2.5**	**2.5**	2.0	2.5	2.0	2.5	0.0	7.4
	Performance	**3.0**	**3.0**	2.0	2.5	2.0	2.5	0.0	7.6
Option 3	Performance	4.0	4.0	2.0	2.5	2.0	2.0	0.0	7.9
	Performance	4.0	4.0	**3.0**	2.0	**1.5**	**1.5**	0.0	**8.0**

The performance of the greenPod was also modelled for four additional locations and four different orientations, for a total of 16 simulations. It can be seen from the results presented in Figure 36 that the greenPod has been heavily optimized for the standard test condition (Brisbane with north orientation) as it reaches the best thermal performance under these conditions. The greenPod also performs well in Melbourne, with a rating around 7 stars for all the orientations and in Hobart with a consistent rating close to 7.9 stars for all orientations, which is better than expected, and due to the good levels of insulation.

The greenPod design could be further improved if orientation specific optimizations or simple onsite adjustments are carried out. For example, the very low rating in Brisbane when facing east (the only rating below 6 stars) is mainly due to the non-symmetrical shading of the patio door that covers the west sun but not the east sun. In this case, the shading could be just swapped to accommodate the circumstances, which is a flexibility that should be inbuilt in the deck/shading design.

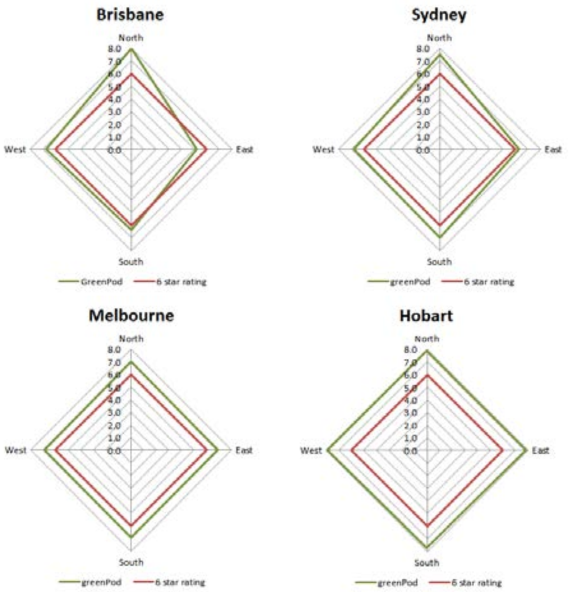

Figure 36 - Thermal performance results for the greenPod

7.4Installation time

As mentioned before, one of the main goals was to reduce installation time for the Pods and many of the improvements included above (like the integration of services and renewable energy systems) contribute to that goal. Here we present the concepts developed in the project to improve other aspects of the design in order to facilitate the installation. These include the integration of a deck and external shade for the main window and the provision of legs.

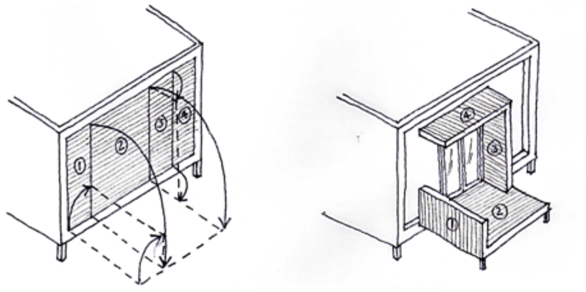

Figure 37 - Assembling process of the integrated deck and shade

The chosen option for the deck and shade requires a recess in the north wall, which reduces the available interior space of the greenPod by 150mm. Although it is not ideal to reduce the internal space, it was the best solution found within the limitations of the Pod and the deck and shade can be easily assembled on site as shown in Figure 37.

Providing adjustable legs to the greenPod was an important change as it significantly improves the ease of installation and minimizes site preparation. Sliding legs were chosen as the most straightforward option using current structural elements of the Pod. A vertical post is integrated within the corner column of the Pod, which can slide up or down to accommodate the required height and then be secured by pins. An additional height adjusting mechanism could be incorporated by using a threaded rod, as shown in Figure 38

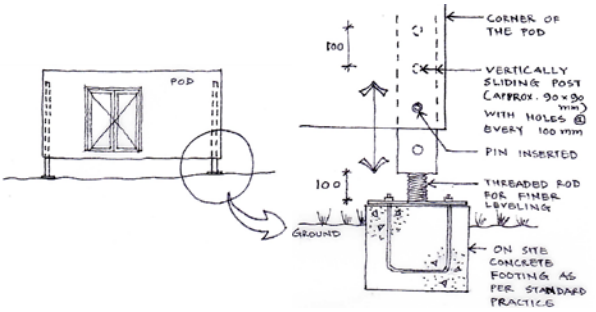

Figure 38 - Option of the Pod’s leg integrated into the end columns

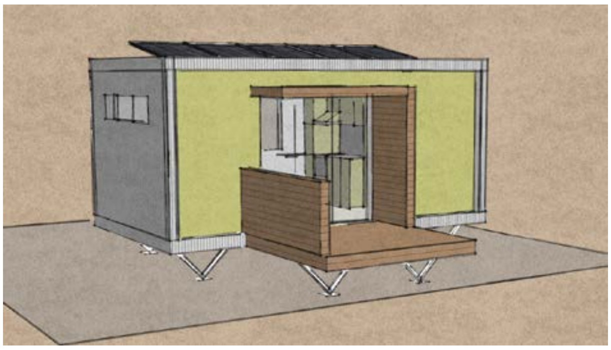

Figure 39 - Perspective of the front of the Pod with metal cladding and painted FC in the north wall

8 Conclusion

At the centre of this research project has been the investigation of the possible advancements though Design thinking of sustainable, affordable living in modular residential dwellings. The investigation of these dwelling designs within a sustainability context occurred on a range of levels. From information and data gathering around life cycle analysis of construction and transportation and the materials utilised in the production and assembly through to sustainable principles and holistic building ideals associated around site orientation in numerous locations, climates and contexts. The breath of the project's undertaking and data is captured within the main body of this report.

The outcomes of this research permit a further and more complex understanding of the notion of modular residential housing and how sustainable efficiencies, both materials and products, may be contextualised as part of the overall design process. The constraints that are apparent given the complexity of the need for specific orientation and location (bespoke and costly) versus the benefits associated with a type of production line modularity and offsite produced product ready to use dwelling has been unpacked to determine the breadth of these possible efficiencies. It is hoped that this applied research, experimental investigations, data gathering, eventual analysis, research findings and recommendations would be used by the CRCLCL industry partner specifically, and modular housing industry generally, to address the needs of sustainable and affordable prefabricated homes in Australia and beyond.