HOME^3
SISCA Report 2016

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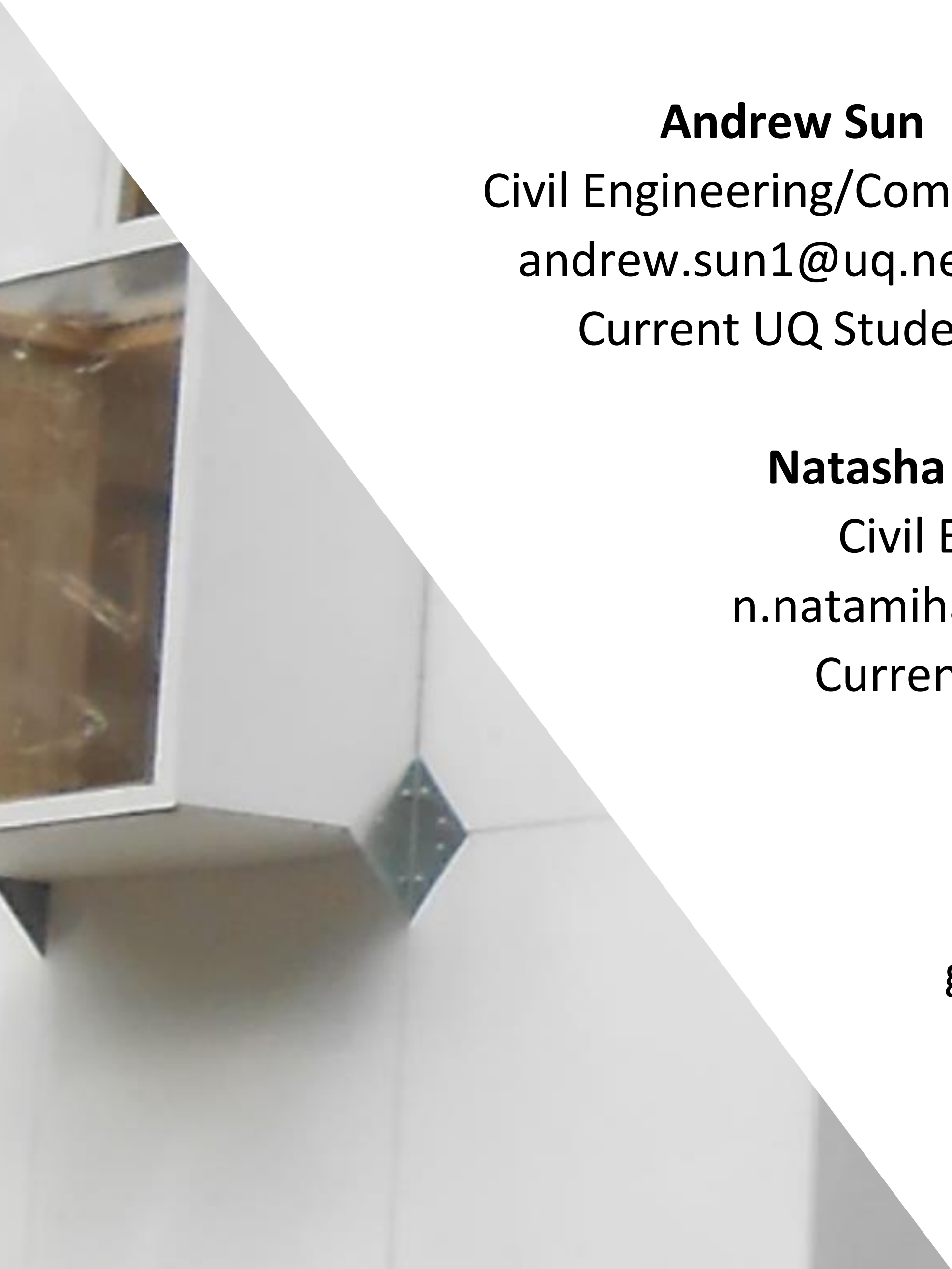


Executive Summary

Incremental innovation doesn't exist; innovation only becomes significant if it achieves an order of magnitude increase in creating value for a solution to a global problem. The $HOME^3$ achieves this in three important metrics for the housing crisis: the cost per square meter, the time of construction and the amount of greenhouse gases emitted. The $HOME^3$ is 11 times cheaper to build and 11 times faster to build compared with the average Australian house for the same size. Furthermore, the $HOME^3$, because of its utilization of plywood, *absorbs* 34 tonnes of CO_2e (CO_2 equivalent) while the average house *emits* 43 tonnes of CO_2e during construction.

There are three main $HOME^3$ components: the connector, the steel tube and the panel (Figure 1). The connectors twist into the 1m long steel tubes to form a steel frame. Panels are then placed in the frame and bolted together using brackets. This elegant design creates value by improving current construction methods and removing inefficiencies (see Table 1).

A full scale 3mx3mx3m prototype has been developed using the funds raised as runner up of the SISCA competition in 2015. A website and Facebook page has been launched to provide more information (www.cubitcommunity.com and https://www.facebook.com/cubitcommunity). A second full scale prototype is presently under construction and will be completed in December this year with the first $HOME^3$ sales planned to occur in the first half of 2017. First sales will target developing countries and refugees where a number of contacts have already been established. The $HOME^3$ is also suited to capture the housing market in developed countries with planned future expansion after preliminary implementation in developing countries.

Table 1: Eliminate-Reduce-Raise-Create Table for the $HOME^3$

Eliminate	**Raise**
Skilled Construction Labour	Mass Production
Specialized Tools	Simplicity
Heavy Equipment	Sustainability
Reduce	**Create**
Cost	Modular System
Time	Disassemble Structures
CO_2 emissions	Flexible Designs

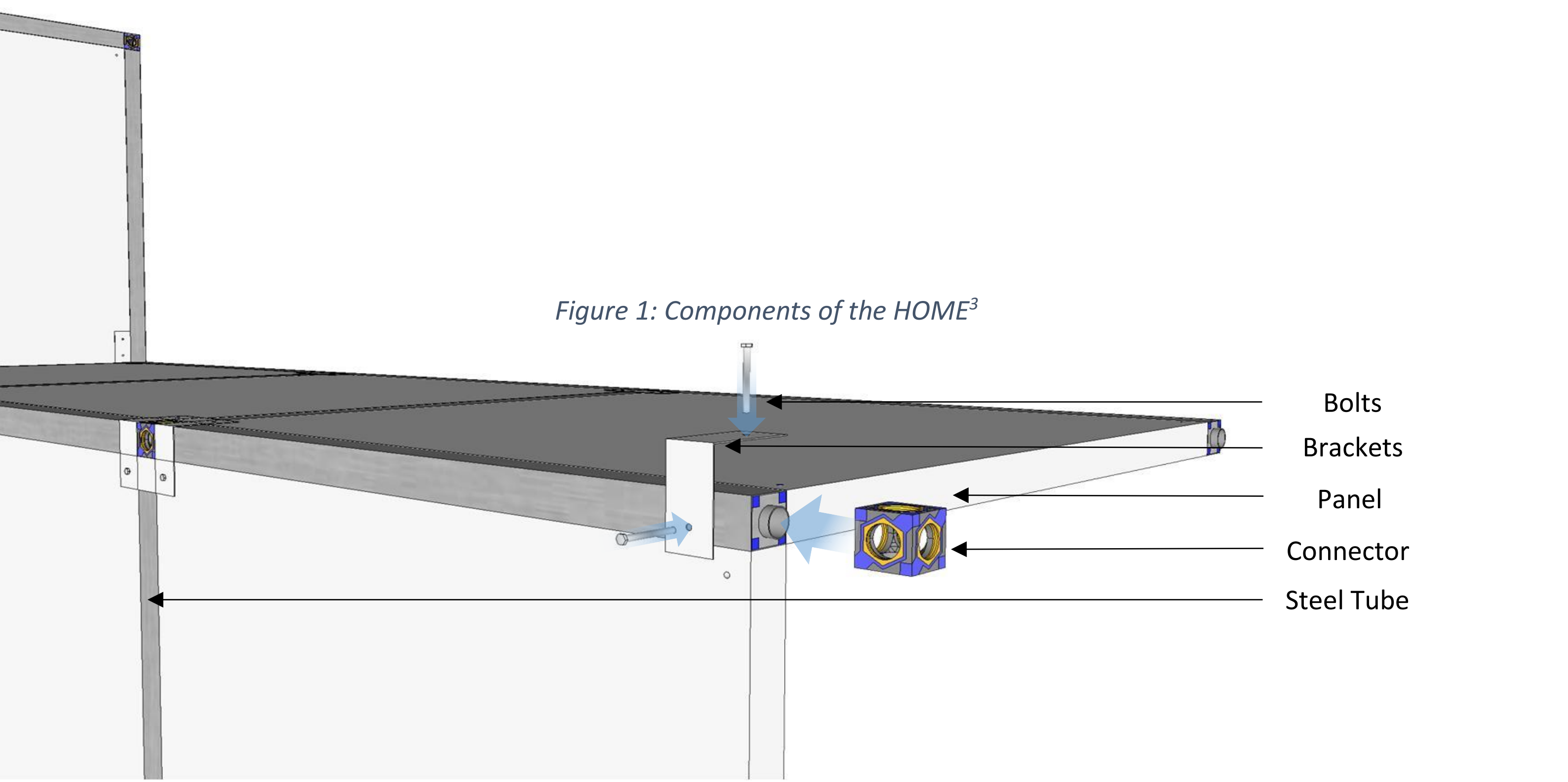


Figure 1: Components of the $HOME^3$

Industry Analysis

1200 million people currently live in inadequate housing (MGI, 2014). In comparison only 795 million are malnourished (WFP, 2016), 783 million people don't have access to clean drinking water (UN, 2016) and 17 million die annually of infectious diseases (WHO, 2016). The majority of the development focus is on these problems where the number of people affected are dramatically being reduced every year.

However, unlike those other problems housing is only getting worse, with 1600 million people predicted to be living in inadequate shelter by 2025 (MGI, 2014). Furthermore, the intersection of many of these problems originate in the home. If the home has water tanks and plumbing then they have clean water, if they have solar panels and wiring then they will be electrified; if excrement can be collected and treated on site then infectious diseases will be prevented. The HOME^3 by addressing all these issues has the potential to solve not only the housing problem but many other global problems as well.

Australia supports a $340 billion construction industry which in 2014 increased by 4.1% (IBISWorld, 2015) and emits 60MT of CO_2e annually (ABS, 2013). However, this housing industry is highly fragmented with 41,900 active businesses, none of which possesses a substantial market share (IBISWorld, 2015). This means that these business cannot utilize mass production, buying in bulk or utilization of shared resources, limiting their efficiency unlike the HOME^3. Furthermore, the long construction times increase the risk of making quotes as material and labour costs can vary significantly during a build. The construction industry as a whole has seen productivity decline by 10% to 20% in many countries over the past 20 years (MGI, 2014), which is why construction costs per square meter for housing has increased by 110% since 1993 in Australia (figure XXX) (Figure 2) (Australian Bureau of Statistics, 2010).

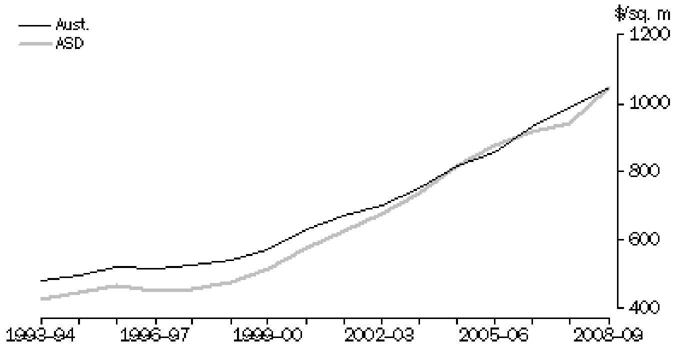
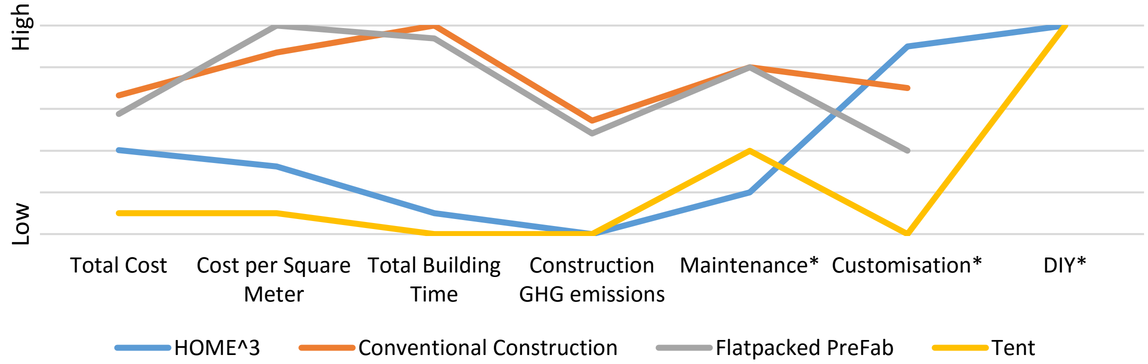


Figure 2: Increase in Australian House Prices (ABS, 2010)

As can be seen in the strategy canvas (Figure 3, Appendix 1) the value curves of conventional housing and flat packed prefabricated housing (based on the IKEA flat packed house) are remarkably similar suggesting no significant difference in their value offering to customers. However, the value curve of the HOME^3 is distinctly different, having greater similarity with tents in terms of value even though it is made from steel frame and ply construction. Furthermore, the HOME^3 uniquely offers the additional functionality of DIY construction. Thus the HOME^3 is well suited for application in both developing and developed countries alike.

Figure 3: Strategy Canvas of the HOME^3 (Appendix 1)



*Qualitatively Determined

Product Idea

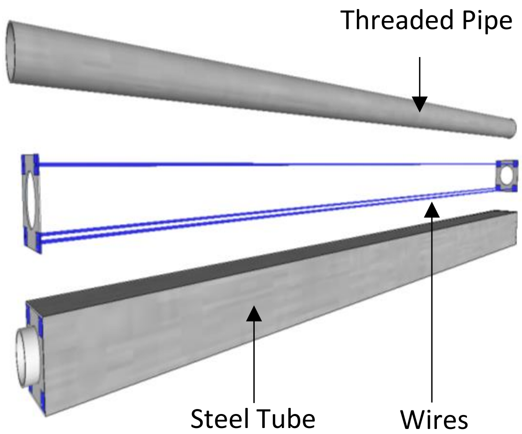
Critical to the HOME^3 achieving ten times improvement in housing is the simplicity of the design. The HOME^3 has a total of nine components; the connector, the tube, the panel, cladding for the panel, three brackets for the panel, bolts and the foundation piece. All of these can be intuitively put together and all are made from commonly available, cheap, raw materials.

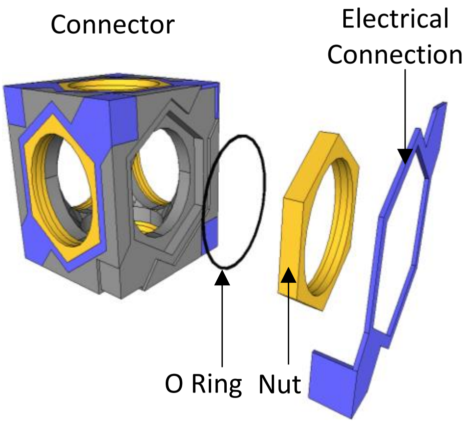
Panel

The panels are typically 1mx1m and 5cm deep with bolt holes in each corner. They are connected together via braces and bolts. Their material, cladding and function however can all be different. Even their size and shape can vary as long as matches the meter metric. This will be done for the door which will be a 2.05mx1m panel with a door from a hardware store inset into a plywood panel. The panels and their cladding enable each HOME^3 to be unique and become infused with a local flavour.

Tube

The steel tubes are 1mx5cmx5cm and 1mm thick. They contain the plumbing and wiring for the HOME^3. The pipe inside is held inside the tube by a plastic insert and is threaded in opposite directions at either end. To connect the tube to the connectors place them against each other and twist, this will screw the tube into connectors at both ends. Twisting the opposite direction will undo the connection however this can only be done if the panels have been taken out first. This prevents thieves breaking into HOME^{3}s.

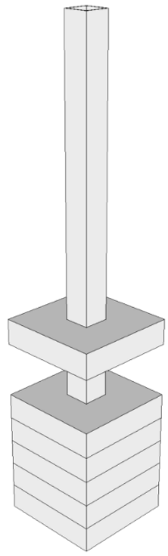


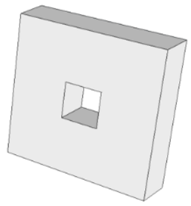


Connector

The connector is a 5cmx5cmx5cm cube with a threaded nut on each face and wiring comprised of electroplated 3D printed plastic across its face. It will either be 3D printed in plastic or metal and connects at the intersection of the steel tubes. The nuts will have alternating threading to match the treading of the tubes. Taps and electrical outlets can be screwed into any connector increasing the flexibility of the interior design. The hollow inside will be occupied by water during normal operation and O-rings will be used to prevent leaks.

Foundation Piece





The foundations are modular concrete columns segmented into 20cmx20cmx10cm concrete blocks weighing 10kg each. They are designed to be strung onto a steel tube through their central hole like beads on a necklace. The number and depth of the foundations will be depended on the soil strength and cyclone and earthquake activity. The foundations will likely be situated on the corners of the cube and along the sides underneath the walls. The foundations could be buried using a shovel or placed on top of the ground or a combination of both for sloping surfaces. This modular approach greatly minimizes ecological disturbances compared to a concrete slab. Furthermore, this design results in a raise floor which is important for hygiene and longevity of the panels, a feature no other competitor for low cost housing has.

Features and benefits

1. Sustainability

Capturing sunlight for electricity, storing rainwater and having modular footings that result in minimal environmental impact makes the HOME^3 truly sustainable. The HOME^3 is carbon negative absorbing 17kgCO_2e per square meter of floor space (see Appendix 2). Because construction contributes 30% to the global CO_2 emissions wide spread adoption would significantly help countries meet international treaties (UNEP, 2009). This is particularly true for poorer countries that need it most.

2. Low Costs

The low initial capital, low total building cost and low maintenance costs alone set the HOME^3 apart from the competition. Customers can buy their way to a full HOME^3 panel by panel with even a 1mx1mx1m lockable cube (costing $75) being invaluable in a slum environment. This ability to provide value with such small amounts of initial capital is totally unique. When compared on a cost per cubic meter metric, the HOME^3 is even cheaper than slum tents (and that is with 100% contingency added see Appendix 2). The material costs of the HOME^3 is 11 times cheaper than the closest competitor (the IKEA refugee shelter). Furthermore, due to its modular design, maintaining or upgrading the HOME^3 is as cheap and easy as swapping in and out panels.

3. Modular Design

The modular design allows for scalability and flexibility. It is possible to scale a HOME^3 from a 1mx1mx1m cube to a mansion of any size. The HOME^3 is flexible due to the wide range of possible panel designs and configurations. Only the connections in the four corners of the panels must maintain consistency to connect the structure. Panels containing hinging windows and doors are possible as are panels containing storage or even made of fabric to allow maximum ventilation. Local craftsmen can make panels locally wherever the HOME^3 is sold, which will inject a local flavour that will make every HOME^3 unique and contribute to community culture.

4. Transportation

The size of the HOME^3 modules are based on the individual. The largest and heaviest component of the HOME^3 is the 1mx1m panel weighing 10kg it is the perfect size and weight for a single person to carry. The components can also be flat packed for efficient transportation and are small enough to fit inside a standard car. The components for a 3mx3mx3m cube can fit into three 1mx1mx1m boxes.

A quarter of a million 3mx3mx3m $HOME^3$s can be transported in a single cargo ship (Marine Traffic, 2016) making this ideal for disaster relief.

5. Time

The average Australian house is $250m^2$ and takes a team of specialists 217 days to build. It would take one person 20 eight-hour days to assemble a $HOME^3$ of the same volume, which equates to $1m^3$ every 16 minutes (see Appendix 2).

6. Simplicity

The $HOME^3$ is designed with twist connections that connect up the plumbing and the wiring automatically. Electrical outlets and taps are connected the same way. The electrical system consists of three components, all of which are modular and easy to assemble. The construction instructions could consist of a short YouTube clip or a pictographic depiction of the assembly. The only tools required are a shovel for the modular footings and a spanner to bolt the panels together. This eliminates heavy equipment and specialised labour (plumbers and electricians).

$HOME^3$ Utilities

$POWER^3$

The $POWER^3$ system provides a self-sufficient electrical system for $200. It utilizes a modular design comprised of three modules:

1. The battery module (33Wh $20/ea)
2. The solar panel (40W $60/ea)
3. The power cube (1500W $120/ea)

The solar panels produce the electrical energy, the batteries store the energy and the power cube regulates and converts the energy into the correct form. Although the initial capacity of the system is small, every component is scalable making the final capacity perfectly match the user's needs without paying for added capacity. All connections between the components use an intuitive snap on or plug in connection that doesn't require specialist knowledge. These modules have a 3D printed design which reduces material costs, labour costs and quality assurance issues. However conductive 3D printed filament and conductive paint have resistances 100 times too high to be used for this application. Electroplating copper on to the surfaces of these 3D printed parts will provide the conductivity needed. The $POWER^3$ will be installed inside a $HOME^3$ panel integrating seamlessly into the wiring located in the tubes.

A functional $POWER^3$ system costs $200; this is 8 times cheaper than the lowest cost competitor Orison and 25 times cheaper than the Tesla Powerwall, even though their systems aren't stand-alone. Furthermore, the $POWER^3$ has a 35% lower price per kilowatt hour ($/kWh) than the best market competitor. Thus the $POWER^3$ can be sold separate from the $HOME^3$ diversifying income while spreading risk.

Plumbing/Waste Treatment

Plumbing and wiring are installed in every steel tube and connector piece, and are connected automatically when the tube is twisted into the connector. Plumbing and electrical outlets can thus be located at every connector allowing for flexible design. The pipes under normal conditions will be filled with water. When a tap is turned on water will drain from a small 15L water reservoir on the roof. A pump located next to the water tank on the ground will detect the drop in water level of the reservoir and will pump more water to it.

Rainwater will be collected by placing grates on the connectors on the roof allowing the rainwater to enter the HOME^3 plumbing system. This will then drain into a waterproof tank constructed out of the HOME^3 system situated on the ground.

Water will be heated at the point of use through the use of modular electric water heaters. Each module will only increase the water temperature 5 to 10 degrees however they can be stacked to heat water up to 100°C. This will avoid the cost and complexity of installing a separate hot water piping system and will be considerably more energy efficient compared to hot water tanks.

Not all systems have to be reinvented to fit into the HOME^3; standard doors and windows can be fitted into the panels and standard furnishings and appliances can be used. In fact, if you use the panel cladding and add some retrofitting the HOME^3 could look identical to a standard house but for a fraction of the price. This goes for the treatment of human excrement too. A standard toilet can be connected to the urban sewerage network or septic tank. However, a more cost effective solution requiring less water and energy resources has already been developed by Peepoople. Peepoople are a multinational company selling bags that not only hold the waste but treat it by reacting it with a small amount of urea located in every bag (see Figure 4). Treatment takes one month and kills all harmful pathogens and their eggs resulting in a valuable fertilizer commodity that can be sold. Alternatively, the bags can just be buried immediately after use where they will biodegrade in the soil. Bags cost 3 cents each and require no other infrastructure to be developed (Peepoople, 2016).

Figure 4: Bag by Peepoople used to collect and treat human excrement (Peepoople, 2016)

The HOME^3 of the Future

By 2025 there will be one trillion objects connected to the internet of things (MGI, 2013). The HOME^3 will extend the internet of things to include the very structures that we live in. A RFID chip will be embedded into every HOME^3 component; one for every connector, tube, panel and foundation piece. This chip will record information about the component such as the date it was manufactured, the material and labour cost of manufacture, how many people have owned it before, estimated retail price based on condition and current location, recommendations for repair or replacement, current warranty status and much more.

Strategic Overview

The Proposed Business Model

The inherent value in the HOME^3 design appeals to markets in both developing and developed countries. Initially the HOME^3 will target refugees and the poor in developing countries because these people represent both the greatest need and the largest markets with the fewest regulatory hurdles.

In order to effectively target the impoverished communities of developing countries a new business model has to be developed. Customers from these communities require significant contact time with the seller before a purchase is made and yet typically only small profit margins are possible, resulting in impossible to scale business models. However, customers of the HOME^3 are not just buying a product but rather they are joining a community -- the Cubit Community. This global community enables people to connect with other members, keep track of their HOME^3 components, claim warranty on faulty products, provide feedback and, most importantly allows them to resell their HOME^3 using an intuitive and transparent online system that builds trust. All this is made possible by the RFID chips connecting the HOME^3 components to the internet of things as described in the Product Idea: HOME^3 of the future section. This results in every customer becoming a distribution point for the HOME^3 products (see Figure 5). This is a similar business model to the one being successfully implemented by Pollinate Energy in India.

A supply centre will be located in every major city in a region, the customers will then distribute HOME^{3}s through resales to the surrounding area. The supply centre will not only sell HOME^3 products but will also include an assembling plant that utilizes local labour to assemble the necessary components of the HOME^3 from raw materials. This distributed manufacturing will increase local employment, decrease costs of transport and labour, decrease initial capital expenditure and spread risk.

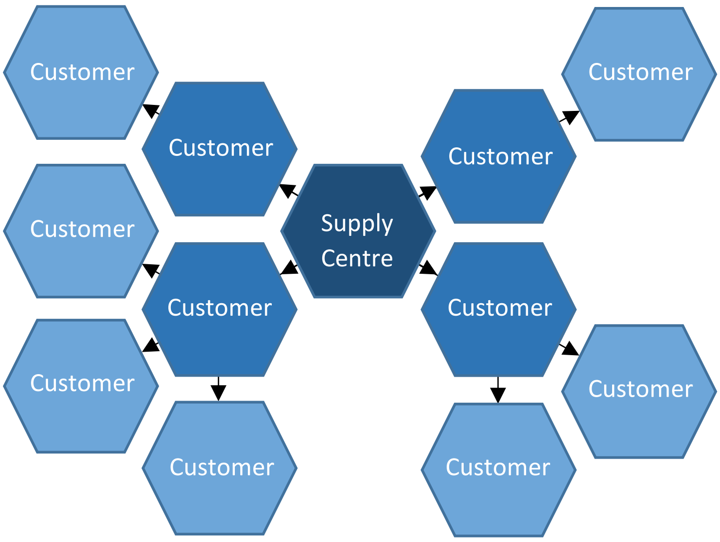


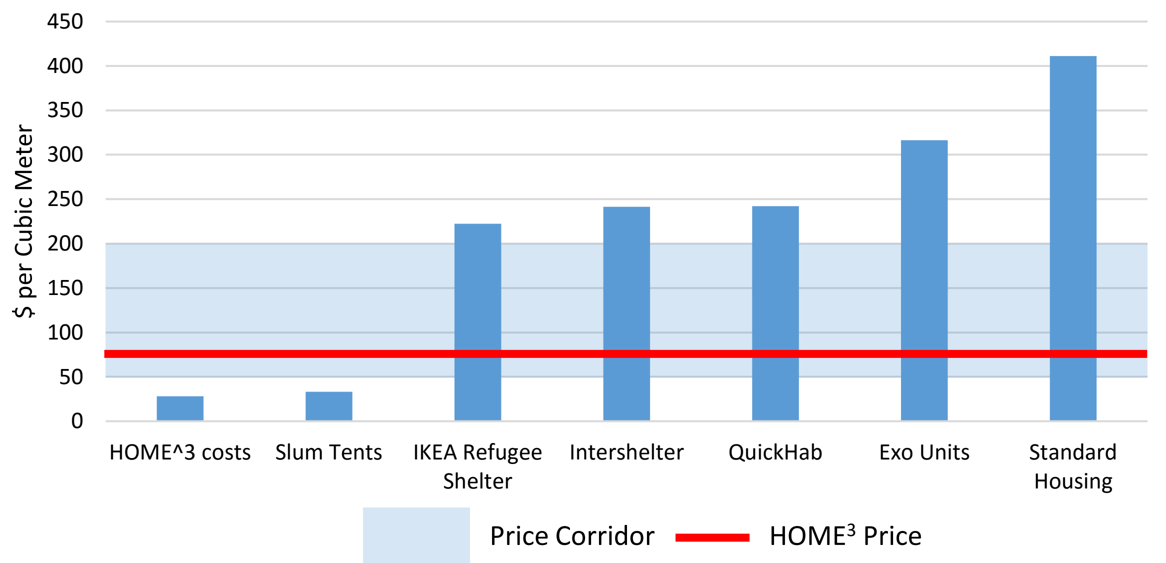
Figure 5: The distrubtion system of the HOME^3

Pricing

To price the HOME^3 strategically it is important to set the price at its true value instead of factoring in an arbitrary profit margin. To determine this a price corridor was developed as seen in Figure 6 based on the HOME^3 cost comparison against the current solution and other competitors. When considering the HOME^3's application in developing countries and refugee camps the existing solution is often slum tents. During my internship at Pollinate Energy in Hyderabad India I was given the opportunity to survey over fifty slum communities asking about their construction methods and costs. The average slum tent costs $75 for 4.5m^3 and requires maintenance costs of $75 a year. The HOME^3 could meet that price point if there was no profit margin. The HOME^3, however, has a higher value offering to customers than slum tents, which should be reflected in a higher price. That said it is important that the final price be within reach of the slum dweller budgets.

There are a variety of competitors acting in this space who are mainly focused on refugees. The IKEA design for refugees is the best alternative providing a large, flat pack shelter with solar panels and easy construction. However, it has very small windows, no plumbing, no floor and a high cost at $10,000. Although the HOME^3 has a higher value offering than the IKEA shelter and other competitors its price point should be below theirs to dissuade future competition. This results in a price corridor between $50/m^3 to $200/m^3 which allows large price flexibility. To capture the mass market primarily composed of slum dwellers the HOME^3 will be priced at $75/m^3 which equates to $2000 for a 3mx3mx3m cube.

Figure 6: HOME^3 Price Corridor



(Mallonee, 2014), (ABS, 2009).

Key Assumptions

The HOME^3 utilizes more structural steel than a conventional house. However, this steel is more segmented resulting in more joints which can be weak points. These joints allow for increased flexibility but reduces a piece's individual strength which may or may not be advantageous for cyclone and earthquake conditions. Computer simulations and real world testing must be completed to determine if the required strength can be obtained to meet regulations.

Regulatory requirements are another area of concern. Although this building could be classified as a class 10a structure in Australia, it is possible that the more stringent regulations of a class 1a structure would have to be applied. Meeting these regulations without compromising the design is a significant issue. Further research into these regulations is needed.

Current Stage of Development

The timeline for the HOME^3 is shown in Figure 7. The concept of the HOME^3 was initiated at the start of 2015. It was further developed and entered into a series of competitions of which it won the

Merit Award in the Singapore Future Cities competition and was Runner up in the 2015 Dow SISCA competition. The prize money was invested to develop a physical prototype and conduct preliminary analysis and testing completed in the UQ Advanced Engineering Civil Engineering Laboratories as a part of the ICARUS programme. A full scale 3mx3mx3m HOME^3 was completed in December 2015. The website was launched and an active Facebook page developed which can be viewed at www.cubitcommunity.com and https://www.facebook.com/cubitcommunity. Connections with manufacturers of the critical raw materials such as plywood and steel have been made and quotes and samples have been obtained.

Future goals include the construction of a second full scale fully functional prototype based on an improved design by December 2016. This will enable full scale ergonomic and structural testing of the HOME^3 resulting in the development of the minimum viable product. Once a proven product has been developed negotiations with NGO's, governmental agencies and social businesses both in Australia and overseas will be pursued to develop partnerships. (See the delivery team section for more information on contacts that have already been developed.)

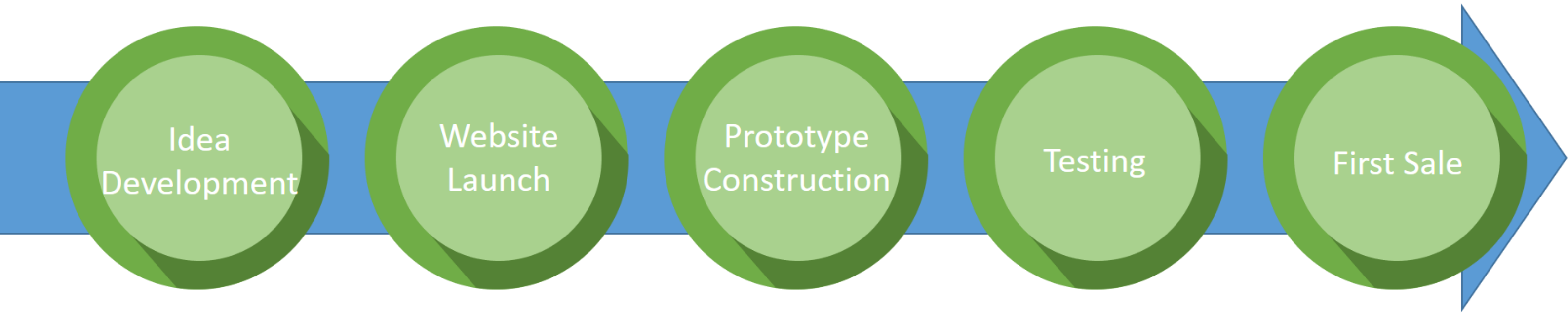


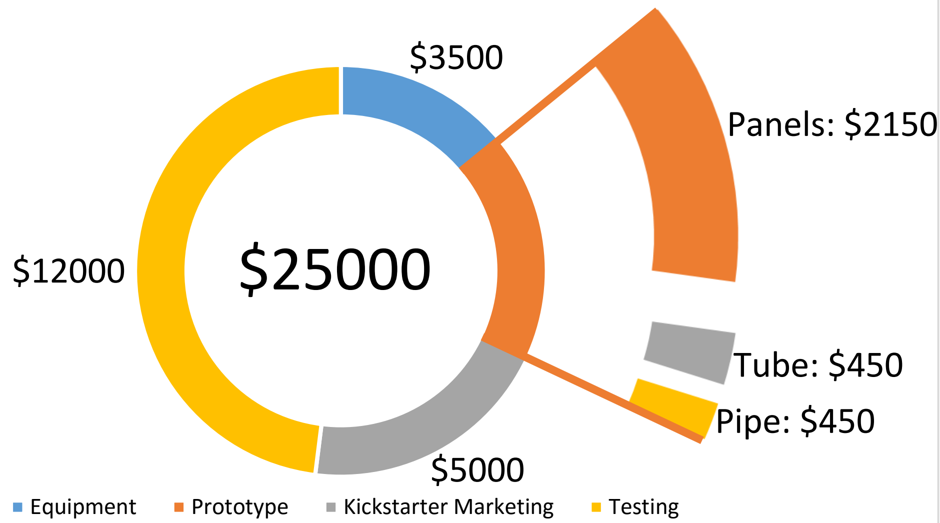
Figure 7: HOME^3 timeline

Finance

The $25,000 prize money from this competition will be crucial to complete the second prototype of the HOME^3 which will have fully functioning utilities, to structurally test the HOME^3 and to launch a Kickstarter campaign (see Figure 8). The Kickstarter campaign will be needed to obtain the $55,000 necessary to unlock economies of scale and mass produce HOME^{3}s (see Figure 9).

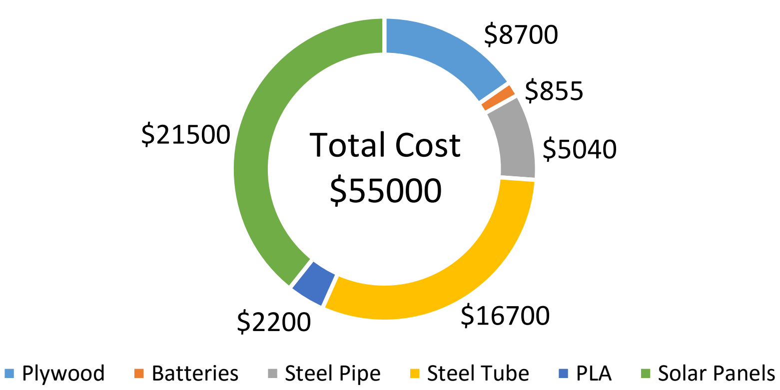
The largest cost will be completing the structural cyclone testing at the James Cook University Cyclone Testing Station in Townsville (CTS, 2016). This money will also be used to conduct structural testing at the University of Queensland Civil Engineering Laboratories. In order to complete these tests a full scale 3mx3mx3m cube needs to be built using more expensive local materials. The material cost will be $4,500 with a 50% contingency and the equipment cost will be $3,500 with a 50% contingency. The equipment needed includes a tap and die set to thread the steel pipes ($500), 3D printer ($500) and electroplating equipment to make the conductive connections needed in the wiring and the POWER^3 ($1,300). Finally, $5,000 is needed to launch a crowdfunding campaign that will most likely be through Kickstarter (Barnett, 2013).

Figure 8: Use of funds breakdown



$55,000 is needed to meet the minimum order quantities and unlock value from economies of scale, this would enable the construction of 75 3mx3mx3m cubes. Figure 9 displays the breakdown of this cost. The solar panels are the most expensive component because they have to be customized with a MOQ of 500 units. Some of this cost can be reduced by ordering from retailers who sell at a higher price but lower minimum order quantity and this will be done to build the prototype. A Kickstarter campaign is one way to raise the funds needed to order these minimum order quantities once the prototype has been developed and tested.

Figure 9: Economies of Scale Costs



Delivery Team

Key Team Members

The HOME^3 multidisciplinary team has both the experience and technical knowledge to transition the HOME^3 from an idea into a successful business. Between us we represent five disciplines including Civil Engineering, Physics, Commerce, Information Technology and Chemical Engineering, and have valuable experience in achieving a successful start-up business before.

Team Leader: David Nelson
(CEO of Printory3D, Bachelor of Chemical Engineering and Bachelor of Physics graduate of 2016 UQ)
As the HOME^3 initial visionary David has been responsible for bringing together a team to fill the

necessary skill gaps to ensure that the $HOME^3$ becomes a reality. David also brings to the team his valuable experience in achieving a successful start-up on a shoestring budget. As CEO of Printory3D he has obtained both the resources and knowledge to design many of the 3D printed components of the $HOME^3$.

Business Director: Andrew Sun
(3rd year Bachelor of Civil Engineering and Bachelor of Commerce UQ)
Andrew's business advice and strategic vision has guided the $HOME^3$ from day one. His ability to combine his understanding of civil engineering with business sensibilities allows him to generate insights into creating customer value.

Structural Engineer: Gabrielle Hodge
(3rd year Bachelor of Civil Engineering and Bachelor of Information Technology UQ)
Design and calculation of the $HOME^3$ structural components would not have been possible without Gabrielle's insight. Furthermore, her input has resulting the development of integrating the $HOME^3$ into the internet of things. Her knowledge in information technology has been displayed in developing the early prototypes of the apps to connect to RFID chips.

Media Manager: Natasha Natamihardja
(2nd year Bachelor of Civil Engineering UQ)
Natasha has been responsible for developing the media and web presence for the $HOME^3$. Furthermore, her contributions to the prototype construction and design has left a permanent impact on the $HOME^3$. Her passion for empowering communities in developing countries has led to a renewed focus for the $HOME^3$ in that direction.

Investors, Strategic Partners and Alliances

A number of contacts have been made with strategic businesses in the retail and manufacturing industries. The initial idea for the $POWER^3$ was developed during an internship with Pollinate Energy who has expressed interest in selling new products to people in slums in India. Another important contact is Dr Diego Lopez a postdoctoral research fellow in the DOW Centre who if satisfied by the prototype functionality by December of this year will present the $HOME^3$ to government officials in his home country Paraguay. Furthermore, Dr Lopez has provided advice based on his experience in the plastics and steel industries.

In order to test the $HOME^3$ structurally contacts have been made with UQ's Advanced Engineering Civil Laboratories and the James Cook University Cyclone Testing Station in Townsville. Testing will be initiated once the second full scale prototype has been developed.

Contacts have also been made with numerous manufacturers of the raw materials needed for the $HOME^3$. After careful consideration the following companies have been selected; Shenzhen Baishitelong Technology Company will supply the Li-ion batteries, Zhuhai Sunlu Industrial Company will supply the PLA and Yunnan Yaochuang Energy Development Company will supply the solar panels. Communications with other companies to supply the other needed materials are ongoing.

Further governmental agencies, social businesses and non-profit organisations will be contacted once a fully functional prototype that is ready to be produced at scale is achieved. This is expected to occur in December 2016.

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Appendix 1

To develop the strategy canvas the HOME^3 was compare with three alternatives; conventional construction, flat packed prefabrication housing and tents. These were chosen to give a sense of scale. The total cost, cost per square meter, total building time, construction GHG emissions are determined quantitatively from a number of difference sources. Customisation, maintenance, DIY and percentage of initial cost over total cost were determined qualitatively.

The strategy canvas was generated from the table below and scaled logarithmically, this number was then scaled linearly to fit between zero and ten. Numbers that are negative or zero were assigned the value zero and the value one remained as one.

		HOME^3	*Standard*	*Tilt Up*	*Flatpacked PreFab*	*Tent*
Cost	Total Cost	16800[1]	236,000[2]	3,600,000[3]	114,000[4]	317[5]
	Cost per Square Meter ($/m^2)	85[1]	987[2]	605[6]	1,655[2]	30[5]
Time	Total Building Time (days)	1[1]	217[7]	112[8]	155[9]	0[5]
Sustainability	Construction GHG emissions (ton CO2e)	-34[1]	43[10]	1000[11]	28[10]	0
Other	Customisation	8	8	2	4	1
	Maintenance	2	8	1	8	2
	DIY	10	0	0	0	10
	Percentage of Initial Cost over Total Cost	10%	100%	100%	100%	100%

[1] See appendix 2, [2] (ABS, 2009), [3] Assuming an average building area of 6000m^3 (TCA, 2011), [4] Based on the Ikea flat pack BoKlok house (Ikea, 2016), [5] Based on the Coleman Tent ranked best value tent (Chance, 2016), [6] (Cessnock City Council, 2012), [7] (USCB, 2016), [8] 4 weeks design time (TCA, 2016) + 12 weeks construction time (Elayache, 2014). [9] (Williams, 2016), [10] (Monahan & Powell, 2011), [11] Based on as square layout of a 6000m^2 structure with 10m high walls at 100kgCO2e/m^2 of wall assuming that walls amount to 30% of the total emissions (Omahen, 2002).

Appendix 2 Material Costs of the HOME[3]

Material	Cost per unit ($USD)	Embedded Carbon ($kgCO_2e/kg$)	Density (kg/m^3)
Plywood	$0.42/kg [3]	-1.22[6]	600
Steel	Tube: $0.8/m[1] Pipe: $1.2/m[5]	0.48[2]	8000
PLA	$9/kg[6]	0[4]	1250

[1] Quote from Chengsen Enterprises, [2] (Hammond & Jones, 2008), [3] Quote from Langfang Nijia Trading Company, [4] (Corbion Purac, 2016), [5] Quote from Chengdu Derbo Import and Export Company, [6] (Puettmann, Oneil, Wilson, & Johnson, 2013), [6] Quote from Zhuhai Sunlu Industrial Company.

Panel

The basic panel design consists of two 5mm plywood sheets separated by a supporting material and lined on the edge with rubber to provide water proofing.

$$Volume = V = 2LWD = 2 \times 1m \times 1m \times 0.05m = 0.01m^3$$
$$Mass = \rho V = 600kg/m^3 \times 0.01m^3 = 6kg$$
$$Cost = 6kg \times \$0.42/kg = \$2.5$$
$$Embedded\ Carbon = 6kg \times -\frac{1.22kgCO_2e}{kg} = -7.3kgCO_2e$$

Steel Tube

The steel tube consists of a steel pipe inside of a steel square hollow section.

$$Volume = V_{total} = V_{tube} + V_{pipe}$$
$$V_{tube} = 0.001m \times 4 \times 0.05m \times 1m = 2 \times 10^{-4}m^3$$
$$V_{pipe} = 0.003 \times 2\pi \times 0.02 \times 1m = 3.8 \times 10^{-4}m^3$$
$$V_{total} = 5.8 \times 10^{-4}m^3$$
$$Mass = \rho V_{total} = 8000kg/m^3 \times 5.8 \times 10^{-4}m^3 = 4.6kg$$
$$Cost = \$0.81 + \$1.2 = \$2$$
$$Embedded\ Carbon = 4.6kg \times 0.48kgCO_2e/kg = 2.2kgCO_2e$$

Connector

The connector consists of a 3D printed PLA plastic body with six threaded rings to connect panels to each of the faces. It will also contain wiring and rubber O-Rings for waterproofing.

$$Volume = V = 4.7 \times 10^{-5}m^3$$
$$Mass = \rho V = 1250kg/m^3 \times 4.7 \times 10^{-5}m^3 = 0.06kg$$
$$Cost = 0.06kg \times \$9/kg = \$0.53$$
$$Embedded\ Carbon = 0.06kg \times 0kgCO_2e/kg = 0$$

$\mathbf{1m \times 1m \times 1m\ Cube}$

$8 \times Connectors + 12 \times Tubes + 6 \times Panels$

$Embedded\ Carbon = 12 \times 2.2 + 6 \times -7.3 = -17.4kgCO_2e$

$Time\ of\ Construction = 12 \times 1 + 6 \times 2 + 100\%\ Contingency = 45\ minutes$

$8 \times \$0.53 + 12 \times \$2 + 6 \times \$2.5 + 100\%\ Contingency$

$\mathbf{Cost = \$86/cube = \$86/m^3 = \$86/m^2}$

$\mathbf{2m \times 2m \times 2m\ Cube}$

$26 \times Connectors + 48 \times Tubes + 24 \times Panels$

$Embedded\ Carbon = 48 \times 2.2 + 24 \times -7.3 = -70kgCO_2e$

$Time\ of\ Construction = 48 \times 1 + 24 \times 2 + 100\%\ Contingency = 3.2\ hours$
$26 \times \$0.53 + 48 \times \$2 + 24 \times \$2.5 + 100\%\ Contingency$
$\boldsymbol{Cost = \$340/cube = \$42/m^3 = \$85/m^2}$

$\boldsymbol{3m \times 3m \times 3m\ Cube}$
$56 \times Connectors + 108 \times Tubes + 54 \times Panels$
$Embedded\ Carbon = 108 \times 2.2 + 54 \times 1.3 = -155 kgCO_2e$
$Time\ of\ Construction = 108 \times 1 + 54 \times 2 + 100\%\ Contingency = 7.2\ hours$
$56 \times \$0.53 + 108 \times \$2 + 54 \times \$2.5 + 100\%\ Contingency$
$\boldsymbol{Cost = \$761/cube = \$28/m^3 = \$85/m^2}$

The HOME^3 cost estimates used in the rest of the report use the figures for a 3mx3mx3m Cube.