

Reflections on Building a House:

Testing the Capabilities of a Digital Workflow, Designing for Affordable Sustainability, and Reassessing the Recipe for Small Space Living.

by

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Abstract

I believe the way we design and make buildings is transiting through a major point in history where the flow of ideas through to workmanship is being restructured. As the format changes, opportunities are emerging to provoke a new wave of design innovation. Through a full scale housing experiment, taking shape as a design-build research tiny house, I explore a prototypical alternative housing project aimed at exploring the capability of building production utilizing a complete digital workflow, what it takes to build an affordable sustainable home, and how spatial organization can pull everything together. This full scale experiment serves to help advance how we think about building housing in the 21st century.

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Chapter 1: Introduction



Fig. 001 - Waffle grid construction complete at the Architecture Building's high bay.

1.1 An Overview of the Design-Build Research Project

I decided to build a house to experiment with emerging building technologies at a livable scale. The house serves as a site of critical reflection for this thesis, and fodder for my career in architecture. The project was also a personal journey that revealed much to me including the idea of risk that lies at the heart of craft¹, the potential for not only what we build, but how we build to redefine sustainability, and the potential for digital design and

¹ Pye, D. (1968). *The nature and art Of workmanship: David Pye* . University Press.

fabrication to contribute new modes of architecture to society, and make delightful spaces available to a broader range of building types.

Throughout my tenure in architecture school, most of my projects trended towards freeform spatial creations that bordered on unbuildable. The projects were also consistently centred around social issues as I was drawn to the power that architecture has to help shape and meaningfully contribute to society. But it never sat well with me that these concepts were just theoretical and largely would be abandoned as I headed into the “real world,” post-academia. I decided to design one more project that encapsulated what caused me to fall in love with architecture, and then take on the challenge to actually build it.



Fig. 002 - DIY campervan project in Europe “The Hobbitvan”.

My personal understanding of affordable building and construction was seated in my construction of a wooden campervan, built whilst living in Europe to support my career as a national team athlete for whitewater kayaking. This camper was the product of the need for my own affordable housing and transportation for six months of the year as I travelled to competitions and trained with the best athletes in the world. This was my first real attempt at building anything at a livable scale and ended up being my most affordable solution to the problem of setting up a home away from home.

For my masters project, I wanted to create something that was designed to be a permanent dwelling that would not require sacrifice in lifestyle to reside in. It needed to be affordable, as I was funding it on grants and sponsorships, but also serve as a prototype for new ways to design for the affordable housing crisis in North America. Most importantly, it needed to be a high quality place to live in that served to advance a conversation about how 21st century affordable housing could be approached. It has been my opinion that digital design and fabrication technologies are not being pushed to their fullest capability in this area, and I wanted to understand the reasons why.

The typology of a tiny house was chosen as a testing bed for this project, not from any particular belief in mass market viability of tiny houses, but for the ability to design, construct, and test a functional 1:1 housing prototype within the high bay at Carleton University's architecture building. Building at human scale allowed for the opportunity to challenge broad concepts of the way we build by using real building products as well

allowing thermal performance to be tested under real world conditions. The proximity to the architecture department allowed access to advanced digital fabrication tools and a fast feedback loop from expert advisors in the fields of building envelope science, architectural design, digital fabrication, and solar thermal engineering. As the project went into the design phase, I decided to focus on three key areas of innovation: the potential of digitally fabricated construction, affordable sustainable design, and how to make small space living appealing in North America.

Exploring the Digital Workflow

The house that I wanted to build would express the potential of digital fabrication tools in doing more than simply replacing manual labour. When considering design styles for the building's components, a self imposed mandate was created that each element should be either impossible or prohibitively time consuming to complete in any other way than through digital fabrication. By inserting this rule, my design would be forced to explore the potential of these tools and innovate based on the capability of constructing in this manner. Ultimately, I hoped to contribute to the development of a new language of digital design that can create spatial experiences unlike other historical precedents which were bound by different constraints.

My process of designing and building the tiny house effectively was made through the utilization of BIM (Building Information Modelling). I choose to describe my process in

terms of a digital workflow rather than BIM because I believe that BIM has subsumed a set of design principles that is currently falling short of what it could be. BIM is used to streamline a typical pathway for bringing a building into reality. As I understand it, this process is effectively translating what used to be accomplished on a drafting table and software packages into a more flexible and precise document. What interests me for this thesis is testing the limits of these digital assets whose capability I believe is not being fully utilized and exploring types of design that have only recently become possible with the advent of this way of working.

Affordable Sustainability

In regards to sustainable design, I wanted the housing prototype to achieve a low environmental impact from cradle to cradle, while also being affordable to construct and maintain. The ability to build sustainably is rendered irrelevant if the cost incentive clearly favours the unsustainable solution. I selected an experimental low cost solar thermal system that would be the sole heating source throughout a Canadian winter. The lowest embodied energy construction materials needed to be chosen when weighed against their useful life cycle, and ability to be disassembled and reused. The building needed to last 200 years and be comprised of parts that are easily replicated, repaired, and replaced.

Small Space Design Methodology

The final goal of the design was to create a minimized floor space dwelling, while maximizing all other functionalities and qualities that contribute to an attractive home. In North America, the size of a space and its desirability are often entwined. Realtors post square footage alongside price when selling or renting a home and it has become a ubiquitous metric for the usefulness and desirability of a given space. Good design is often a secondary important criteria once a minimum floor area has been established. I wanted to see if that value set could be flipped and create a home that is designed to be compelling in spite of its small square footage.

The floor space available for interior living on the tiny house trailer was 180 square feet (16.72m²). This ruled out designing for families but allowed for tailoring to young couples, single occupants, empty nesters, or students working within the priorities of North American clientele. I believed that if I could reduce the size and material usage of a building, some of the cost savings associated with material savings could be reapplied to increased functionality and add finishing quality to the overall design. The goal was for this tiny house to be competitive with a typical 500 square foot bachelor condominium offering in North America.

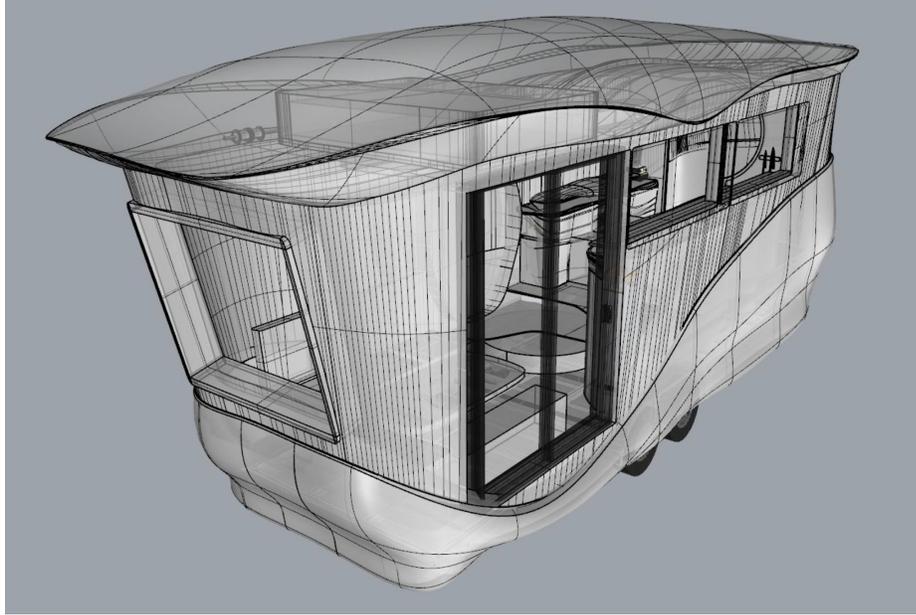


Fig. 003 - CAD Model Development of the Tiny House.

1.2 The Digital Workflow.

Why do we not have more playful buildings in the world? There are simple and more nuanced answers to that question but it has been one that has stuck with me throughout my time at architecture school. Spending time in Barcelona's Parc Guell, observing Antoni Gaudi's field of evolving curvaceous stone work experiments, I am left with the feeling that the field of architecture is losing its sense of play. With the exception of some anomalies, building parts are typically standardized, labour is expensive, and housing design in particular is low risk and makes minor innovations. With the advancement of powerful CAD software and the wide availability of digital fabrication tools, I believe there is now a window of opportunity that has reshuffled fundamental limitations and is allowing us to completely rethink how design can incorporate play with an end goal of producing more delightful space.

Historical examples such as Jorn Utzon's Sydney Opera House demonstrated significant challenges in resolving unconventional buildings. Utzon's competition winning entry was altered from its free form shell design to one that involved the utilization of sections of a sphere to allow engineering teams to structurally plan the complex geometry.²



Fig 004 - The Spherical Solution Model by Jørn Utzon (National Library of Australia)

“After three years of intensive search for a basic geometry for the shell complex I arrived in October 1961 at the spherical solution shown here. I call this my “key to the shells” because it solves all the problems at construction by opening up for mass production, precision in manufacture and simple erection and with the geometrical system I attain full harmony between all the shapes in the fantastic complex.”³

-Jørn Utzon

² Utzon, J. (1962). Platforms and plateaus: ideas of a Danish architect, *Zodiac*, 10.

³ Utzon, J. (1989). Jørn Utzon on architecture. A conversation with Henrik Steen Møller. *Living Architecture. Scandinavia Design*, 8.

In spite of Utzon's simplification method, the Sydney Opera House ran well over schedule and over budget, setting one of many precedents of the large cost associated with creating iconic structures. In today's world, now that CAD is paired with a direct digital communication pathway to the machine that precisely fabricates the building component, I argue that the opportunity to resolve extremely complex designs has become viable and affordable.

Utzon was bound by the construction methods of his time which sat within the conventions of mathematically resolved drawings, whereby a series of translations from the design to the fabrication are needed without the aid of computers. The construction was also governed by industry conventions which suited mass production, prefabrication, and assembly of parts construction.

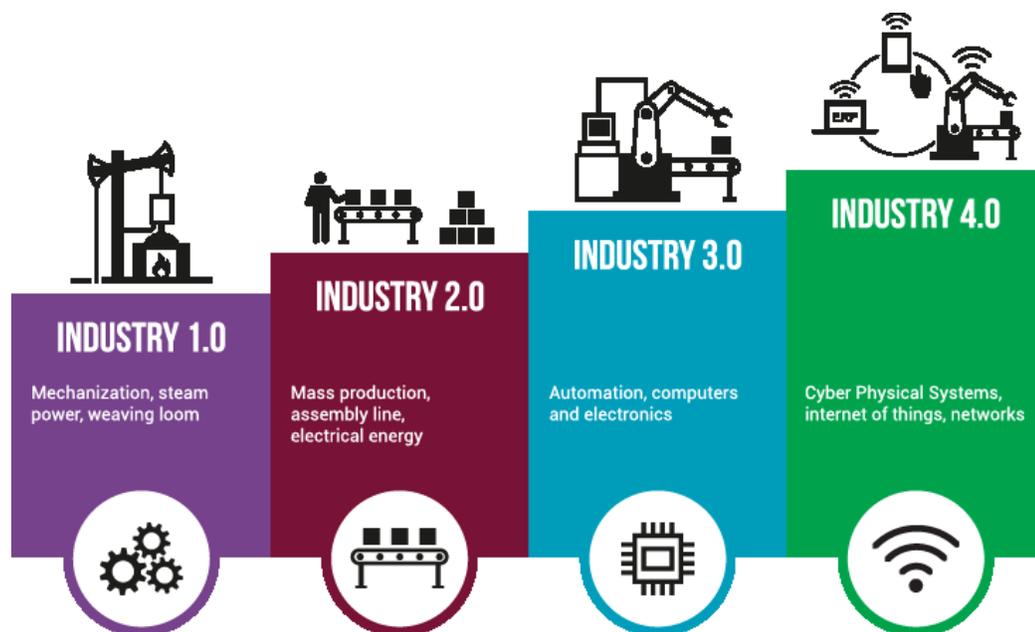


Fig 005 - Highlights of industrial revolutions (Erik Kucera)⁴

The industrial revolution can arguably be segmented into four major points of technological innovation, which each significantly altered the method of manufacturing and production. As pictured above, these demarkations have been noted as mechanization with the advent of steam power, mass production complemented by electrical energy, automation paired computational control, and cyber physical systems.⁴ Industrialization is arguably transiting between a third and fourth major delineation of the industrial revolution. The fourth wave industrial revolution is marked partially by the introduction of mass customized production but also in the implementation of networks of data of exchange with manufacturing technology.

Architecture, in the context of the first wave industrial revolution, was typically one-off versions that relied heavily on manual labour and craftsmanship. A Canadian precedent of this time is the Commercial Block designed by William Blackmore in Gastown, Vancouver. This building's design reflects a reliance on skilled manual labour in its interplay of brick and stone masonry. A high level of material knowledge and craftsmanship was required to flattening the stone used in columns and lintels in this building while preserving the rough split aesthetic of the exterior face.

⁴ Erik Kucera et al., "Emerging Technologies for Industry 4.0: OPC Unified Architecture and Virtual / Mixed Reality," 2018.



Fig 006 - Commercial Block, Gastown, Vancouver. William Blackmore, 1893. (Ted McGrath)

Tract housing, modular housing, and kit of parts construction are all various evolutions in the development of mass produced architecture denoted a shift into a second wave of industrial revolution. Moshe Safdie's Habitat 67 in Montreal is an example of early explorations into affordable housing made using mass produced prefabricated building components. Mass produced building components such as concrete masonry units, batt insulation, sheathing, and vinyl siding are all examples where the dimensions of the factory made material often informs or influences the design of the architecture they are used within.

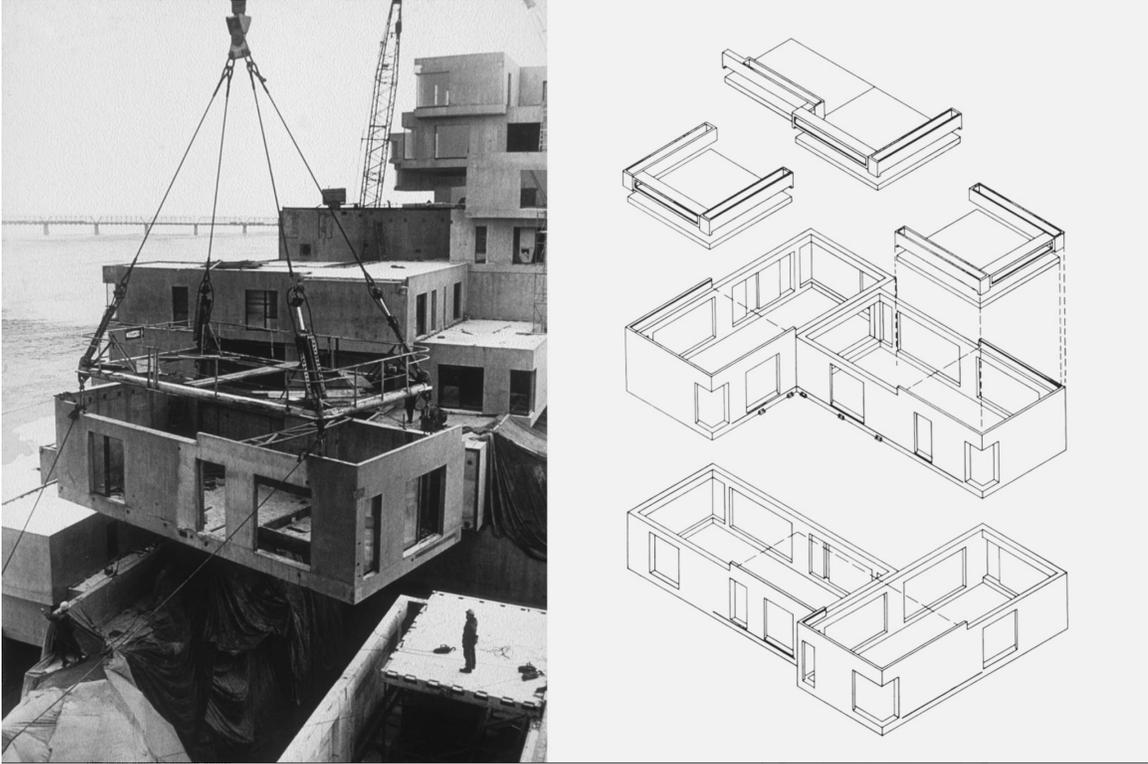


Fig 007 - Habitat 67. Moshe Safdie, 1967. (Safdie Architects)

The transition from mass production in architecture to an inclusion of automation is a line that is more blurry in the building industry. Many components were made in automated factory facilities but there are still few examples of entire building projects being factory produced with the assistance of automation. WikiHouse provides a helpful graphic defining five existing practices for factory built housing following a ‘Design for Manufacturing and Assembly (DfMA)’ mandate. They have been mapped out in a spectrum between more work in a factory versus more work on site that comes with each strategy.

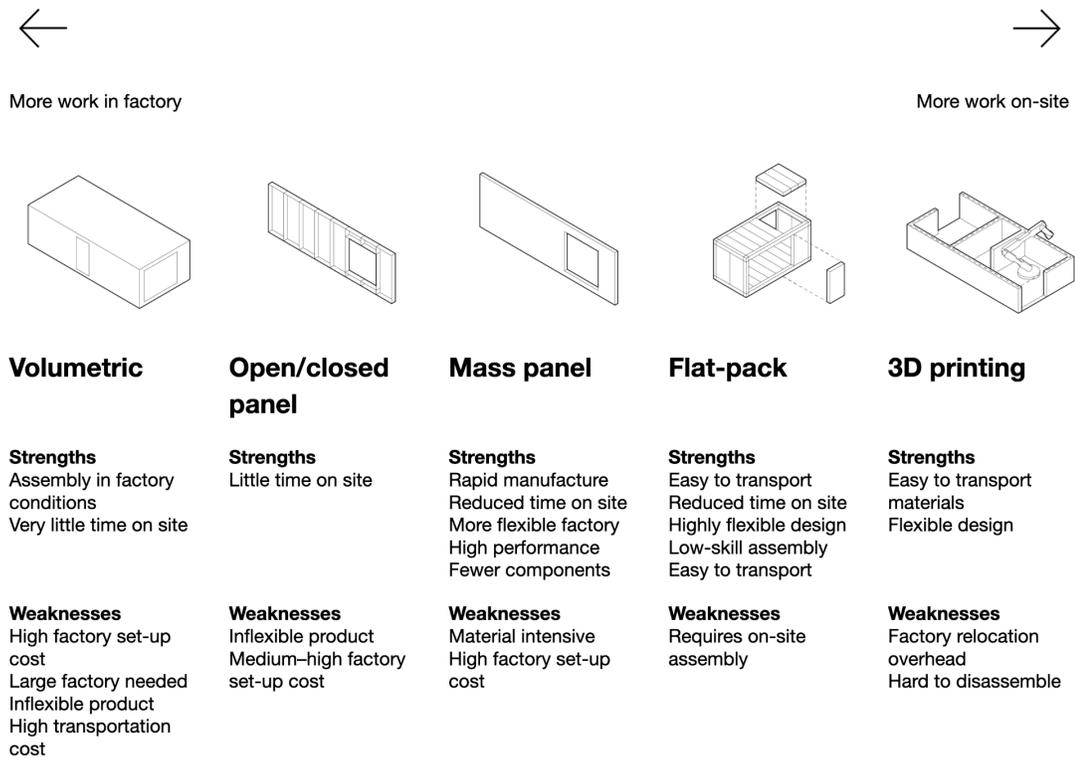


Fig 008 - WikiHouse DfMA Spectrum. Open Systems Lab, 2019. (Open Systems Lab)

Mass customized architecture sits on the bridge between a third and fourth wave of industrial revolution; industrial automation with computerized design, and networks of cyber-physical systems that reduce the friction between moving designs between the digital world and the physical world. When designs and their respective building components are considered as interdependent variables within a CAD program, this presents the first steps for how mass-customised architecture can be approached.⁵

⁵ Carlos Roberto Barrios Hernandez, "Thinking Parametric Design: Introducing Parametric Gaudi," *Design Studies*, Digital Design, 27, no. 3 (May 1, 2006): 309–24, <https://doi.org/10.1016/j.destud.2005.11.006>.

There is a wide range of precedents in pavilion design where architects have been exploring mass customized concepts at full scale. Exciting potential has been demonstrated, such as improved precision, and increased freedom of design, and adaptability to a complex set of variables. Thus far, low cost building projects have received little benefit from this approach and are still predominantly using methods of mass production with automation to create affordable buildings. Notable forays into automated factory production with mass customization have occurred with companies such as Katerra⁶, Kasita⁷, and Sidewalk Labs⁸. In all three of these examples, these companies confronted challenges that either bankrupted their operations or have indefinitely stalled their projects based on the complexity and scale required to reinvent the building industry. Examples of companies still exploring this territory are WikiHouse⁹, Mighty Buildings¹⁰, and ICON¹¹ which take varying approaches in their attempt to bring digital fabrication into factory made housing.

⁶ “Bankrupt Katerra Sells off Massive Factories,” Woodworking Network, accessed September 20, 2021, <https://www.woodworkingnetwork.com/news/woodworking-industry-news/bankrupt-katerra-sells-massive-factories>.

⁷ “The Little House That Couldn’t,” *Texas Architect Magazine* (blog), July 15, 2019, <http://magazine3.texasarchitects.org/2019/07/15/the-little-house-that-couldnt/>.

⁸ Andrew J. Hawkins, “Alphabet’s Sidewalk Labs Shuts down Toronto Smart City Project,” *The Verge*, May 7, 2020,

<https://www.theverge.com/2020/5/7/21250594/alphabet-sidewalk-labs-toronto-quayside-shutting-down>.

⁹ Zara, Janelle. “Free: Download a Construction Kit to Build Your Own ‘Wikihouse’ - Architizer Journal.” *Journal*, May 19, 2021.

<https://architizer.com/blog/practice/materials/wikihouse-the-open-source-diy-home/>.

¹⁰ Azevedo, Mary Ann. “Mighty Buildings Nabs \$40M Series B to 3D Print Your next House.” *TechCrunch*. *TechCrunch*, February 9, 2021.

<https://social.techcrunch.com/2021/02/09/khosla-backs-construction-tech-startup-mighty-buildings-plans-to-create-3d-printed-homes/>.

¹¹ Dan Howarth | 31 August 2021 Leave a comment. “Icon Completes ‘First 3D-Printed Homes for Sale in the US.’” *Dezeen*, August 31, 2021.

<https://www.dezeen.com/2021/08/31/east-17th-street-residences-3d-printed-homes-icon-austin/>.

I believe the potential exists to further optimize and enhance affordable housing through a more intensive investigation into the merits of mass customization. I chose to focus on affordable housing simply because I have observed less innovation in this area and I wished to understand if there are prohibitive issues associated with pairing mass customization with affordability.



Fig 009 - Example waffle grid for simple shape fabrication (Manuel Kretzer)⁹

1.3 Introduction to the Waffle Grid

The tiny house utilized a waffle grid structure which was a conducive system to the goal of exploring building techniques that are feasible only with an end to end digital workflow. Unlike timber framing, this system is a network of plywood pieces that slot together as a three dimensional puzzle. The precision of the machining allows for friction-fit joinery to be used and eliminates the need for fasteners. The system embraces the potential of mass customization and allows for the ability to define endless permutations of complex curvature while retaining structural integrity and ease of assembly.

⁹ Kretzer, Manuel. "Rhino 3D - Digital Crafting Tutorial." Braunschweig University of Art, 2016.

Plywood was chosen for structural performance, availability, affordability, and the nature of wood's ability to capture and sequester carbon during its life as a tree.¹⁰ Plywood can be produced from younger trees harvested from sustainably managed forests. The downside is that this material uses adhesives and preserving agents that increase its environmental footprint and increases the difficulty to recycle the product at the end of life. The versatility and availability of plywood ultimately outweighed these drawbacks but it would be useful to continue material research and explore the potential for an even better all-around product if this technique were to enter scale production.

Using a 4' x 8' sheet material allowed for pieces to be easily milled on the university's three-axis CNC machine. This is a common and low cost digital fabrication tool, theoretically allowing fabrication instructions to be emailed anywhere in the world in the form of CAD drawings or G-Code. This process ensures accurate repeatability when compared to working from drawings and also takes advantage of using locally sourced materials rather than shipping prefabricated components.

The waffle grid allows for a singular structural system which is formed by a network from the intersecting vertices of material. Three planes of structural plywood intersect with each other along two opposing vertical axes and one horizontal axis at a spacing relative to the structural needs of the building. In the case of the tiny house, 16" x 16" spacing of

¹⁰ Joost G. Vogtländer, Natascha M. van der Velden, and Pablo van der Lugt, "Carbon Sequestration in LCA, a Proposal for a New Approach Based on the Global Carbon Cycle; Cases on Wood and on Bamboo," *The International Journal of Life Cycle Assessment* 19, no. 1 (January 1, 2014): 13–23, <https://doi.org/10.1007/s11367-013-0629-6>.

grid planes was used and was chosen to suit batt insulation sizing. The grid also allowed windows to be placed within the structure at any point due to the redundant structural network of the grid. Walls could be thickened or thinned dynamically based on requirements of the building envelope design or the spatial intentions.

When compared to the construction of a stick-framed house of similar size, less skill and effort was required when assembling the waffle grid and higher levels of precision were achieved with the finished structure. Framing, on site or using prefabrication, requires the following steps that are not required for waffle grid assembly:

- Selecting straight strong lumber. By using engineered wood, the Waffle Grid can take advantage of consistent feedstock material that is less prone to problems resulting from checks, warping, or knots.
- Measuring and cutting framing members. The waffle grid shifts this process to the CNC and cuts material with a higher tolerance than typically expected of hand operated power tool cutting. A significant portion of construction site injuries and errors occur when cutting material on-site.¹¹ By removing cutting from the list of skilled work required to erect a building, a safer workplace with higher precision results.
- Leveling and fastening framing members according to construction drawings.

The 3D puzzle method of assembly in the waffle grid alleviates the need for pieces

¹¹ “Statistics - WorkSafeBC,” accessed August 20, 2021, <https://www.worksafebc.com/en/health-safety/industries/construction/statistics>.

to be leveled and squared to each other. The assembly of pieces can only fit together one way and as pieces are connected together, the structure self-aligns. The waffle grid pieces do not require fasteners as they are designed to slot together and form an interconnected structural network of wood joinery.

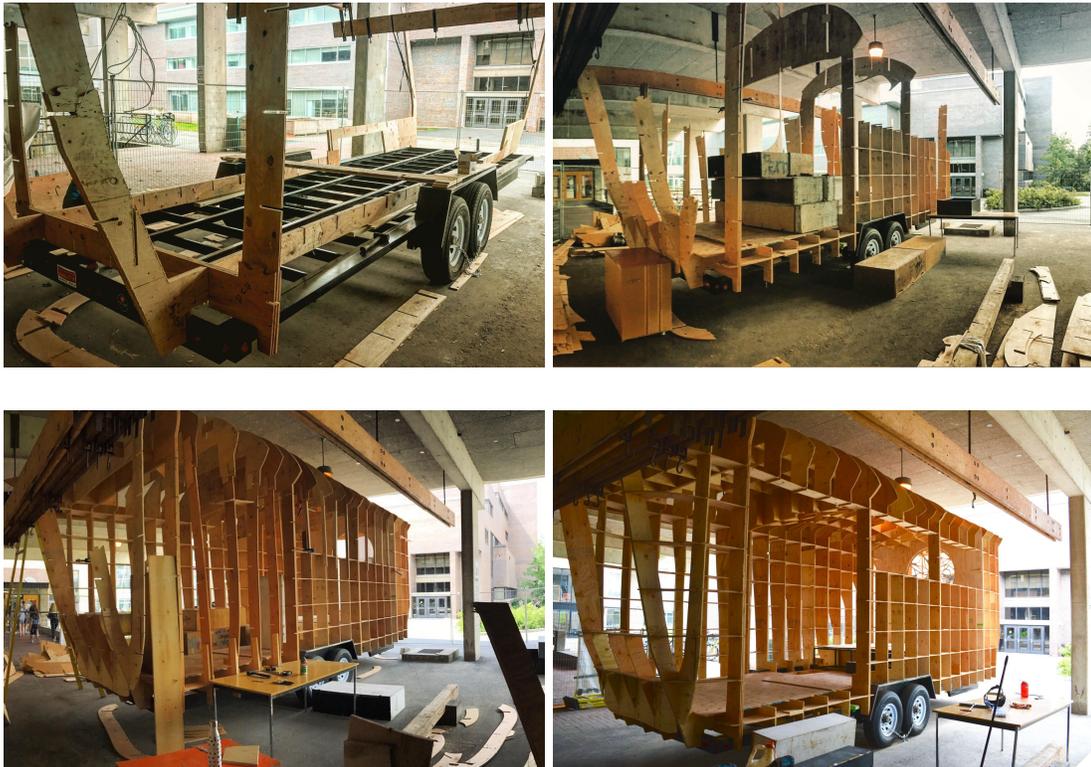


Fig 010 - Construction progress demonstrating waffle joints, auto alignment of pieces, and dust free assembly.

1.4 Thermal Energy Management.

When dealing with life cycle energy usage, the design needed to encompass the best practice building envelope design, an energy efficient heat source, and low energy draw appliances. From the outset, I decided to use an entirely electric system, using no fossil

fuels for cooking, domestic water heating or space heating. This was important as the tiny house was mobile and required the ability to adapt to a sustainable energy generation solution in accordance with the site. In some cases, simply plugging into the grid may be the most sensible option for the location, if the grid is powered by sustainable energy, while in other situations, using wind or solar power might make more sense.

Indoor heating during the cool seasons in a Canadian climate posed the largest energy load and required a simple, affordable solution in off-grid deployments of the tiny house. Simple and affordable were the key terms that gave rise to an investigation into systems that not only met the energy demands, but were cost competitive when compared with unsustainable solutions. Carleton University is home to the Urbandale Centre for Home Energy Research building which is: “A full-scale experimental facility that is used for conducting long-term explorations of novel and unproven concepts aimed at radically reducing the reliance of Canadian housing on conventional energy sources.”¹² Access to this research facility and the academics spearheading this initiative, allowed me to understand the capability of solar thermal energy capture as a viable alternative to the standard modes of practice. This test facility is home to two large underground solar batteries that collect energy as heat throughout the summer and discharge heat throughout the winter. The system works incredibly well but it is built to test the maximal capability of what this type of technology can offer. As a prototype for affordable living, the

¹² Beausoleil-Morrison, Ian. “Urbandale Centre for Home Energy Research.” Urbandale Centre for Home Energy Research - Sustainable Building Energy Systems, 2015.
<https://carleton.ca/sbes/research-facilities/urbandale-centre-for-home-energy-research/>.

motivating factor for my project would need to be reversed to find a minimum viable solution for solar thermal to achieve the lowest cost. This system also could not be so complicated that it was expensive to be maintained over time. The solution found was an experimental photovoltaic heating system, which satisfied these objectives but must be paired with a high performing building envelope. The integration of this building system within the design of the tiny house became yet another parameter for the design.

The building envelope assembly was dictated by material selection, the capabilities of the waffle grid, and passive solar gain. These three factors needed to be kept in harmony as an optimal solution was developed. Wall assembly components were selected based on low embodied energy, life cycle performance, and end of life reuse. The waffle grid allowed for seamless spatial and structural transitions as walls could blend into roofs to reduce vulnerable joints and junctions. The tiny house was given a particular orientation that it must be parked so that the fenestration positioning could take advantage of the passive solar gain throughout the day. A heat recovery ventilator was also used to minimize energy loss in the exchange of air.



Fig 011 - Site plan depicting Summer (red) and Winter (orange) sun pathways.

The combination of affordable solar thermal and efficient building envelope design was geared at setting an important precedent: if the system proved viable from a performance standpoint, and remained as or more cost effective than conventional heating methods, there would be no compelling reason not to transition to sustainable heating in affordable housing.

1.5 Small Space Living.

Small space living solutions are commonplace in all areas of the world with the exception of some of the former British colonies. Canada, USA, Australia, and New Zealand, provide some notable examples of the settling of conquered lands with a mindset of an endless spatial frontier. Whether it be financial or environmental cost, the impetus to

build smaller footprint dwellings is now particularly present in North America as desirable land is expensive and efficient material usage is becoming a more prescient consideration.¹³ External requirements to build smaller living spaces based on economic and environmental conditions may not necessarily be met with a desire to do so. By considering this dichotomy at the outset of the design for the tiny house prototype, I sought to tailor a relatively compromise-free small space living experience for the North American market, one in which consumers are more accustomed to larger dwellings. This is the third primary mission of the tiny house prototype: design a small space dwelling that is desirable to a North American clientele.

The first place to start was to set a benchmark. The tiny house design set out to be as or more desirable to live in than a bachelor condo three times its size. To accomplish this, the following strategy was employed:

- Use spatial organization to make the volume feel larger than it is.
- Integrate easy to use space saving elements that eliminate functional compromise.
- Re-appropriate some of the budget saved on material reduction towards high end finishes and unique elements.

The square footage of a competitive benchmark bachelor condos is between 500-600 square feet (46.45m²-55.74m²). The tiny house by contrast is built on a 24' x 8' 6" trailer (7.32m x 2.59m) with a working interior area of 180 square feet (16.72m²).

¹³ "Bulletin-Green-Buildings-Policy-for-Rezoning.Pdf," accessed August 25, 2021, <https://bylaws.vancouver.ca/Bulletin/bulletin-green-buildings-policy-for-rezoning.pdf>.

Paradigm Shift: From Segregation of Space to Adaptability of Space.

One reason behind large format North American homes, is the common design strategy to divide and segregate space. Even with the advent of more “open concept” floor plans that are currently in vogue, zones of the dwelling are organized to serve a single function. For example, a bedroom, a home office or a dining room are laid out to only serve the purpose of sleeping, working, or dining respectively. The idea of flexible space, in the place of segregated space, is often impractical due to the inflexibility of furniture elements. The tiny house design aimed to challenge this by making space transition effortless in ways that served to enhance the quality of the overall living space.

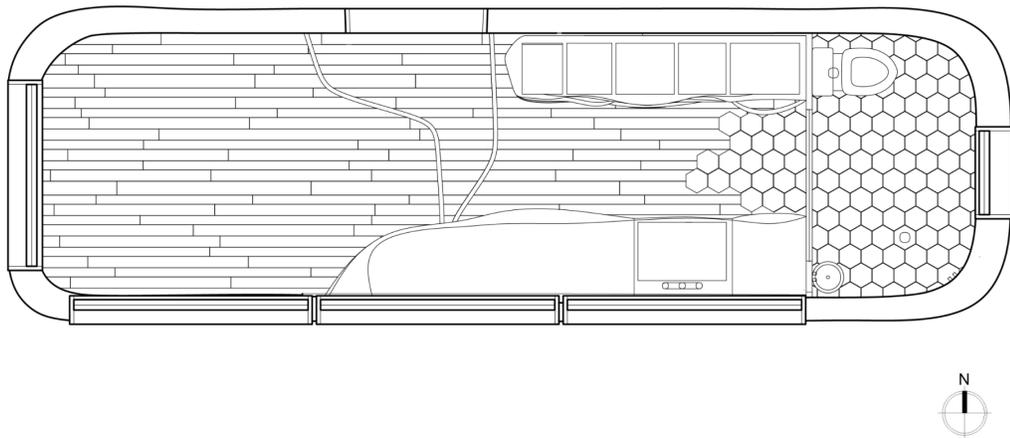


Fig 012 - Floor plan.

Ultimately this exercise is the most subjective of the three areas that I chose to investigate. It is challenging to empirically determine if a design-intensive space is more desirable than one that places the priority on square footage. Regardless, I believe it to be an important exercise to add more precedents into the world which attempt to capture maximal functionality in a minimal amount of space.

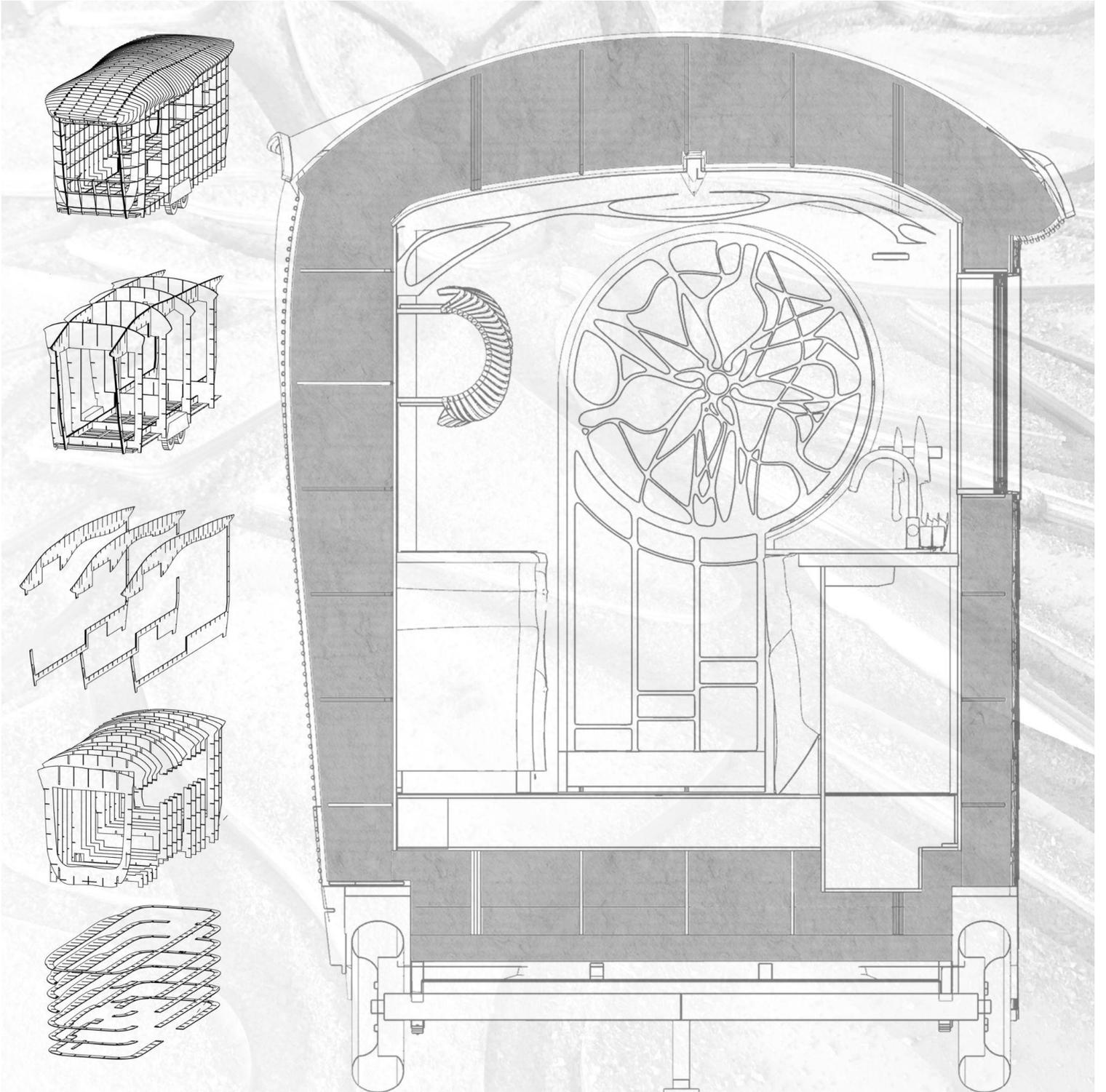


Fig 013 - Waffle grid assembly diagrams.

Chapter 2: Exploring the Merits of a Digital Workflow.

2.1 Understanding Digital Craft

Three Dimensional Sketching

To better analyze a complete digital workflow from design to finished structure, I set myself the challenge to never pick up a pencil for the entire design process, and start from an empty digital workspace. I chose the software Rhino as the CAD program to complete this design after testing 3DS Max, Revit, SketchUp, and Maya. While each CAD program offered various strengths and weaknesses, Rhino felt the most capable to perform free form three dimensional sketching, while also retaining a high degree of precision. The digital design process was more akin to sculpting than drafting and offered the experiential quality of looking around from inside a three dimensional sketch.

When approaching a project for the first time, I have previously worked by designing a space with a pencil and paper and resolving the space from the inside out. I usually start with a section sketch and move onto drawing floor plans. I iterate back and forth between section and plan sketches until a volume or series of volumes begin to coalesce around a perspective sketch. Eventually, I migrate the drawings to a computer program to build out complexity and details and more fully resolve the design. When three-dimensional sketching for this project, I found it more helpful to play directly with the spatial manipulation, as if I were forming plasticine with my hands, or arranging Lego blocks.

This allowed me to receive real time feedback on a space's interplay with light, its spatial characteristics from all angles, and a higher degree of precision when compared to hand sketching. Notably, the freedom of design was limited by my choices in geometry build commands. I often found myself struggling to imagine the correct sequence of inputs I would need to feed into the computer to achieve an imagined shape that existed in my mind. This process did not feel like the nature of sketching as I had felt in analog, it felt more like the process of drawing; where measurements, rulers, angles, and french curves are employed to achieve a specific outcome. This battle between the upside of accuracy and immersive design, weighed against the downside lack of a fluid creative process in the computer program led to the design becoming partially influenced by the medium in which it was created. Like all tools, a mastery of the commands of the CAD program would have led to a more fluid creative process, just like analog drawing tools need to be mastered. But I believe there is a missing gestural element to three dimensional sketching, perhaps not critical to the design process, but one I believe is important to reduce friction in creativity. An advanced virtual reality implementation may provide the fluid expression I am looking for, or it may remain clunky, like the mouse cursor and keyboard. What was clear to me at the end of this exercise was just like starting with a paint brush, charcoal, or a fine tip pen; the process of three dimensional sketching in a CAD program influences the outcome of the design.

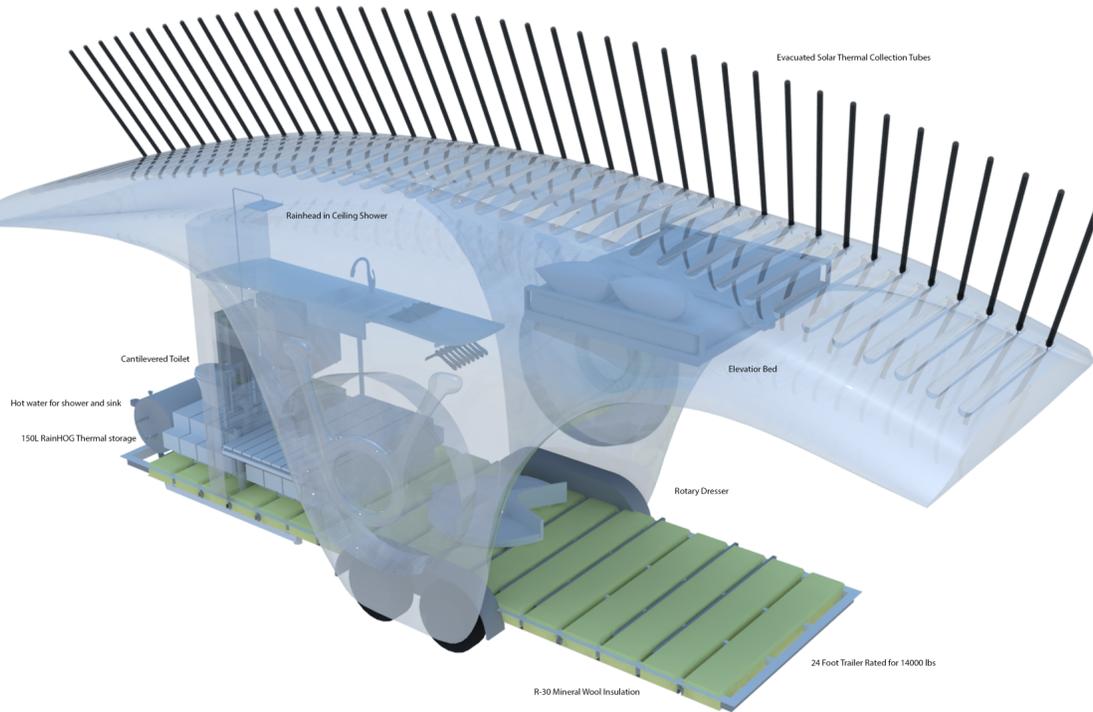


Fig 014 - Building Systems Iteration

Early iterations in this design began from building systems explorations, attempting to qualify the parts that this space needed to be morphed around. I had first attempted an evacuated glass tube solar array that would act as the building's heating collection method. This was later abandoned due to high cost and complexity. I had also tried to define the thermal storage battery volumetric requirements which lead to an elevation change in the floor. It was an early intention of mine to integrate compromise-free building amenities into the housing prototype, which led to the inclusion and placement of a flushing toilet and full size shower. At this point I was able to design the layout of the space from the inside out.

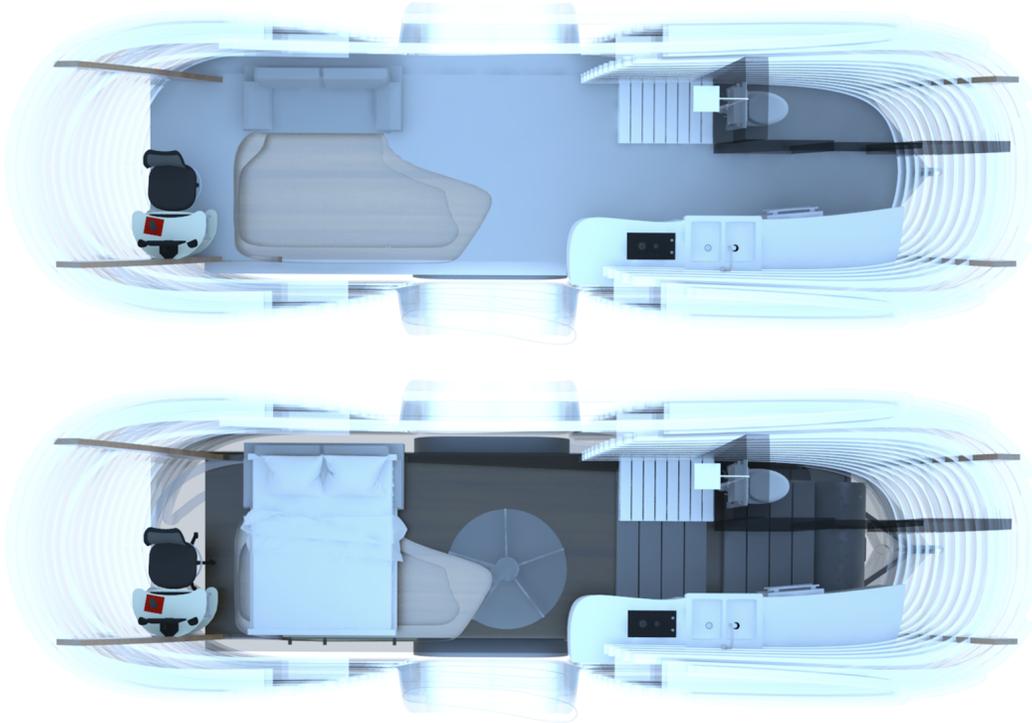


Fig 015 - Floor Plan Iteration.

The floorplan was left as open as possible to maximise the feeling of spaciousness. I was exploring an elevator bed system that descended to the living room to activate the need for a loft. I had also placed the toilet and shower back to back to minimize plumbing materials but this was later changed to a wet room style bathroom which occupied the entire end of the tiny house floor space. Side entry front door was retained in the final layout but the kitchen was amended to enlarge the working surface area and room for appliances. At the point of this iteration, I had not yet resolved the structure or building envelope and had only a rough idea of where to place windows.

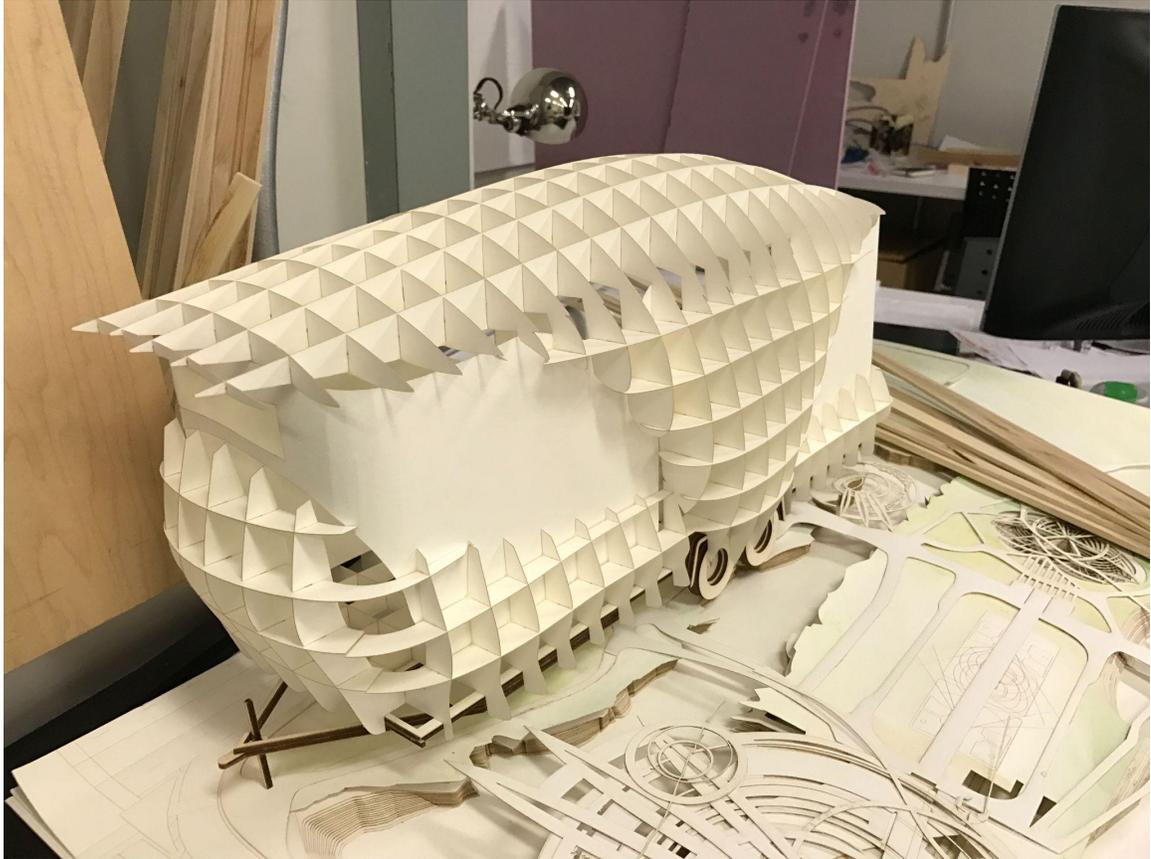


Fig 016 - Laser Cut Model

Arriving at the waffle grid for structural resolution came after having a developed idea of the space that needed to be enclosed. I created a test volume and subdivided it into a structural puzzle to be laser cut from water colour paper. The most surprising result of this investigation was how strong the model became as it was pieced together. It was very easy to make adjustments to the geometry of the waffle grid while retaining the subdividing logic to ensure a sound structure. This model helped provide confidence that a waffle grid made of plywood would meet or exceed the structural requirements required for a full sized tiny house.



Fig 017 - Facade Study Model

A facade study was made using 1:1 materials using the CNC that would ultimately go on to cut the final construction pieces. After experimenting with steam bending of wood to try and match complex curvature in the digital model, I arrived at the understanding that this would be too laborious to do in practice. I ran physical tests of various thicknesses of cedar strips to understand how I could pin the piece into flexion without exceeding its elastic deformation. The best combination I found was the experiment pictured above which used $\frac{1}{8}$ " thick and $\frac{3}{4}$ " wide pieces of air dried cedar. By CNC milling the cradles that each piece was held by, I retained a high degree of control over the geometry of the facade but also ensured that assembly was as easy as installing conventional siding.

Migrating to the final construction drawings, a parametric script was attached to the volume to subdivide it into three opposing axes at 16” spacing: a horizontal axis, a long section axis, and a short section axis.

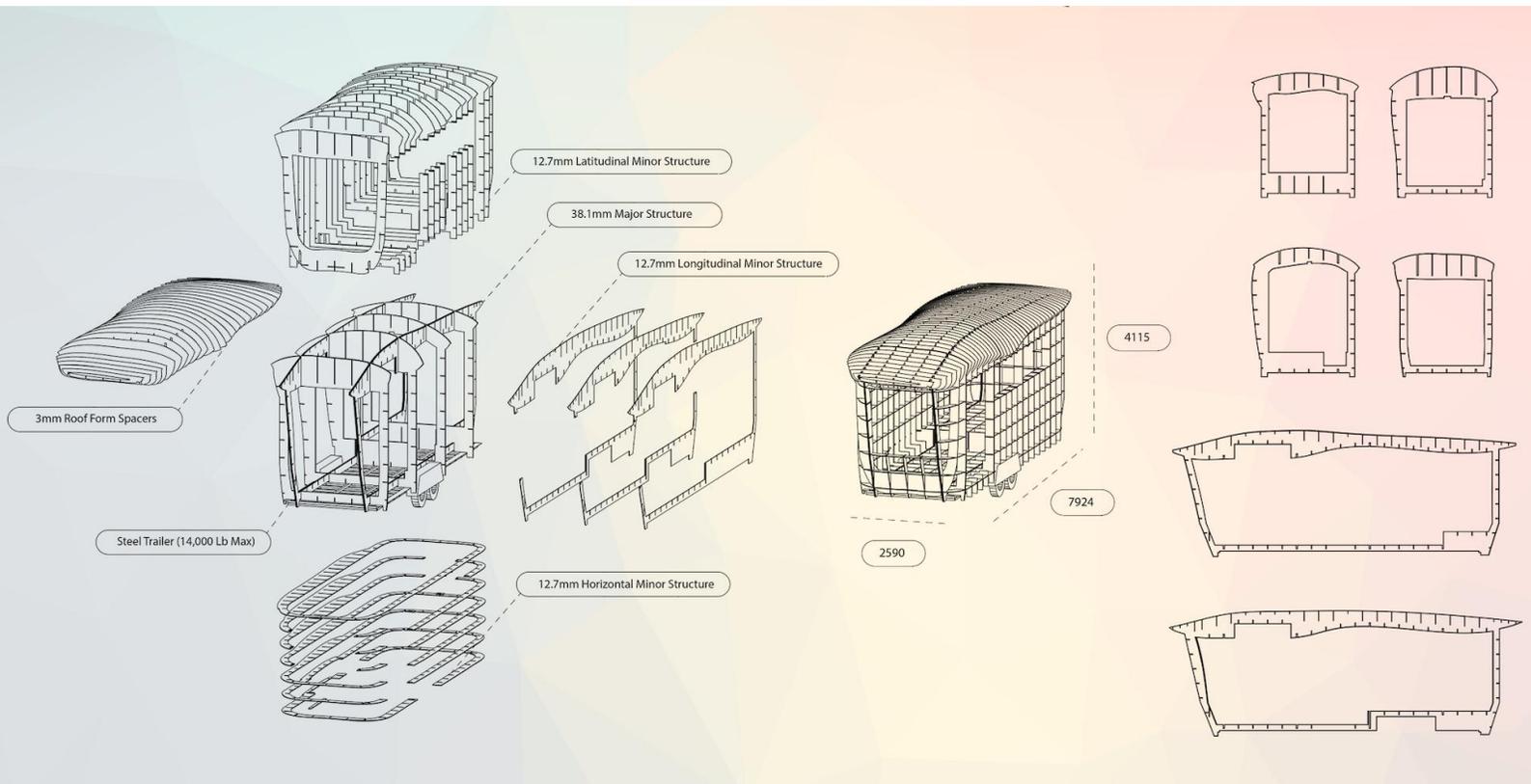


Fig 018 - Waffle grid subdivision.

This allowed for real time feedback from the modeling process for how to resolve the design and optimize it for construction. By making constant minor adjustments to the volume, a catalog of building products could be specified to both work with the intended design and also line up with the structure. It became clear that continuous unbroken sections of the waffle grid structure were important to maintain in strategic areas for

structural integrity. This constraint was then applied to every 5th waffle grid segment in the short section axis and every 4th segment in the long section axis. These continuous rings of plywood, running uninterrupted inside the walls, would serve as mounting points for window and door installation. I decided to thicken the plywood along the uninterrupted rings to three layers of ½” plywood while one layer would be used for all other waffle grid components. A logic was formed around how to emmesh with the triple thick plywood rings “the major structure” and the single layer plywood rings “the minor structure.”

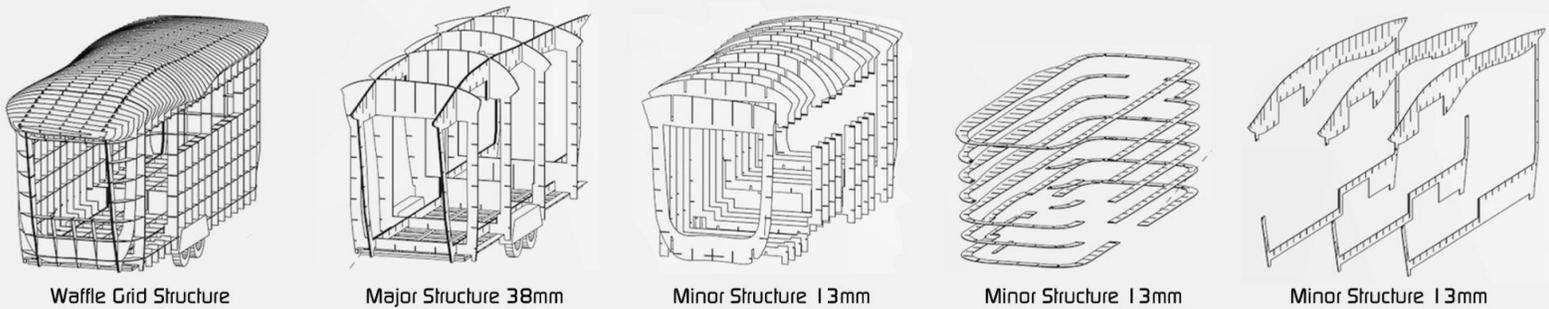


Fig 019 - Waffle grid subdivision.

Building envelope design could then be worked into the project as additional design parameters. A solar orientation was established as well as the decision to use mineral wool insulation. The malleability of the walls, rigged with the waffle grid segmentation script, allowed precise thickening and thinning of the building envelope according to need. The north wall of the structure, for instance, was thickened in the areas where it would receive the least amount of sunlight throughout the day. The ceiling could be

thickened according to the convection of rising hot air within the interior. The waffle grid was then amended to recess half of all composite members away from being in contact with the building skin, limiting the thermal bridging effect.

Working in this iterative manner of starting with complete freedom and then building in parameters for a functional design resulted in an increasingly highly resolved computer model that progressed as close as possible to a digital twin of the real world structure.

The degree of risk associated with this project was high due to its scale and lack of similar precedents to scrutinize. Most of the risk, however, lay in the virtualization of the design itself, being completely devoid of natural light, wind, heat, moisture, friction, and gravity. The hypothesis of how the designed components would coalesce needed to reach a tipping point of confidence required to proceed with sending the cut files to the machine.



Fig 020 - Offcuts left from CNC milling path.

Digital Craftsmanship

Digital craft is a complex concept, potentially an oxymoron, and has been explored by academics such as Neri Oxman who attempted to quantify the term in a 2007 paper.¹⁴

The method of work that it describes is only a decade or two old and lacks the maturity and diverse precedents required for a set of tenets around it to establish. The concept of digital craftsmanship is one I find captivating and it contains a thought exercise that I believe is rich for development. The tiny house project is one steeped in the interest of exploring the capability of digital design and digital workmanship, and in that, exploring the idea that there may be clearer explanations of digital craft.

To start, I have found the work of David Pye useful.¹⁵ As a designer, craftsperson, and academic, Pye dissects the ideas of workmanship, craftsmanship, and the role of design in a way that hones an understanding of each of these term's roles within various processes of bringing an object into being.

“If I must describe the meaning to the word craftsmanship, I shall say as a first approximation that it means simply workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on judgment, dexterity and care which the maker exercises as he works. The essential

¹⁴ 2007 Oxman N., in Workshop Proceedings for Ubicomp 2007: International Conference on Ubiquitous Computing. September; Innsbruck, Austria, 534-538

¹⁵ Pye, D., The nature and art of workmanship, UK: Cambridge University Press (1968).

idea is that the quality of the result is continually at risk during the process of making; and so I shall call this kind of workmanship ‘The workmanship of risk’: an uncouth phrase but at least descriptive.”

- *David Pye, 2. Workmanship of risk and the workmanship of certainty.*

In the context of the tiny house design-build, I believe ‘The workmanship of risk’ provides an important terminology in attempting to analyse the place of craftsmanship in this project. Pye contrasts ‘Workmanship of risk’ with ‘Workmanship of certainty’:

“With the workmanship of risk we may contrast the workmanship of certainty, always to be found in quantity production, and found in its purest state in full automation. In workmanship of this sort the quality of the result is exactly predetermined before a single salable thing is made.”

- *David Pye, 2. Workmanship of risk and the workmanship of certainty.*

Digital fabrication, I believe, would have warranted several more chapters in Pye’s “The Nature of Art and Workmanship” if he had lived past 1993 to observe the technology’s emergence. At face value, sending a file to a CNC machine represents a “purest state” of the workmanship of certainty. The automated router can execute cuts with 0.0001” accuracy. The machine does precisely what it is told to do, even if the instructions sent to it are erroneous.

The error in design is where I believe the new risk lies in digital craftsmanship. In all moments throughout history, there has never been a communication pathway between design and manufacturing which does not have to pass through a level of interpretation. Good workmanship consists of the interpretation of the intention of the design being followed or enhanced by the workman's skill.⁷ In digital design and fabrication, the designer embodies the workman in the sense that they must become accountable for risk when the design is transferred to real material. An extensive knowledge of the tool's capabilities as well as understanding materials' ability to receive this method of manipulation is required to achieve successful workmanship in this case.

An analogous practice may be a digital graphic artist rendering a final composition and then ultimately sending the document to be materialized on an inkjet printer. There is risk and skill in their craft as design ideas flow between pixels and sprayed ink particles on the page. But digital fabrication goes a step further than this in the added complexity of material processing as they are cut into or built upon. The properties of the material require knowledge and skill to digitally fabricate pieces from them, each feed stock possessing unique qualities that will alter the way digital fabrication must be executed.

This concept of how a digital workflow intensifies the risk and responsibility into the hands of the designer has been explored by James Stevens and Ralph Nelson in the term they have coined for the subject, 'Digital Vernacular'.

“The Digital Vernacular compresses and intensifies the process of design by integrating all aspects of design and construction into one entity. The architect can be wholly responsible for design and construction, reaching beyond the limitations of normative practice. The combination of designing and constructing is counter to the organizational structure set forth by many professional and trade organizations within the discipline of architecture. When an architect is directly involved in the making and implementation of a proposal, there is a shift of responsibility that is not currently recognized within the bounds of normative professional practice.”¹⁶

- *Digital Vernacular: Practice and Pedagogy, James Stevens & Ralph Nelson*

The points made by Stevens and Nelson in regards to the concentration of responsibility resounded with me in how I found the digital fabrication workflow starkly different than simply producing drawing sets to be passed off and interpreted. The direct line of communication with your tools, allows a very high degree of control over an entire project. This fosters a heightened sense of responsibility but also one of capability surrounding what is possible and achievable.

This heightened control authority over a project was not what I found most inspiring about this exercise. I am fascinated with the potential that lies in the world of opportunity that is opened for designs only possible to make in this way. Much of the complexity that

¹⁶ Stevens, James, and Ralph Nelson. “Digital Vernacular: Practice and Pedagogy.” In *Working out, Thinking WHILE Building: Papers from the 2014 Fall Conference*, 319–328. ACSA Press, 2014.

has been unrealistic or impossible to do prior to the advent of this process, has now become easily accessible. I am most inspired by a new language of architecture being ushered in by this capability of design and manufacturing.



Fig. 021 - Empty trailer bed placed at construction.

2.2 From Design to Implementation

Structure

As elegant as the notion sounded, to be able to send off the digital cut-file to the CNC machine and then just knock it together with a mallet, in reality was much messier. The process of beginning the construction phase of this project started with the acquisition of a trailer fabricated in Brampton and designed specifically for DIY tiny house construction. The trailer was measured for discrepancies between its plan and reality, and several were found that caused minor adjustments in the digital model of the tiny house.

I was operating on a \$6000 budget from a CUROP grant that was enough to cover the trailer cost as well as some of the building material. When selecting wood for milling I chose a half inch spruce plywood board due to its affordability and availability. I quickly became familiar with the strengths and weaknesses of various plywoods and their respective ability to be worked on a CNC machine. The spruce plywood I had chosen caused major challenges in trying to achieve accurate cuts due to anomalies in the material. The wood was filled with checks and knots that would prevent the vacuum table on the CNC machine to effectively hold them down. Pieces often needed to be screwed or clamped in place which was tedious and required cut path planning to avoid these areas. Further, the plywood was not flat and straight as I had expected it would be. Many boards were warped to the point that they were unusable by the CNC. I ended up plywood shopping as I would shop for fresh produce instead of ordering it by the lift; selecting only the highest quality items to use and leaving the problem pieces at the store. For certain structurally integral areas, or places that would be visible to the interior when finished, I selected G1S spruce plywood with maple as the finished veneer layer. This material was consistently flat and without major defects, allowing for a much easier cutting sequence on the CNC, but would have tripled the cost of the construction if used throughout. I would find it useful to gain a better understanding of the manufacturing process of plywood for future waffle grid projects as CNC optimized low cost plywood may be possible to specify on the manufacturing end.



Fig 022 - Collection of pieces fresh off the CNC to be organized and assembled.

The waffle grid was intended to utilize friction-fit wood joinery, with no need for glue or screws. In reality, glue and screws were used, in areas where I believed that it was required. One of these issues being the necessity to create continuous rings of plywood in three different axes of orientation. In order to create continuous rings, puzzle piece shaped wooden connections are used that are then screwed together with plate fasteners.



Fig 023 - Plate connections over puzzle piece joints.

Another area that required reinforcement was in the primary structural plywood rings that were three layers thick. The connecting joints were offset from each other between each of the three plywood layers, and glue and screws were used to increase shear and moment force resistance.



Fig 024 - Building up three layer primary structure with offset puzzle joints.



Fig 025 - Connecting continuous rings of plywood.

One of the major benefits of constructing in this way was that there was no need for leveling or squaring any of the connecting members, as there is in framing.

Coincidentally, the engineering department was building a tiny house of their own that had commenced a few months after my project was underway. I watched them hire a professional framer to lead construction and they went to great lengths to ensure their trailer was level before starting work. In contrast, I had no need to level my trailer (or ascertain any level of prior skill) to be able to assemble my network of pieces. The waffle grid only had one way it could go together, like a giant three dimensional jigsaw puzzle, with an instruction sheet for which piece goes where. The pieces pulled themselves into level and square orientations to each other. The final waffle grid structure looked precise as it did in the CAD program and was never further than 1/32" out of alignment.

While the structure appeared to be incredibly strong and held up well to shake testing, it proved to be nearly impossible to calculate effective structural diagrams for validating integrity. I was particularly concerned with a design oversight that I had made in the rear corner of the trailer that connected the sliding patio door and slanted office window. The triple thick plywood primary structure, reduced to a very thin moment as it transitioned from the rear window to the trailer. This, combined with numerous wood joint connections located in that area, made for a weak structure. The rear of the trailer was going to be the most susceptible to bumps in highway driving, and I was not confident it would withstand the repetitive stress. In a conversation with visiting lecturer Maria Mingallon, an accomplished structural engineer from ARUP, I questioned what the

process would entail to calculate an accurate analysis of the waffle grid's overall structural integrity. She offered to have her office take a look at the CAD model but unfortunately the complexity of the design, and additional amendments made to it post fabrication, meant it would be nearly impossible to analyse. I resolved the problem of the weak member by bolting a ¼" steel plate overtop of the area.

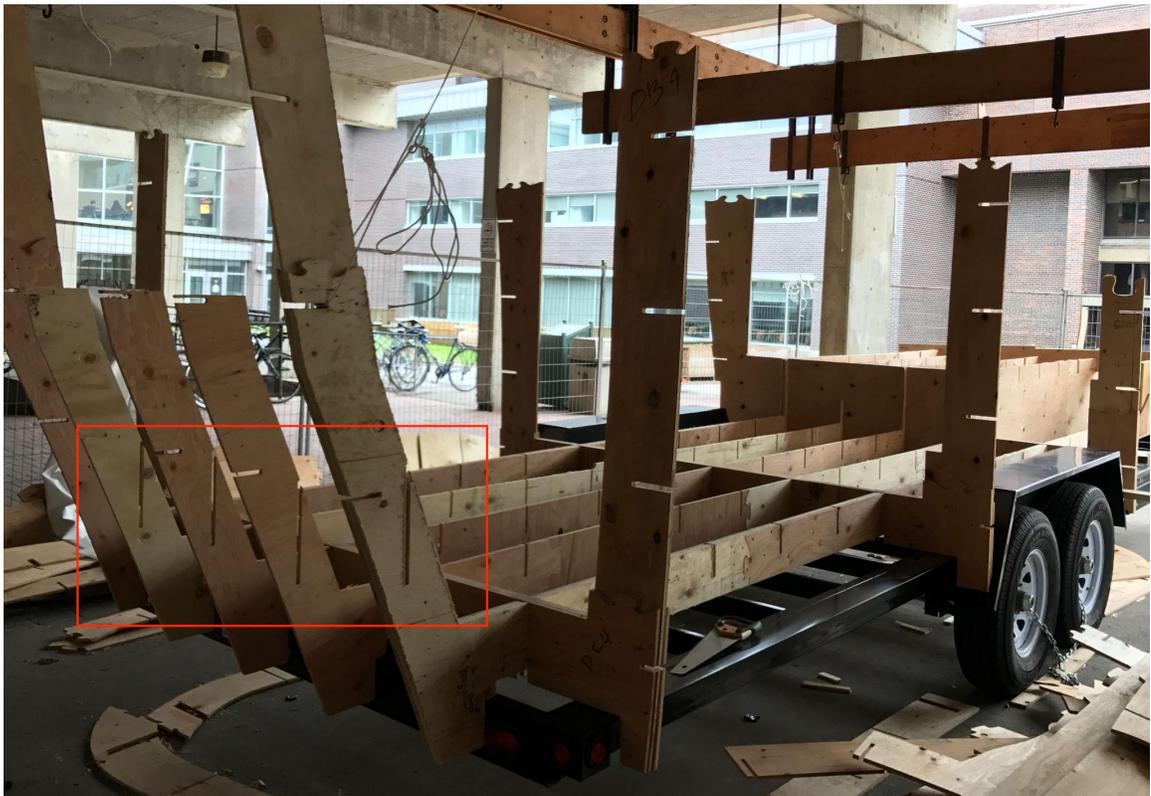


Fig 026 - Weak structure created by poor joint placement.



Fig 027 - Building envelope progression.

Building Envelope

The vast majority of architecture is built using straight lines and planar faces. In contrast, the vast majority of other industrial design involves the use of complex curvature in the interest of ergonomics, aerodynamics, structural integrity, or aesthetics. The difference lies in that architecture is typically comprised of many mass-manufactured generalized components. Digital fabrication offers the potential for mass customized manufacturing and in turn may increase architecture's access to designing with the level of case specificity found in industrial design. For this reason, I was intentional with the tiny house design to maximize complexity throughout all of its aspects and test the limitations of this approach.

I had explored various implementations of building skins that would be expressive of the complex geometries that the waffle grid was capable of defining. A cedar strip lamp was built as a prototype that could achieve expressive complex curvature, while also remaining low cost and easy to install.



Fig 028 - Cedar strip lamp facade study model.

The strategy for this lamp was to CNC cut various mounting brackets that could receive thin cedar strips and hold them in a defined shape without need for steam bending or glue lamination. I used this strategy for parts of the tiny house facade that contained the most accentuated free form curvature to it. For the rest of the facade I was inspired by Airstream trailers in their utilization of a reflective metal surface. The large metal

shaping dies that Airstream uses in production are not conducive to mass customization and are a tool better suited to mass production. I selected a 12" x 12" diamond shaped galvanized steel shingle that could wrap around soft curvature and create a 'scale like' aesthetic that could vary based on the curved structure it was affixed to.

Both of these jobs required fastening into the structure at a perpendicular angle. Due to the axis orientation of the three planes of waffle grid, every exterior mounting point option was end grain plywood. Fastening into endgrain is not best practice nor was it conducive to a long lasting structure. I used 45° angle screw connections throughout which made the process of attaching exterior finishing labour intensive and error prone. To keep the building super air tight, a second, vapour permeable air barrier was installed on the exterior. This product often needed to be patched when a screw did not enter properly. In addition to this challenging workflow, waffle grid members were offset to allow 1 ½" of board insulation to act as thermal breaks, which made it difficult to find the plywood that the screw needed to hit.

In the case of diamond steel shingles, used across three faces of the facade, a steel hat-track strapping was installed to allow sturdy perpendicular connection points that could hold the curves defined by the waffle grid. The hat track proved to be a good solution but it added unanticipated cost, complexity and weight to the project. In retrospect the diamond steel shingles were an off-the-shelf building component that I was requiring to respond to curves for which it was never designed. This disparity caused a

challenging and tedious assembly, yet the size and connection method of the shingles proved workable and ultimately the product succeeded in its installed function.



Fig 029 - Diamond steel shingle installation with steel hat-track strapping as mounting locations.

I had selected a vegetative roof for this tiny house for several reasons. I believed that the curvature achievable through the waffle grid would be best achieved by a rolling hill style vegetative roof. The plant matter would assist with longevity as it protects the waterproof membrane from UV light and damaging heavy precipitation. It would also be possible to purify greywater onsite by pumping water onto the roof and filtering through the plant's root system and soil. The natural mass would also assist with insulation in both cooling and heating seasons.¹⁷

The roof deck was approached in a slightly different strategy than the facade. Two layers of ¼" flexible plywood were built up with offset joints to each other. A PVC curb was added to the edge of the roof for drainage redirection. The entire surface was covered with a liquid adhered membrane which bonded to the wood and PVC, making a single impervious barrier. While this strategy was effective, the liquid applied membrane is a non-deconstructable building material that is a problematic fossil fuel product. It emitted toxic fumes when installing and would be problematic to dispose of due to its inability to break down. This product appeared to be the best option to achieve the desired shape and durability, however a rethink of the roof design would be needed to avoid using this product at scale.

The need for skilled labour presented itself in the forms of electrical work, plumbing, roofing, insulating, siding, and interior finishing. With the exception of electrical work, I

¹⁷ Wong, Michael. "Environmental Benefits of Green Roof." Hitchins Group Ltd., n.d.

did not have the budget to hire out trades to perform these tasks and learned to do it myself. Fellow students and friends that had developed an interest in the project started offering regular volunteer assistance and became integral in helping me distribute the high workload associated with enclosing the structure. Fifty different people ultimately laid hands on the project, most with no prior building experience, but with a shared passion to help see this project through. Without them, this project would have proved an insurmountable challenge for one person.

Interior

Fabrication of the waffle consisted of milling flat plywood to ultimately connect and form a three dimensional network. Three dimensional carving was an area of digital fabrication that I wanted to experiment with as well. Wood sculpture and ornamentation, while previously commonplace in buildings, has become cost prohibitive in most architecture and especially low cost housing. I believed there was room to bring carving back with digital fabrication as a method of value addition that outweighs its cost. I was inspired by two projects by the architecture firm PARTISANS; Grotto Sauna and Bar Raval. Both of these projects played with CNC sculpture in a way that I felt was in line with advancing a new aesthetic language of digital design.



Fig 030 - Grotto Sauna¹⁸ (left) and Bar Raval¹⁹ (right) by PARTISANS.

“The textures you see at Bar Raval are really just a mistake. We thought that making the Grotto [Sauna] was so difficult for these surfaces to be smooth and link up to each other. So we thought, if we add a texture, it would be easier. We were so wrong. We had to rewrite software to renormalize what was 90° to a line, and I know that sounds crazy, but you have to go into that kind of detail when you are working on architecture at this kind of boundary. When you are actually simulating the piece being cut.”²⁰

- Alex Josephson (Principal at PARTISANS)

¹⁸ “Partisans_GrottoSauna.Pdf,” accessed August 27, 2021, https://partisans.com/wp-content/uploads/2020/04/Partisans_GrottoSauna.pdf.

¹⁹ “Partisans_BarRaval.Pdf,” accessed August 27, 2021, https://partisans.com/wp-content/uploads/2020/04/Partisans_BarRaval.pdf.

²⁰ London Society of Architects LSA, *LSA PARTISANS - Alex Josephson*, accessed August 22, 2021, https://www.youtube.com/watch?v=HJ3MuR0aXfE&ab_channel=LondonSocietyofArchitectsLSA.

My process for integrating a digital sculpture became focused on the kitchen layout. I created many iterations of a sculpture that I believed enhanced the beauty, functionality, and ergonomics of the kitchen. The sculpture would add a level of tactility to the space, creating comfortable moments to rest a hand or lean against. The depth of the counters gradually trail off as the kitchen space blends into the living room. The two step elevation change down to the living room gave the opportunity for the counter to also serve as a closet. On the kitchen end of the counter, it was positioned at an optimal work surface height, but as it remained high past the steps down to the living room, it became a functional closet to hang clothes. This blending of space was important to the philosophy of adapting space to use rather than segregating space. The lack of hard corners also helped muddle perspective points in the eye of the occupant, making the space feel larger than it is.

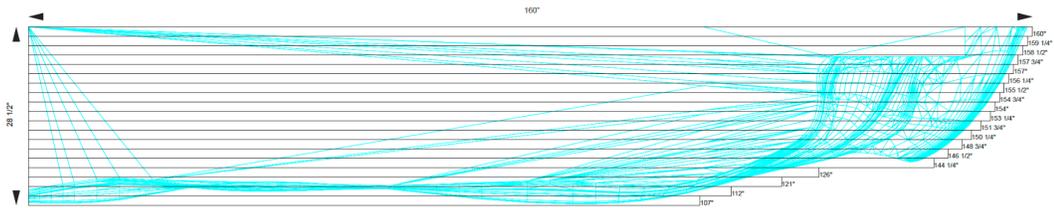


Fig 031 - Maple counter blending from kitchen to livingroom.

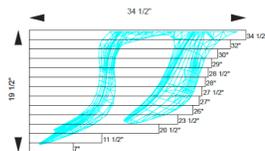
A galley kitchen layout was chosen and a three point movement efficiency plan was based around the sink, refrigerator, and oven. The counter sizing and spacing provided large amounts of workspace for multiple people to work comfortably in the space but also housed the building's mechanical systems and most of the storage in the tiny house. I found myself tailoring millimeter adjustments and creating mock cardboard versions of the kitchen layout to test comfort of use. Maple was chosen as the counter material due to availability in eastern Canada and it is a food safe species of wood. The density of this wood grain also lent itself well to high resolution sculpture on the CNC.

Fabrication was rich with challenges but most of them were centred around minimizing wood waste. It would have been straightforward to laminate a huge block of maple boards together and reduce it down to the form that was to be found in the digital model, but this would have turned the majority of the material into waste. Instead, I optimized the counter and cupboard doors into segmented pieces which required maple to be laminated in specific locations conducive to the panel shape.

A-1: Main Surface



A-2: Wave Section



Corner Section: 1 1/2" x 1 1/2" Maple Strips

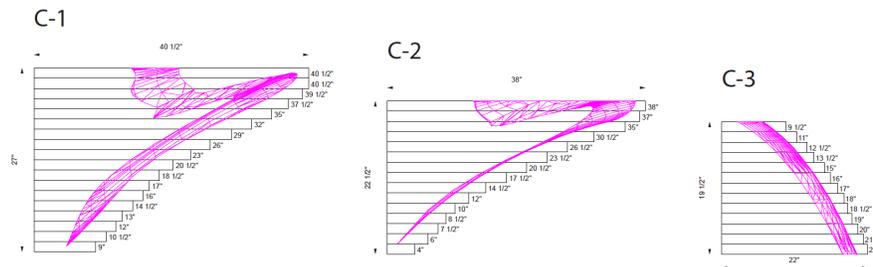


Fig 032 - Diagrams denoting wood lamination blanks and the respective real space location of each digital carving.

This added complexity within the lamination process but also in ensuring accurate alignment between the blank of material and the positioning of the CNC's milling path to produce the digital sculpture. Continuous wood grain and joint lines needed to flow from panel to panel without breaks or variation. Calibration of the CNC and placement of the piece was critical to ensure a high quality transition from digital space into real space.

The subsequent assembly of the counter top was challenging due to many pieces that had already been sculpted, requiring lamination to other carved pieces. Sanding was required to smooth out tool paths and glue lines. I believe that this finishing pass by hand is an important step in digital workmanship. Until the form has been found within the material, there was no possible way to predict the specific wood grain or the way light interacts with the shape of the real material. This sanding to finish step offers a last opportunity for fine tuning, to bring out the design intention of the piece.



Fig 033 - Challenging lamination of counter pieces after CNC milling.

2.3 Challenges and Limitations

In theory this design was intended to be easier to build than conventional timber framing but through the process of executing the construction, issues were encountered that exposed some limitations of this method.

Friction fitting in a non-conditioned environment.

Friction-fit joinery when it was used in practice caused significant issues. If built in an air conditioned facility, it would have been possible to cut dry plywood on the CNC, piece the structure together, and then expose the completed waffle grid to ambient humidity to naturally lock the structure together. However, I was building the waffle grid outdoors in the middle of Ottawa summer which reached 100% humidity at times. I had created a -0.005” offset in the wood joinery areas of the waffle grid to try and ensure a tight fit but not be too tight to piece together. My estimate was way off and a better knowledge of how this type of spruce plywood interacts with humidity would have been useful when determining the joint size. It was impossible for me to time correctly the dry plywood pieces coming off the CNC with installing them in their respective grid position before they swelled and outgrew their wood joinery tolerance. This was an avoidable problem that with better material knowledge or an interior building space would have alleviated. Each joint had to be hand widened which was tedious and sacrificed part of the machining precision that was important to this construction method.



*Fig 034 - Challenges with wood swelling and higher than anticipated friction.
Tedious clamping work done to force pieces into place.*

Waste.

Material waste, from CNC milling, proved to be substantial as cutsheet optimization was not fully considered in the design. The construction averaged 18% wood waste which is unacceptably high for a building method I believed demonstrated various environmental benefits. This wastage can be dramatically reduced through a parametric script added for material savings. A curve optimizing function can ensure that when a curve exists on a given piece, the negative of that same curve may be used elsewhere in the design without significant additional milling. Additionally, the bounding area of the 4' x 8' sheet of plywood must be included as an additional constraint and force straight lines in the design along the factory-made edges of plywood material. The entire shape of the waffle

grid would change but likely not by significant enough amounts to lose the intent of the original design. Instead of claiming that the waffle grid is able to conform to any arbitrary geometry and rationalize it in a structural system, a waste-reducing waffle grid design would achieve a structure that is close to any arbitrary geometry, bound by the logic of a waste reduction algorithm.



Fig 035 - Unreasonably high levels of off-cut wastage.

Insulation of the Waffle Grid.

The mineral wool insulation that was selected for the building was both labour intensive to install and created a dusty and itchy workplace environment. To build at scale, the mineral wool insulation combined with waffle grid construction would need to be

reconsidered. A cellulose-based insulation was not chosen due to concerns around lifespan, moisture susceptibility, settling, potential for mould growth, and high combustibility. Spray foam was never considered due to its severe environmental impact during production and installation. Spray foam also contracts over time and undergoes a thermal shift and does not allow for deconstruction of the building at end of life. If a spray foam product were to be developed that addressed these problems, its application method would be highly compelling in a waffle grid structure.



Fig 036 - Messy and challenging installation of mineral wool.

Fasteners and Edge.

Finally, the most significant limitation of the waffle grid was the difficulty attaching conventional building materials to the structure. The edge of the plywood structure is what served to define the bounds of the complex desired geometry, yet this was the end

grain of the plywood which cannot receive structural fasteners.. Attaching the building's internal vapour barrier, interior finishing panels, exterior waterproof membrane, and exterior siding, proved to be extremely difficult to attach with precision. A clip system which connects to the intersecting points of the waffle grid would be helpful to create a more sturdy connection at the strongest point of the structure. This clip system would add a layer of complexity and cost to the construction which would need to be considered in its fabrication and material selection. It would also represent a potential thermal bridge in the building envelope and should be accounted for in its contribution to energy loss.



Fig 037 - Potential fiberglass clip application (Cascadia Clips). This clip system would need to be fabricated in order to attach to the building in line with the plywood waffle grid instead of perpendicular to the structure as depicted.

2.4 Potential Evolutions From Built Work

Learning from the process of building this project full scale, a major rethink of how this project could be further iterated, will help evolve the digital workflow methodology.

Firstly, a reconsidered material other than plywood could reduce material wastage from the 4' x 8' sheet constraint, problematic preserving additives and adhesives, and the need for a clip system for attaching interior and exterior finishing.

Potential Alternative Material Selection:

- CLT or Micro-CLT: Using a cross laminated timber material would alleviate most problems created by the end grain of plywood used in the tiny house. By exposing the cross grain to the edge of the structure, building components could be attached at any point around the edges of the Waffle Grid structure. The increased strength of CLT would also allow for a widening of grid spacing in the Waffle Grid. This could allow for a simpler installation of insulation and a reduction in thermal bridging. The problems that could arise from this method exist in complexity to reduce material wastage. Similar to plywood, a constraining algorithm would be needed to prevent the cut piece inventory from causing excess wood wastage due to curved designs. The problem of adhesives still exists with CLT unless a dowel-connected product is used. The latter would involve an additional constraint to the design in ensuring structural integrity and appropriate quantity of dowel locations are not adversely affected.

- Metal: A steel or aluminum construction would likely save weight and offer an even more precise assembly of digitally fabricated pieces. The off-cuts from sheet metal can be recycled more easily than wood, especially if the off-cuts are kept uncontaminated. The carbon footprint would be increased both in production of sheet metal and in recycling of offcuts when compared to the production of wood products. Additionally, the carbon sequestration benefit of utilizing a wood product would be lost. Thermal bridging would pose a more significant problem than with a wood design and would need to be carefully considered in the complete building envelope design.
- Cellulose Fibreboard: Emerging technologies that can produce microfibrillated cellulose building products pose a compelling alternative to plywood for a waffle grid system. Similarly to making paper, plant fibre (recycled or new) can be pulped and pressed to form sheet material which rivals the performance of plywood.²¹ The material can be CNC milled and offcuts can simply be shredded and pulped again for a low energy recycling solution. The emerging nature of this technology leaves some critical questions unanswered such as its life cycle performance, susceptibility to moisture and mould, combustibility, structural integrity, and energy usage at scale. If these questions are satisfied, the material would allow for edge fastening at all points in a Waffle Grid structure, eliminated the need for a design constraining material wastage algorithm due to the ease of

²¹ Bird, Jesse. "Building the Paper Economy: Finding Spatial and Cultural Agency through Recycled Paper." Thesis, Carleton University, 2020.

recycling, and offer a more compelling environmental footprint as there are no adhesives used to bind the material together.

Platform construction:

A further evolution that would be made if this project were to be reattempted would be the building platform. This experimental design-build was conducted in the typology of a tiny house, built on a 24' twin axle steel trailer. This was selected due to the precedent of other tiny houses succeeding on this platform and the perceived ease of mobility. The project could be relocated from the university and be easily transported across the country without a specialized drivers licence. Ultimately, the project would settle into a permanent location where it could be occupied and connected to water and power.

Weight:

Firstly, the weight of the project was much higher than anticipated as design changes were made to increase building performance and quality of finishes. Heavy elements like the motorized furniture, solid maple countertops, exterior metal strapping and mineral wool insulation were selected as the project was already underway and contributed to the maximum weight capacity of the trailer being arrived at sooner than expected. The balance scale between weight savings or building improvement posed an additional unaccounted for constraint that ran counter to the initial thesis of exploring the best small living space that a completely digital workflow can achieve.

Weight Distribution:

Secondly, the difficulty to run accurate structural engineering calculations left uncertainty regarding its roadworthiness. The construction is top heavy and never was designed to be a campervan that would roam around the continent. It was designed with the intention to be semi permanent, technically allowing movement but with a frequency of once every five to ten years if need be. The hydronic radiant floor heating system works best when its energy collection system is optimized to a particular site. The conventional flushing toilet requires conventional plumbing and is not designed to be mobile. The green roof also cannot be in place during transportation and needs to be replanted on arrival to a long-term location. For these reasons the trailer platform was not well suited to the structure's needs and could have been simplified.



Fig 038 - Platform container foundation allowing for infrequent mobility to a long term site.

Abandoning the trailer platform in favour of a shipping container platform would have allowed the design to be less constrained by weight and would have allowed for design simplifications to be made through eliminating the wheel arch cutouts which caused problematic thermal bridging. Building on a flat steel platform with universal shipping container connections would have allowed for a professional driver to relocate the structure when needed. While this is more costly than self hauling, cost associated would be offset by the reduction of cost in the trailer bed and eliminate the need to register the trailer.

Chapter 3: The Affordable High Performance Building Paradox.

3.1 Setting the Stage: Options and Trade-Offs.

According to Natural Resources Canada, the greatest consumption of energy in Canadian homes is dedicated to space heating and averages 62% of the total energy use in a building.²² The tiny house project employs an experimental solar thermal heating system which is designed to alleviate this largest energy usage with a low cost sustainable system. Hydronic solar thermal is the industry standard for collecting heat from the sun but a new photovoltaic solar thermal system recently attained the fundamentals to be both cost competitive and energy sufficient.²³ The two competing heating systems differ significantly in their approach to energy collection:

- Hydronic Solar Thermal: Energy collected as heat by capturing solar radiation into a liquid. This can be accomplished through the use of evacuated glass tubes which are warmed via the absorption of infrared and visible light waves. The thermal energy is captured and transferred to the interior space via a heat exchanger. For climates that experience freezing seasonal temperatures, a glycol mixture must be used in the heat collection fluid.

²² Government of Canada, Natural Resources Canada. "Energy Use in the Residential Sector." Energy Use in Canada: Trends Publications | Natural Resources Canada, November 4, 2016. <https://oee.nrcan.gc.ca/publications/statistics/trends/2017/residential.cfm#L3>.

²³ Norwood, Zack, Emil Nyholm, Todd Otanicar, and Filip Johnsson. "A Geospatial Comparison of Distributed Solar Heat and Power in Europe and the US." *PLoS ONE* 9, no. 12 (2014). <https://doi.org/10.1371/journal.pone.0112442>.

- Photovoltaic Solar Thermal: Collecting electricity from photons impacting semiconductors which then convert electricity to thermal energy via a resistive coil. The installed panels can be monocrystalline, polycrystalline, or thin film panels but also allow freedom to diversify energy collection based on site conditions. Wind and hydro generators can also be integrated with this system. No batteries or transformers are required as electricity generated is immediately transferred into heat and stored within an inboard water tank for space heating use. This water is then pumped throughout a radiant floor heating system.

From an efficiency standpoint, hydronic beats photovoltaic as a system because there are fewer conversions of energy. The balancing factor is the cost of installation and maintenance.

In northern regions, hydronic solar thermal involves additional complexity when compared to milder climates due to wide temperature fluctuations throughout the year. The exterior to interior plumbing system required involves a complex mechanical circulatory system and requires specific detailing to account for building envelope punctures. Both indoor and outdoor plumbing loops must exchange heat with each other and account for pressure fluctuations based on expansion and contraction. This is expensive to install and requires skilled professionals with specialized parts to maintain. Evacuated glass tubes are susceptible to hail or debris damage and their vacuum seals fail over time. Cost of parts and labour required to update or maintain a system is high.

In contrast, a photovoltaic system involves a comparatively simple installation. A solar array is wired directly into an indoor insulated hot water tank and is heated via a resistive coil. The hot water tank acts as a thermal battery, retaining energy to be utilized overnight or during cloudier days. The more the sun shines, the hotter the water gets and there is no need for electric batteries or transformers. These components are widely available from local hardware stores around the world and require little expertise to install. The initial cost is significantly lower and the system can be maintained without specialized labour and uses readily available replacement parts.

The tipping point between the systems took place in the last decade when the hyper competitive market of photovoltaics, and scale of efficiency in their production, passed cost savings to the end user.²⁴ The photovoltaics sector has been following a Moore's Law progression of price reduction. While there have been very few precedents of this system being deployed, it was selected for the prototypical tiny house due to its potential as a low cost heating source for affordable housing. An efficient building envelope and specific solar orientation is required to maximize passive heating and reduce the load placed on the active heating system. If successful, this system could potentially be more cost competitive and desirable than natural gas or other conventional heating methods in new builds and help accelerate our society's transition to sustainable energy generation.

²⁴ Mollick, Atiqur Rahman. "Solar PV vs Solar THERMAL Everything You Need To Know(2021)." EcoWowLife, February 4, 2021.



LUNOS HRV System

The LUNOS e2 is a heat recovery ventilator which works in pairs to mechanically refresh the interior air. While one unit exhausts, the other intakes. Every 45 seconds, the cycle is reversed. Each unit contains a ceramic block to recover heat. The units also relieve the need for complicated ventilation ductwork.



Take Your Pick

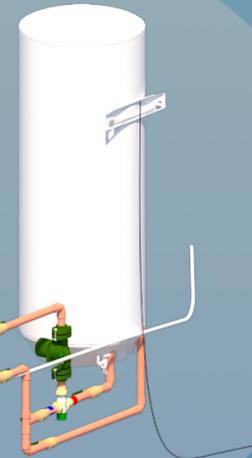
One or multiple renewable energy systems may be implemented to manage the thermal load. These systems should be chosen on a site specific basis.

In a northern Canadian climate, heating accounts for over 70% of energy consumption annually. The electric solar-thermal system will demonstrate a system to generate sustainable and affordable heat with a system that is cheap to install and easy to maintain.

The home can be heated from photovoltaics, a micro wind turbine or a micro hydro electric generator. The system delivers electricity directly to a heating element which supplies the hydronic underfloor heating. A storage tank acts as a thermal battery, retaining hot water to be utilized overnight. This method is more economical and requires less maintenance when compared to hydronic solar-thermal. This system requires an efficient building envelope and proper solar orientation to maximize passive heating and reduce the load on the low energy heating system.

DC Thermal Battery

The thermal battery is designed to offer the easiest to manage renewable energy powered heating system. The direct current heating elements are fed directly by wind, water, or solar systems plugged into the tank. There are no transformers or electric batteries to maintain. Energy is stored as heat and pumped throughout the radiant pipes when needed.



Active Mechanical Systems

Fig 039 - Active thermal management.

3.2 Design and Implementation.

Researching the correct sizing of this experimental system involved collaboration with several experts who specialize areas relevant to the variables involved. There were four critical interdependent components to be balanced.

1. Energy capture, which determined the size of the solar array.
2. Heat storage, sizing and insulating the hot water tank used for space heating.
3. Heat distribution, designing and optimizing the heating zones of the house.
4. Building envelope science, reducing loss of heat energy inside the conditioned space.

It was difficult to proceed with one of these components without a developed understanding of how that decision would impact the other co-dependent variables. Size of the solar array would increase energy capture but the sizing of thermal storage capacity was needed in order to make an informed decision. Thermal storage capacity was dependent on the heat loss potential of the building envelope weighted against passive solar heating potential. The heat distribution system was the only variable in this design that had a clear best practice installation that would remain valid regardless of the other variables.

I collaborated with a specialist from Uponor, Jerry Leyte, to design a hydronic radiant heating system that would most efficiently warm the space. His recommendation for

system sizing could be simplified by the understanding that the largest system was the best one. The example he used was that a small cast iron radiator, found in the corner of rooms in old buildings, needs to run water at near boiling temperatures to heat the entire room. A best case scenario radiator would be one that was distributed over all surfaces in the room and would only need to run water just above desired room temperature to have the same effect. The energy efficiency of a large system versus a smaller system would remain valid regardless of the source of energy supplying the heat. For this reason, the decision was made to include radiant heating zones under the floor and behind most walls. Heating behind appliances and behind furniture were advised to be ineffective areas for distribution, and because heat rises, distributing heat behind the ceiling would be unnecessary. Wherever there was open floor and open wall space, PEX tubing was installed there and connected to a manifold in the tiny house's mechanical systems area.

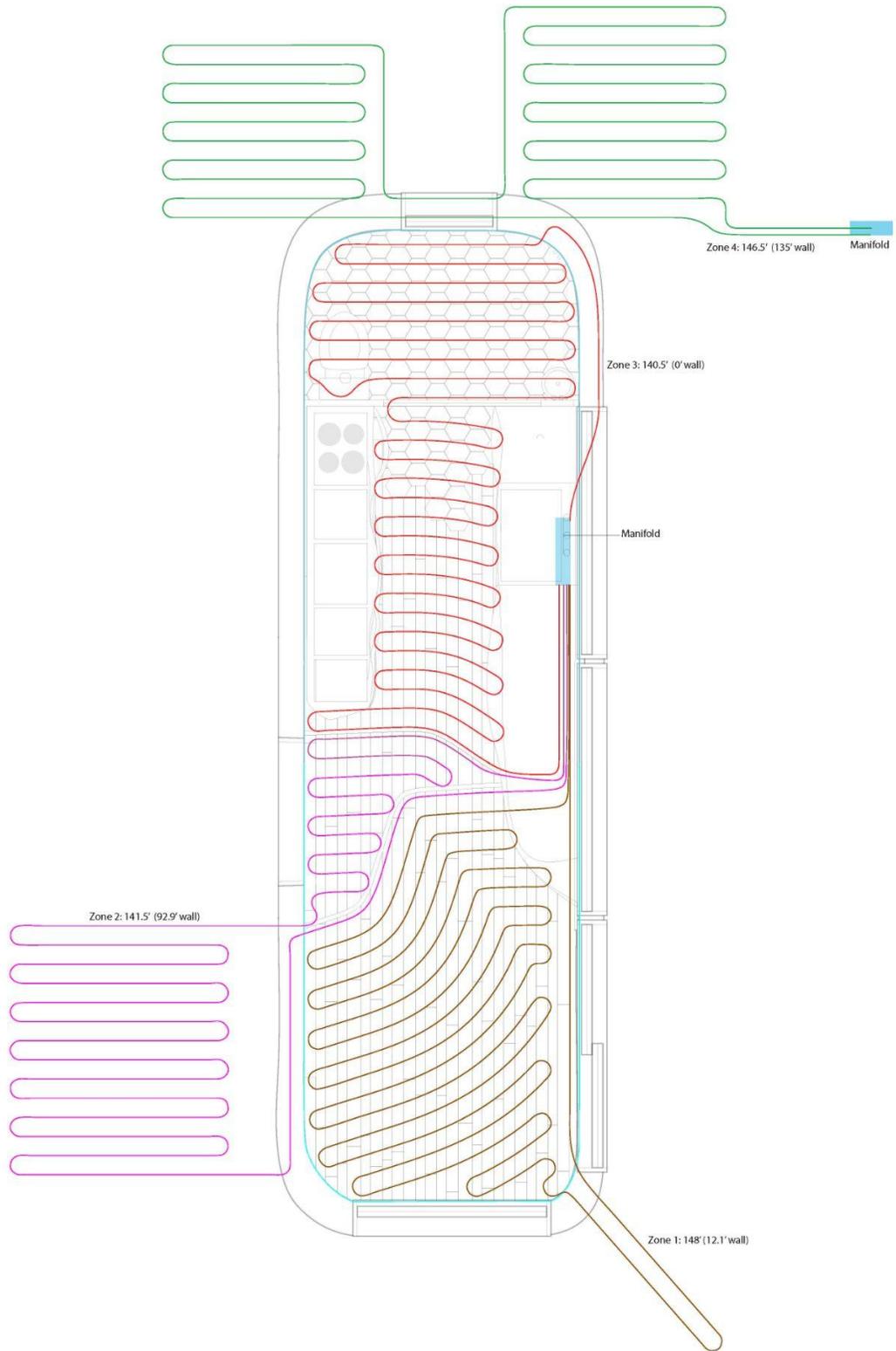


Fig 040 - Radiant heating zones.

The optimization was added into the digital workflow of the tiny house by milling tracks for PEX tubing directly into the subfloor. This addition allowed for appropriate spacing that could be programmed as one additional parametric geometry constraint added to the CAD model. The installation was made easy as all elements had been preprogrammed to fit.



Fig 041 - Optimized radiant heating tracks milled into subfloor.

Building Envelope - Digital Fabrication as Performance

The waffle grid structural system allowed for the building envelope to blend wall into roof into floor, seamlessly. Joints and junctions are the most vulnerable places in buildings for air and vapour leakage, affecting building longevity and energy performance. By making it a seamless condition, the tiny house assembly also tied to minimize building punctures by utilizes air admittance valves in its plumbing. A thermally broken mineral wool insulation was chosen due to the materials longevity and lower embodied energy compared to foam insulation. The tiny house could have benefited from utilizing a carbon capture insulation. Products like hemp or reclaimed cellulose fibre have vulnerability to mould, moisture and settling and ultimately were not selected.

Building Envelope - Green Roof

This particular exterior material assembly was chosen for various reasons. An extensive vegetative roof allowed for additional insulate value whilst providing a connection to the life around the building site. Tiny houses are a placeless architecture and the response to nature, helps connect this home to any landscape. The roof also is watered by building grey water which serves to help filter and utilize this waste product.

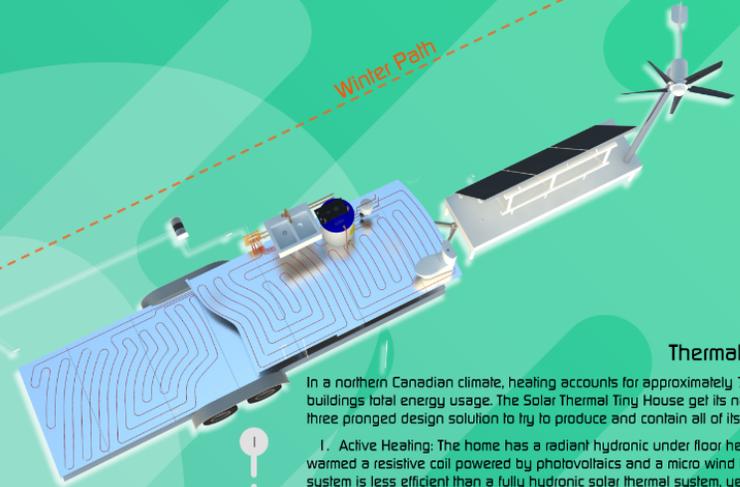


- Sedum Vegetative Roof
- Irrigation Mat
- Alsac RS Waterproof Membrane
- Cedar Strip Facade
- Galvanized Steel Shingle
- Aluminum Frame
- Triple Glaze, Argon Fill, Low E Coating

- PVC Window Frame
- Roxul Batt Insulation 203mm
- Roxul Board Insulation 38mm
- Galvanized Steel Formable Half Channel
- G15 Plywood 13mm
- Reflective Vapour Barrier
- SopraStick VP Waterproof Membrane

Building Envelope - Facade

The hybrid of galvanized steel shingles and cedar strip facade were chosen to express the design possible when utilizing digital fabrication. They respond to the varying degrees of curvature found throughout this building. By adjusting like fish scales and bending to shape across a wide regime of applications, the materials express a performative both artistically and functionally. The shingles are reflective to help reflect excess heat in the summer, while the cedar strips are purely expressive of computer generated form.



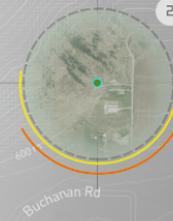
Thermal Delight

In a northern Canadian climate, heating accounts for approximately 70% of a buildings total energy usage. The Solar Thermal Tiny House get its name from a three pronged design solution to try to produce and contain all of its own heat.

1. Active Heating: The home has a radiant hydronic under floor heating system warmed a resistive coil powered by photovoltaics and a micro wind turbine. This system is less efficient than a fully hydronic solar thermal system, yet it is much cheaper and easier to maintain over time.

2. Passive Heating: Solar orientation is key to the heat management as window openings are positioned to take advantage of winter sun paths. The north wall thickens and has a higher r-value based on where it is shaded.

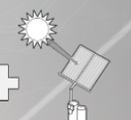
3. Building Envelope: A high performing building envelope allows a low power heating strategy to function as the primary system. The building is super airtight, utilizes a twinned Lunos heat recovery ventilation system, and uses a thermally broken wall assembly.



Tiny House Platform¹



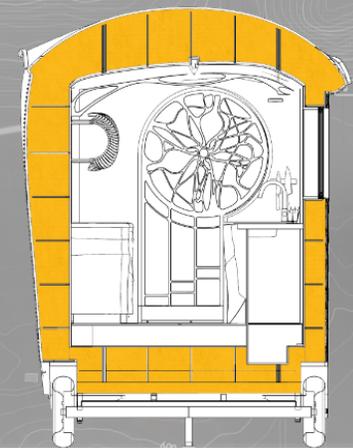
Digital Fabrication²



PV Solar Thermal³



Partis Diagram



Section of Solar Thermal Tiny House

Fig 042 - Building envelope and active heat management system

3.3 Passive Heating and High Performance Building Envelope.

To account for the lower efficiency of a photovoltaic solar thermal heating source, further measures are needed to be taken in the design of the tiny house to ensure that this active heating system could meet all heating requirements throughout a Canadian winter.

Passive heating strategies and high performance building envelope design work in tandem to ensure that the active heating system is minimally relied upon.

Tiny houses, by nature, are placeless forms of architecture. Their mobility creates uncertainty when attempting to optimize for a site. Accounting for this, the building envelope was designed for a particular latitude between 49°N and 54°N and a solar orientation which constrains the parking positioning of the structure on site. Glazing is placed predominantly to the southern orientation and the northern wall contains roughly twice the insulation of other walls in the tiny house.

The building envelope reduces heat flow by mitigating convection, conduction, and radiation with continuous and well connected barriers for each. The tiny house follows passive house building practice and has the potential to become certified as a passive house upon deployment and testing.

3.3.1 *Conduction*

Mineral wool batt was chosen as the primary insulator for various reasons. Compared to other mass market insulations like spray foam and fibreglass, mineral wool offers a substantially lower net carbon footprint in spite of its high embodied energy. Mineral wool does not degrade over time and can be easily repurposed post deconstruction. Mineral wool board is used as a thermal break installed over 50% of the structure.

3.3.2 *Convection*

The waffle grid structural system allowed for the building envelope to blend wall into roof into floor, seamlessly. Joints and junctions are the most vulnerable places in buildings for air and vapour leakage, affecting building longevity and energy performance. By making a curving building envelope, rather than a series of right angles, the tiny house benefited from easier to execute air and vapour barrier transitions. The tiny house assembly also minimized building punctures by utilizing air admittance valves in its plumbing, merging range hood exhaust with the bathroom fan, and limiting all places for air leakage.

A LUNOS product was chosen as a heat recovery ventilator which works in pairs to mechanically exchange the interior air. While one unit exhausts, the other intakes. Every 45 seconds, the cycle is reversed. Each unit contains a ceramic block to recover heat. The units working at opposite ends of the tiny house relieving the need for complicated ventilation ductwork.²⁵

²⁵ LunosCanada. Accessed August 25, 2021. <https://lunoscanada.com/>.

3.3.3 Radiation

The vapour barrier used to seal convection is also lined with a reflective coating to prevent radiant heat loss. This barrier is placed inboard in the wall assembly on the floors, ceiling, and walls. It is continuous and sealed with reflective aluminum tape.

Wherever possible, a ½” gap is left between the radiant barrier and the back side of the interior finishing.



Fig 043 - Interior view of the kitchen layout.

Chapter 4: Small Space Living.

4.1 The Recipe for Functional Compact Organization

In order to develop a compelling small space I broke the problem into three areas of focus: Spatial organization, adaptability of function, and material expression. The organization of space was informed by an attempt to understand what the ideal ergonomics would be in a given layout of a tiny house trailer platform, given the waffle grid's potential. Multipurpose furniture was optimized and often required the creation of

bespoke pieces in order to achieve functional optimization. The interior design composition was tailored to not only enhance the overall quality of the project, but speak to it's reason for being, communicating in the same language of digital design that the rest of the project evolved. I tried to capture as many moments as possible in the design of this project that would be noteworthy points of interest and features that have not typically been used in architecture. This was to run contrary to what I believe is a standard mode of typical low cost housing design: reduction and simplification.

4.2 Spatial Organization

“When designing a small dwelling, function and perception of the space must be addressed. Without this combination, the design will not be successful. A boat, for example, is an extremely efficient and functional small space, but few people would want to reside on a boat for a long period of time.”²⁶

- Friedman, Avi. *Narrow Houses : New Directions in Efficient Design*, 205.

Regarding spatial perception of the tiny house I prioritized the moment of ingress. Within seconds, a person will consciously or subconsciously make several critical assumptions about a space. Does it feel spacious or cramped? Is it light or dark? Is the space inviting? Would I want to spend a night here?

²⁶ Friedman, Avi. *Narrow Houses : New Directions in Efficient Design*, 205, Princeton Architectural Press, 2010. ProQuest Ebook Central,

Because the tiny house had no predetermined location for its site, the main entry was unconstrained by other factors. It is common in tiny house layouts to enter from the back bumper of the trailer, presenting a tunnel like house and focusing the forward vision on the interior layout at the opposite end. I chose to place the entrance on the north broad side of the tiny house directly over the wheel well. When entering the home, the viewer's forward vision would be directed at the expansive southern glazing and the outdoor view. The viewer's peripheral vision is directed to the longer ends of the interior, encouraging a sense of spaciousness. This served to maximize positive sensations within the first five seconds of introduction to the home and soften the transition of moving from outdoors to indoors by focusing attention on the exterior views first.

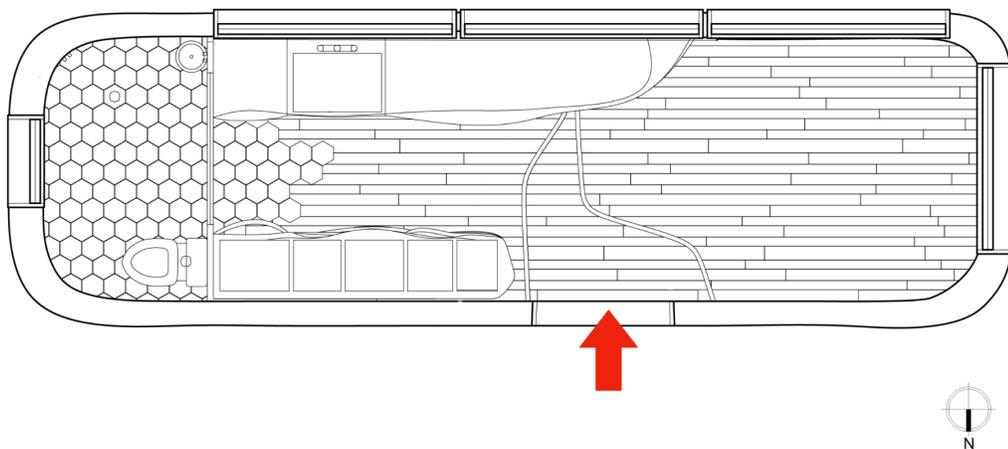


Fig 044 - Side entry with view out expansive glass.

Additionally, I wanted to mark the entry to the home as an occasion. Like scissor doors which enhance the occasion of entering a Lamborghini, I installed a gull wing door, hinged at the top, to open outwards, theatrically welcoming people into the house. This

was a shameless gimmick to stack the deck in the tiny house's favour when provoking an emotional response from a first time entrant. It is a gimmick designed to be functional as well. The door becomes its own awning, both welcoming a person inside the threshold while also sheltering them from the elements. The door is electrically actuated, opening via key fob or button press. Because it is a bespoke door, it is made to be a moving section of highly insulated wall and blends together with the facade and interior when closed. The door is complicated and unnecessary, but it is an example of where cost savings in square footage reduction, leave room in a budget for play and theatrics, if so desired.



Fig 045 - Gull wing door installation.

Continuing on the path indoors, I wanted the sensation of spaciousness and openness to linger long after the moment of ingress and a major factor in creating this sensation was exposure to natural light. For thermal performance reasons, I needed to limit glazing to be under 30% of the building envelope, and also capture maximal passive heat in the winter months. Horizontal ribbon windows were used on the south facade that transitioned into an oversized sliding patio door. Windows are also placed at the front and back ends of the trailer ensuring that natural light is brought into the space from sunrise to sunset.



Fig 046 - Horizontal south facing ribbon windows.

The interior space of the tiny house is segmented into three primary zones: bathroom, kitchen, and living room/bedroom. In the design process I intentionally limited interior partitions as they obstruct lines of sight, segregate space, and block natural light. There is only one interior partition which separates the bathroom from the rest of the living space but even this was designed to be flexible. The bathroom is arranged in a way that sightlines to the toilet and shower are obstructed when the bathroom door is left open, but the view to the window is left clear. A goal of the feature door installed in this partition was for the bathroom to feel like a natural extension of the house. When the door is closed for privacy, frosted glass within the feature door still allows eastern light to filter throughout the living space.

The living space was designed to be adapted to use and blend together. The kitchen is separated from the living room through an elevation change which serves to denote a spatial shift comparable with changing rooms. This, paired with an undulating high ceiling creates an unusual environment that plays with your perspectives as you move throughout the home. The dynamism was made possible by the flexibility of the waffle grid system to help define complex surfaces. The most significant mechanical element of adaptable spatial shift occurs in the living room as it converts, via an elevator bed, to the bedroom.



Fig 047 - Looking forward and backward across the elevation change that denotes livingroom and kitchen.

Lastly, all appliances and furniture pieces were chosen to be placed below shoulder height. The importance of the interior volume to be widened at eye level wherever possible was paramount and resulted in decisions such as choosing a drawer style refrigerator installation instead of a full size unit. A hideaway set of chairs and a table emerge from pockets placed around kitchen cupboards. Being strategic and diligent about designing for all permutations of potential sightlines from the occupant, helped enforce a design strategy that would help maximize the perception of spatial volume.

4.3 Multipurpose Furniture

The implementation of multipurpose furniture is far from a new concept. The differentiation that I wanted to make here was that the selected multipurpose furniture elements truly needed to be compromise free. This would be accomplished by preserving the scale, functionality, and quality of pleasurable interior design. The execution of this would be at the core of addressing the initial intention of the project: to compete with a bachelor condo three times its size.

To further explain this approach to compromise free compact design, I will first start with examples of *preservation of scale*. In other compact spaces, such as RV campers, DIY tiny houses, or sail boats, it is all too common to expect an occupant to cram into a tiny shower, wash their dishes in a tiny sink, and cook on a tiny stove. This is the exact opposite of what I wanted occupants of this house to encounter. The shower needed to feel as large or larger than a typical bachelor condo, the sink would be full sized with a conventional faucet, and the cooking experience would be pleasurable with ample space for food preparation.

Respectively, the shower was designed to take over the entire bathroom area as a wet-room instead of a shower stall. This meant that the available space to shower in was twice the size of a prefabricated shower unit typically found in a condo or a house. The wet room is tiled with tactile reclaimed teak, cut apart and repurposed from old Indonesian buildings. The tile work continued into the main kitchen area before

transitioning to hardwood flooring in order to blend the delineation mark between shower area and living space. When the bathroom door was closed, it would act as the shower curtain and provide privacy.

The kitchen sink is dual farmhouse style and is on the larger end of sinks that are typically found in housing of any kind. It is integrated into the digitally sculpted maple countertop and is central to connecting the occupant to the experience of cooking in a full sized kitchen. The placement is central opposite a large horizontal window to encourage captured attention by outdoor views during menial day-to-day tasks. This combined with high-end cooking appliances, made affordable through cost savings in reduced material usage in the structure, are geared to elevate the kitchen experience above that of a standard bachelor condo.

Functionality is a second metric of compromise-free compact living that overlaps with preservation of scale but extends beyond it in certain cases. A specific example of this is in the installation of a motorized elevator bed. The choice to install this bespoke furniture element was chosen after a wide review of existing precedents. It is most common in tiny houses to include a loft bed due to the ability to build up to 13' of interior ceiling height while still being road-legal. The loft, however, requires compromise in the form of making the bed while crouched over and navigating a ladder or small staircase in the dark. It also left segregated space that was underutilized throughout most of the day. Beds that convert are typically designed in the form of sofa beds or Murphy beds. Neither

of these systems offer seamless transitions and force a tedious exercise in strapping down bed sheets or storing the bedding separately from the mattress. None of these precedents achieved a comparison with a bachelor condo experience.



Fig 048 - Elevator bed descends and retracts automatically from the ceiling.

When exploring elevator beds, a counter weighted non-motorized system was first prototyped but scrapped due to the complexity of moving components and variable balancing requirements. A motorized system allowed for the easiest conversion and has been detailed to retract completely into the ceiling at the push of a button. The most important benefit of the elevator bed solution was that it descends to a typical bed height, allowing for easy ingress and egress but also ergonomic changing of sheets. This system does not even require the occupant to make their bed before hiding it away as the bed frame remains in a level plain and all bedding remains where it was left without a requirement for specific behavioural change. The elevator bed also has a dining room table attached to its underside which can detach within seconds to create seating for six people.

Similarly *functionality* exploration opens opportunities to consolidate redundant items found in a home. Commonly, dwellings will contain both television(s) and a computer monitor in two different areas of the house. These screens effectively use the same display technology and increasingly are both driven by computers with internet connections. By situating the office and living room in a way where this screen can be used for either entertainment or work, a redundant object is eliminated with no significant loss of functionality. Similarly, the kitchen's range hood exhaust fan and a bathroom fan are ubiquitously two separate building envelope punctures and contain their separated mechanical fans and ductwork. By situating the cooking range and bathroom exhaust areas close to each other in the floorplan layout, redundant mechanical devices can be combined into a single unit.

Lastly, the approach to *quality* of interior finishes was governed by a desire to produce a contemporary composition of elements that reflected emerging technological innovation. This was at risk of being jarring to a user but important to align with the value set expressed in the attempt to rethink every aspect of how a home is made. One example of this is the lack of lightswitches in the house. The home exclusively uses wifi enabled LED lighting capable of dimming and changing to any colour, allowing the lighting plan to be based on “scene” rather than “zone”. This is much more akin to the process of tailoring ambient lighting in automotive design than architectural lighting plans. Lights in the tiny house are operated by voice command or a phone application²⁷ and can be automatically fine-tuned based on the sun’s position or the activity that the occupant requires lighting. Lighting plans can even learn from an occupants behaviour and adjust automatically, or be triggered by geofencing when a person arrives home. Scene designing for cooking could program directional lighting to illuminate the countertop surfaces while tailoring indirect ambient lighting throughout the rest of the home based on the occupants' positioning in the kitchen while an “entertainment mode” design could reduce direct lighting throughout the entire house while preserving some wayfinding ambience from the living room to kitchen to bathroom. In the same vein, a “midnight bathroom visit mode” would illuminate the floor in soft orange and red tones, and be less aggressive on eyes adjusted to the dark. Designing by scene rather than circuit opens the capability of the lighting designer to enhance spatial perception with a much finer level of control.

Several other interior design choices were made to reflect the capability of digital fabrication and explore the potential of mass customization. The sculpted maple countertop is a perfect example. The piece is custom designed to allow the kitchen to flow into the living room, seamlessly

²⁷ “Smart Lighting.” Philips Hue. Accessed August 25, 2021. <https://www.philips-hue.com/>

transition from under-counter cupboards into a clothes dresser, and hide away the mechanical components required to service the home. This is an element that with practice is relatively simple to do through a digital workflow and extremely labour and skill intensive to do by hand.

Another product chosen for its reflection of innovative technology is the hardwood floor boards that meet together in curved tongue and groove joints rather than straight lines. The company²⁸ that produces these floorboards slices trees into live edge sections and 3D scans each piece of wood, storing the shape profile in a database. When two trees enter the database with curvature that will emmesh with each other, the two planks are sent to a CNC machine where they are tongue and groove milled to fit perfectly together. This process reduces wood wastage and also creates a unique aesthetic quality intrinsic to its process of digital craft.

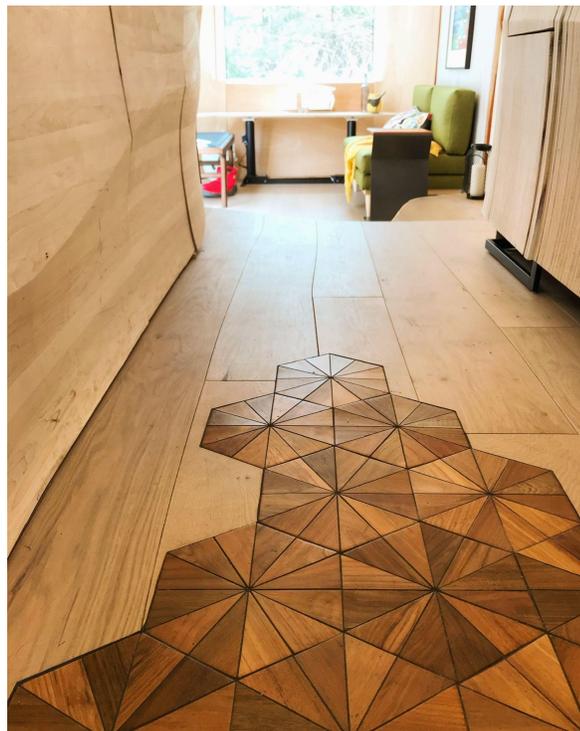


Fig 049 - Bole flooring transitions into reclaimed teak tiles.

²⁸ “Life Is Not a Straight Line.” Bole. Accessed August 25, 2021. <https://www.bole.eu/>.



Fig 050 - Tiny house arrives at permanent home in Vernon, BC.

5. Conclusion

Throughout this building process, the tiny house received numerous media publications in the form of news articles, radio segments, and a television episode which was filmed for HGTV and captured the complete construction of the project. The project has now been moved off campus and is located just outside of Vernon, BC in its new permanent location. All plumbing and electrical systems have been connected and the house is fully

functional. The capability of the experimental solar thermal system will be tested throughout the 2021-2022 winter season.

The chance to both design and construct a full sized housing project was an incredible learning experience that was afforded to me by Carleton University's architecture department. To prove and test these ideas with real building products allowed me to experience the freedom, limits, flexibility, and complexity of what the digital workflow can bring to architecture. The first hand experience of what risk presents itself as in the context of a digital craft helped me gain a deep understanding of what can be asked for or expected when designs become realized with these tools.

Pushing forward with this design took many leaps of faith in attempting to express the possibility of a digital workflow with my limited experience in construction. Through this process of making, there are obvious points for iteration and improvement. But there are also many moments of positive reflection that show promise in the elements that were tried and tested. It gives me hope and excitement for the potential of a new movement of digital design that will emerge throughout the 21st century. I believe it is now possible to add complexity, risk, beauty, and craftsmanship to built work while also simplifying assembly and improving precision. As mass customization reaches maturity, I believe it will give rise to a new movement of art and architecture.

The synthesis of digital workflow, sustainability, and affordability requires further iteration as the process I used is not ready for scalable deployment. I do believe that assembling our buildings like furniture or puzzles is conducive to a future where a harmony of these three factors is found. A more complete understanding of how the sector of mass produced building products can better emmesh with a mass customized building technique is the component that was most lacking in my investigation.

Ultimately, I observed the innovation on the building product side of design to be outpacing innovation in architectural design. Soon there may be an equalization point where building material production and architectural design embrace mass customization and open a new wave of potential. What remains consistent between hand craftsmanship and digital craftsmanship is the high level experience and understanding of tools and material required to accomplish a great piece of workmanship.

An important learning from this design-build exploration is that I believe it is possible to encourage an accelerated transition to sustainable living within the digital workflow.

CAD modeling for digital fabrication forces a hyper-resolved design to exist before any material is touched. As a collective understanding emerges that sustainability is a critical metric of success in our designs, this will ensure that high performing building envelopes, efficient energy usage, and passive energy capture are optimized with software.

A movement towards mass customization and with it, a concentrated focus on design resolution, is a welcome shift to me as someone who cares deeply about the field of

architecture and the career in front of me. I am inspired by a future of optimized designs with novel capability to produce them. The idea of breaking free of mass produced design is one that seems increasingly possible to me and done in a way that can meaningfully affect change in the quality of space that people reside.

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