Embodied Energetics

A Digital Design-Production System
for Passive Solar Walls in Vinalhaven Island, Maine

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Submitted to the Department of Architecture in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Architecture Studies
at the Massachusetts Institute of Technology

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Submitted to the Department of Architecture
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Abstract

I propose a digital design-production system to easily assemble, selectively disassemble, and reassemble novel passive solar walls. The problem statement I tackle is that all houses in Vinalhaven Island, Maine have high home-heating energy burden due to their thermally weak thin walls. Substituting thin walls with typical passive solar walls is a known solution, however such walls would be inundated with (i) high embodied energy in non-recoverable materials, (ii) high complexity of construction, and (iii) high cost of construction and renovation.

Facilitated by a CAD-CAM interface, I develop a methodological framework called *Design for Assembly, Disassembly, and Reassembly* to lower all three parameters efficiently. I demonstrate both the framework and its outcomes by rapidly prototyping a few study models of passive solar walls. I speculate on the urban implications of a widespread integration of walls with reduced and recoverable material embodied energy. In order to effectively visualize this, the system boundary of urbanism scales up from a wall to a house, to two adjacent houses, and finally to five houses in Vinalhaven's downtown. I claim that successful on-site substitution of today’s standard walls with Digital Passive Solar Walls will accelerate Vinalhaven’s island homes toward a holistic energy transition.

Broadly, I encourage professionals in the building industry to embrace such digital systems to recover material embodied energy locked in their designed artifacts.

Thesis Co-Supervisor: Lawrence Sass
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In my statement of motivation for admission to MIT, the last line went ‘I am ready to be mentored by you, MIT’. Though the learning will never stop, the thesis marks the end of this journey. Still no frets - *part of the journey is the end* (Anthony Edward Stark, MIT’87).

Thank-you, MIT’19.

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Preface

In this pre-introductory section of my thesis, I'll give a brief account of who I am, where I come from and where I intend to go. I recommend the reader to read through this in order to better grasp the motivation behind certain decisions and pathways throughout my thesis work. Within this section, I also intend to convey why I deeply care about the problems I tackle in my thesis.

I was born and raised in Andaman Islands of India. My first eighteen years shaped around explicit disadvantages of life in an unbridged island. Burdens were evident in daily life, especially with housing and energy. I grew up within a built environment where dependency on Indian mainland for skilled construction labor and building materials is business as usual. My islands rarely pushed for self-sustainability or locally generated autarkic solutions to these burdens. When 2004 Indian Ocean tsunami left us adrift and alone, all known burdens were amplified in intensity. Infact, we were left with newer burdens like post-disaster building debris. Since I turned 18, I travelled to other islands of sizes big and small, with governments of varying dependencies and with vast socio-economic differences. Undoubtedly, all islands are at the forefront of Climate Change. It was also clear to me that while burdens with housing and energy united the islands of India, Japan and Europe, there wouldn't be a one-solution serves all-islands approach. Thus, over a course of time, my interests in solving for islands have come to define who I am.

While I studied architecture and design, I was overwhelmingly disappointed with lack of serious intent to address housing and energy burdens of the built environment. It wasn't the best moment of my life when, as I prepared for the finals of a national-level architectural quiz, I came across datasets revealing that the building industry has always been a major contributor to greenhouse gas emissions and is struggling to achieve the 'Architecture 2030 ' commitment goals. I understood that we need to systemically reimagine how buildings are made, how we use the materials that presuppose our architecture and how we get rid of them to make place for better ones. It was already obvious to me that we need to test such novel circular systems for the built environment of urban islands. But I still didn't know how. While I worked in architecture and design, I gained core work experience with digital design-production (a technological paradigm to conventional cradle-to-grave construction system). My professional experience in the industry has been with organizations (like WikiHouse Foundation, Nonscale Co. and rat[LAB]) that have capitalized upon existing digital tools of design-production for their building projects. However, it wasn't until I came to MIT that I got the opportunity to dive deeper into digital tools that guide buildings to be fabricated directly from computer models. My research work for two years with Digital Design Fabrication Lab at MIT, under the mentorship of Prof. Lawrence Sass, had one sole objective - to optimize construction methods to lower human error, human labor and time. The goal is to help people construct homes instantly using digital fabrication and make housing more affordable. For the first time, I wondered if the same digital tools could be used to build not just cheap, but also sustainable housing. *Can our buildings be cost-friendly and eco-friendly simultaneously?* I meditated on this for a while. These experiences, inquiries and a string of epiphanies over the last nine years define where I come from. Infact, I am both a techno positivist and an environmentalist.

In summer of 2018 at my research laboratory at MIT, I was working on my first full-scale chair guided by a set of digital design-production tools. It was here that I found my tailwind - *embodied energy.* I learnt that to truly design-build affordably and sustainably, the material embodied energy of artefacts like furniture, smartphones, cars and houses should ideally be reduced and recovered. As of now, the problem persists that there are no standardized methodologies or tools to do so. Being part of the building industry, I care deeply about this problem. Today's increasing focus on clean operating energy for building utilities means further ignorance on significance of embodied energy locked into building construction, assembly and disposal. After studying post-disaster burdens of housing and energy in islands like Puerto Rico due to Hurricane Maria, seeds were planted in my mind. These were questions I aim to answer through my thesis - can a digital design-production system optimize for recoverable material embodied energy as well as cost of construction? If yes, what environmentally benign implications will such a circular system have within the built environment of urban islands? My inquisitiveness took me to Maine's islands in January 2019 (IAP) where I was introduced to a range of housing and energy projects by 'The Island Institute'. Things have never been the same since then. After MIT, my aim is to continue working with digital design-production tools at all scales, from small artefacts/products to large cities/systems. My short-term career goal is to help (re)design and (re)build cities of the future as circular ecosystems. Owing to my experience at MIT, I am convinced that my long-term calling is to help accelerate the ongoing energy transition of our built environment. This is where I intend to go.

Part I: The Problem

In the first part of my thesis, I introduce the problem I attempt to tackle throughout the course of research work. My thesis falls under the category of argumentative thesis. To set up the stage for my argument (detailed in Part II), I initiate discussion through problem-framing. My thesis problematizes the walls of five existing island homes in Vinalhaven's downtown to be the root cause of their energy and housing burdens. Solving for the burdens of all 15 unbridged islands is beyond the scope of my thesis. Thus, I focus my energy on Vinalhaven island, Maine. The island under study has the highest year-round population and three times the average US energy cost for home-heating. In Chapter 1.1, I introduce burdens of Maine islanders, categorizing them broadly into two – energy burden and housing burden. In Chapter 1.2, I define the scope of my thesis by introducing the island of Vinalhaven, then its downtown and finally narrowing down to five island homes in the downtown area. Within Chapter 1.3, I highlight the importance of existing standard walls, their panelization method of construction and assemble, and the role of these wall panels in increased in energy burdens of the five island homes. In section 1.3.2, I create a 3D CAD model of one standard wall panel according to data retrieved from local design-build firm and analyze it across the neighborhood based on a combination of volumetric CAD assessment and Maine's GIS mapping data.

Chapter 1.1. Burdens of Maine islanders

The context under inquiry for my thesis is Maine's islands. Maine is the north-easternmost U.S. state, as seen in Fig.1. I initially got interested in Maine's islands from a comprehensive report titled 'The State of Maine's Environment 2014', produced by the Environmental Policy Group in the Environmental Studies Department at Colby College in Waterville, Maine. In this report, the third chapter titled "State of Maine's Islands 2014" analyses the islands by using different proxies (Hawley, Miller, Vargas & Whitley, 2014). Introduction to this chapter mentions there are more islands in the Gulf of Maine than on the entire East Coast of the United States. Geographically the islands are located off southern coast of the state of Maine, as seen in Fig.1. The same chapter from the report mentions that there are over 4000 islands in Maine. As of 2014, only 15 unbridged Maine islands supported year-round populations, and they served as focus of the report.

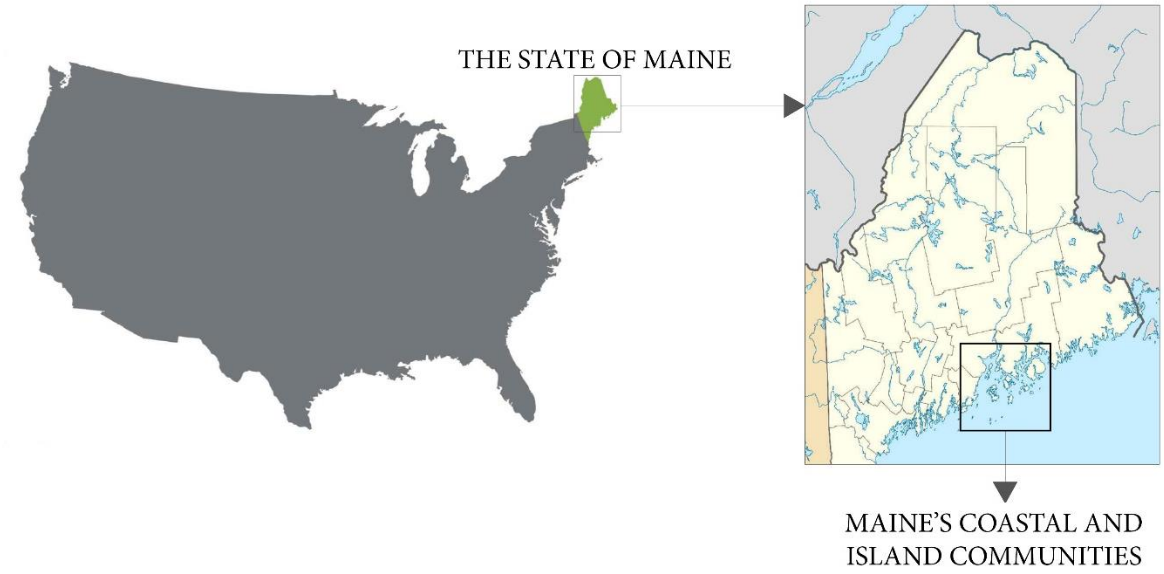

Fig.1. The State of Maine and its island communities.
(Created by Author on GIS mapping data from state of Maine)

In January 2019, I travelled to Maine's islands. The primary aim of my field-visit was to collect data on burdens of the island community. In Rockland, I came across 'The Island Institute' - a non-profit organization in Maine that has active mission to sustain its coastal and island communities. According to the institute's 2017 report titled 'Waypoints: Community Indicators for Maine's Coast and Islands', there are 120 communities included in their reports that comprises of 105 coastal and 15 unbridged, year-round islands. In total, just over 452,000 people were living in these communities as of 2016 (Deese, Granstrom, Carte & Smith, 2017). By end of 2016, this number formed 34% of Maine's total population. With several projects underway, the institute focused on the 15 unbridged island communities in order to explore how presence of people and isolation from the mainland impact them. The report has been divided into three sections - Economy, Community and Environment. Within the scope of my thesis, the section 'Community' presents indicators and datasets specific to sub-sections titled "Home Heating and Energy" and "Affordable Housing" (Deese, Granstrom, Carte & Smith, 2017). Based on my literature study of reports and datasets, I inferred that there are broadly two major burdens of these communities relevant to the scope of my thesis: (i) home heating energy and (ii) affordable housing.

I have identified and prioritised two sets of burdens (Fig. 2.) within the scope of my thesis. More precisely, the data suggests that all 15 unbridged islands of Maine suffer from two types of burdens, namely:

1. *Energy burden: High per person heating oil demand, high greenhouse gas (GHG) emissions and high home heating and operating energy costs.*
2. *Housing burden: Low availability of year-round housing, low housing affordability due to high cost of construction, and low availability of workforce or skilled labor for construction and renovation.*

The intensity of these burdens varies from one island to next. These are not the only burdens identified by The Island Institute over the course of years. Limitations due to an old housing stock, high weatherization cost before winters, high self-employment, seasonal variability of jobs and an ageing population defines the local character of island life. A more detailed summary of the cited report by The Island Institute can be found under Section 4.1.2. ‘Data Collection’ (under Chapter 4 ‘Literature study’ in Part IV ‘The Methodology’).

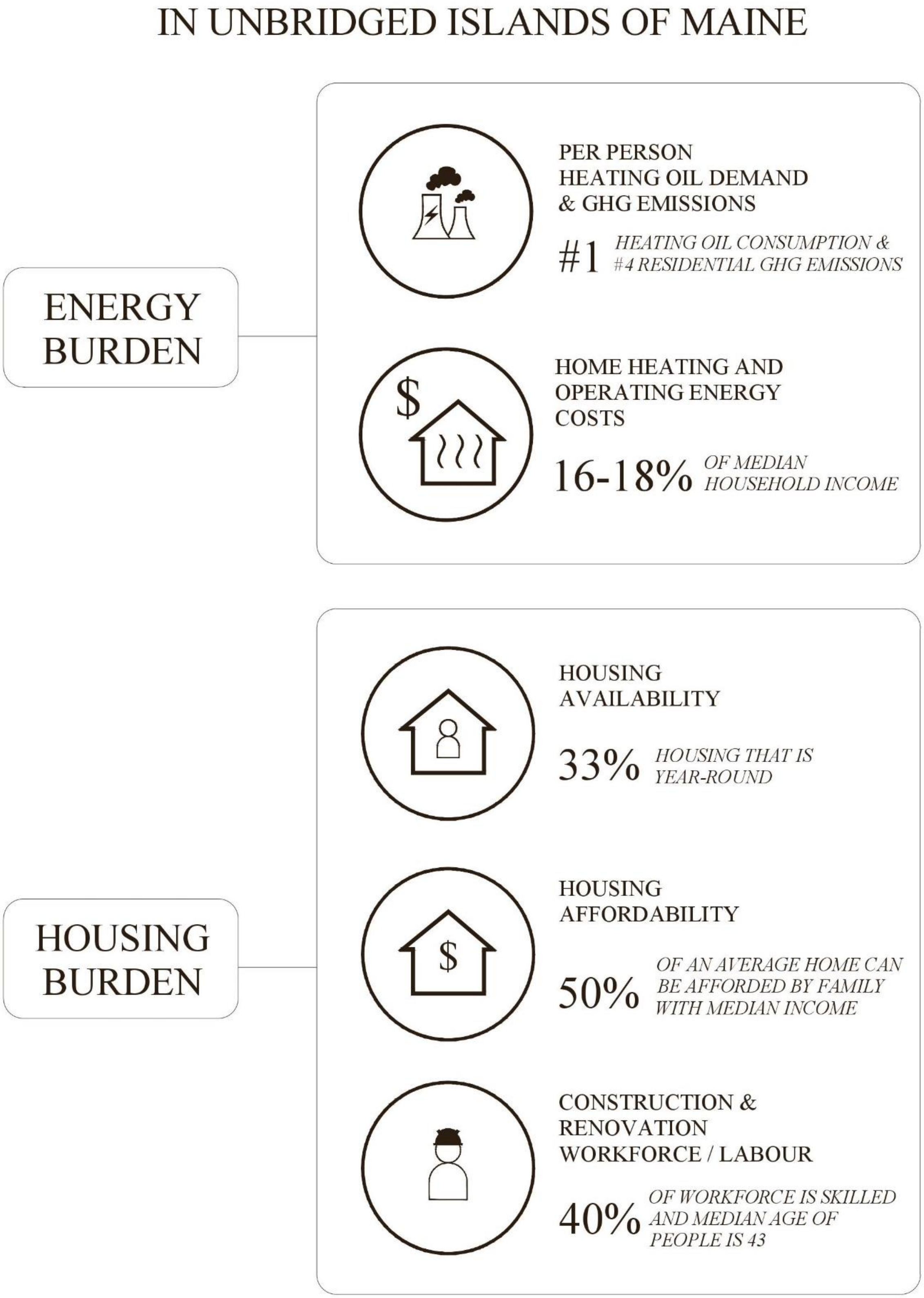

Fig.2: Burdens of unbridged islands of Maine: Energy Burden and Housing Burden.
(Data Source: The Island Institute annual reports)

Chapter 1.2. Definition of Scope

My thesis problematizes the walls of five existing island homes in Vinalhaven’s downtown to be the root cause of their energy and housing burdens. The goal of this section is to explain decisions and pathways I took that led to a narrow focus of my problem statement. First, I narrow the scope from the scale of all 15 unbridged islands of Maine to 6 northern islands and finally down to Vinalhaven Island. Solving for the burdens of all 15 unbridged islands is beyond the scope of my thesis. To define an appropriate scale to work with, I began to focus on six northern island communities that are the farthest from effects of modernity but still hold a thriving year-round population. Located in and to the east of Penobscot Bay, these six unbridged islands are namely Isleboro island, N. Haven island, Frenchboro island, Swan’s island, Isle Au Haut and Vinalhaven island (Fig.3). The Island Institute’s report of 2010-11 titled ‘Island Indicators: Status report on Maine’s year-round island communities’ presents a range of datasets under various sections, including “Community & Civic Trends” and “Affordability Trends” (Curran, 2011). Population, housing, property valuation, electricity rates and heating fuel are few of the primary indicators. The datasets have been sourced from reports by U.S. Energy Information Administration, Public Utilities Commission, Isle au Haut Electric and Swan’s Island Electric Cooperative. A more detailed summary of the cited report by The Island Institute can be found under Section 4.1.2. ‘Data Collection’ (under Chapter 4 ‘Literature study’ in Part IV ‘The Methodology’). To narrow the scope of my thesis to a scale suitable for working with island homes, I studied this comprehensive report and extracted necessary information pertaining to two indicators: year-round population and home operating energy / electricity cost per kilowatt hour. My goal with this preliminary exercise was to focus on one of the six northern islands of Maine.

Fig.3: Six unbridged islands of Maine with year-round population and high operating energy/electricity rates. (Data Source: The Island Institute annual reports, Created by Author on GIS mapping data from state of Maine)

Table 1 enlists the two data on the two indicators for all six islands. Since the study shows that Vinalhaven island has the most year-round population and highest energy costs per kilowatt hour, the rest of my thesis focusses only on this island. With 1,165 people, Vinalhaven island is one of the most populated unbridged islands of Maine (US Census, 2010). According to primary data sourced from U.S. Energy Information Administration in The Island Institute's report 'Island Indicators: Status report on Maine's year-round island communities', energy and electricity rates can hike up to $ 0.34 per kilowatt hour which is thrice the US average of $ 0.10 per kilowatt hour (US EIA report, 2010).

Island	Year-round Population *(US Census 2010)*	Operating energy / electricity rates – per kilowatt hour *(US EIA report 2010)*
Isleboro island	566	$ 0.20
N. Haven island	355	$ 0.30
Frenchboro island	61	$ 0.30
Swan's island	332	$ 0.30
Isle Au Haut	73	$ 0.30
Vinalhaven island	1,165	$ 0.30 - $ 0.34

Table 1: Year-round population and operating energy/electricity rates in six northern unbridged islands of Maine (Data Source: The Island Institute annual reports)

Section 1.2.1. Vinalhaven Island, Maine

My thesis specifically solves for extreme energy and housing burdens faced by year-round population living in island homes of Vinalhaven Island, Maine. Since there is no bridge to the island, Vinalhaven is accessible from Rockland via an approximately hour-and-fifteen-minute ferry ride. According to US Census report from 2010, there were 1,165 people, 545 households, and 320 families residing in the town. There were 1,295 housing units at an average density of 55.2 per square mile (21.3/km^2). Datasets points out that population density is highest at the southern coast of the island, popularly known as Vinalhaven's downtown (US Census report, 2010). Residential settlements or island homes are all located in the downtown area. According to the institute's 2017 report titled 'Waypoints: Community Indicators for Maine's Coast and Islands', 71% of Vinalhaven's households operate their own businesses (Deese, Granstrom, Carte & Smith, 2017). This means that majority of the population lack a steady monthly income that is crucial for energy and housing affordability. Figure 4 presents the map of Vinalhaven island with data on three burdens and indicates the densely populated downtown area. Based on data collected on island homes from my visit to Vinalhaven and datasets from The Island Institute's report 'Island Indicators: Status report on Maine's year-round island communities', I extracted the following information within the scope of my thesis:

1. GHG emissions and operating energy costs of island homes: Islanders use costly energy supplies from fossil fuel source to heat their homes that have thermally weak and thin

standard walls. Oil is used to heat 85% of Vinalhaven's island homes. Energy and electricity costs are thrice the national average.

2. Affordability of island homes: A year-round islander in Vinalhaven earning median income can afford only 76% of the median home price.
3. Workforce for construction and renovation of island homes: The median age of islanders in Vinalhaven is about 45.1 years and only 40% of total workforce is skilled.

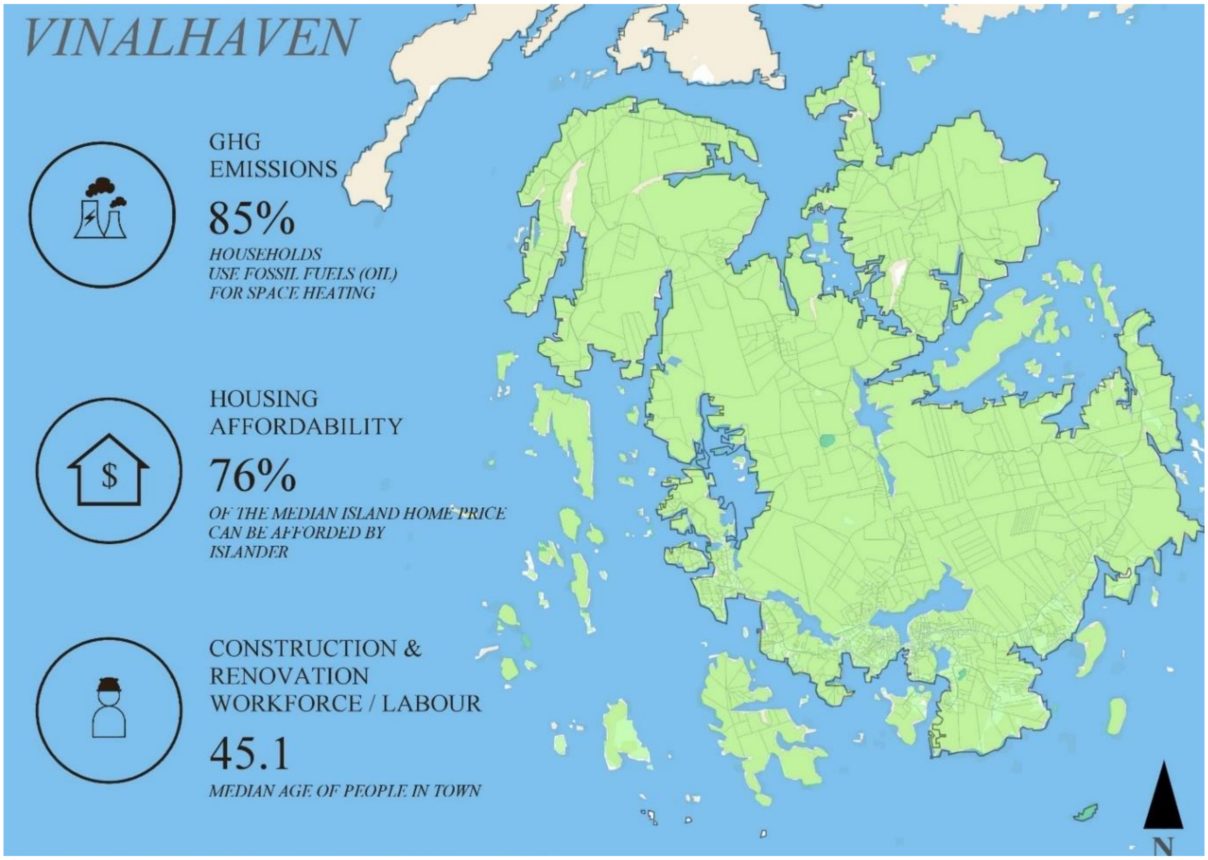

Fig.4: Burdens of unbridged islands of Maine
(Data Source: The Island Institute annual reports)

Section 1.2.2. Vinalhaven's downtown

In January 2019, I visited Vinalhaven's downtown because my preliminary literature study indicated that the year-round population density is highest in the area. This also means the burden of energy and housing is extreme in the downtown. Apart from personal experiences while travelling in the island, my preliminary study of Vinalhaven's downtown is based on a report titled 'Vinalhaven: Turning the Tide'. The report is documentation of a comprehensive program conducted by Design and Resiliency Teams (DART) for Vinalhaven's downtown. The goal of DARTs is to provide pro-bono technical assistance to help communities develop a strategic vision and promote community resiliency, usually by focusing on a specific issue and/or geographic area. The report notes that Vinalhaven applied for DART technical assistance to help it address challenges and concerns about long term threats to the stability of the economy and island way of life (Feiden et al., 2017). Multiple agencies/partners supported the program, including American Institute of Architects and the New England Municipal Sustainability Network. A more detailed summary of the cited report by DART can be found under Section 4.1.2. 'Data Collection' (under Chapter 4 'Literature study' in Part IV 'The Methodology') of my thesis.

The DART report highlights the rapid urbanisation pressure due to year-round population in the island's downtown area. Within the scope of my problem statement, I studied how various downtown housing incentive programs were strategized by the team to create various opportunities including affordable housing units on Main Street. Figure 5 in this section is a perspective view illustration from the report that includes proposals for additional housing (Feiden et al., 2017, p.25). The report also highlights that near the end of 2009, an 'Island Energy Task Force' was established to serve the Vinalhaven community in order to push for a transition to affordable, reliable, domestically produced energy, and on the consumer end, to energy-smart products. The report shows street photographs of current Main Street (Fig. 6). Figure 7 below is a map from the report based on an aerial photograph of Vinalhaven's downtown, overlaid with property lines and labels with land ownership (Feiden et al., 2017, p.26). The DART program suggests that creative solutions are being actively explored to lower energy burden, environmental impacts and housing burden of houses in Vinalhaven's downtown, especially along the active Main Street.

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Fig.5: Strategic vision for Vinalhaven's downtown.
(Data Source: DART report)

Fig.6: Street photographs of Vinalhaven's downtown
(Data Source: DART report)

Fig.7. Aerial map of Vinalhaven's downtown (Source: The DART report)

Based on data collected during my visit to Vinalhaven's downtown and guided by Geographic Information Systems (GIS) mapping data from the town and the state of Maine, I created a map of existing single-family island homes along Main Street (Fig. 8). As shown in the figure in blue solid colours, I have identified five detached single-family houses existing as of today. These houses or 'island homes' vary in size, shape and orientation. I found out during my visit that these five island homes have a common pain point of energy burden. It is crucial to note that none of these homes can be afforded year-round by an average islander. My deeper inquiry into these buildings revealed that the five existing island homes on Main Street were designed and constructed with thermally weak thin standard walls. With pressures from rapid urbanisation, new and upcoming homes along this street would have similar walls. Islanders are locked into a vicious cycle of high un-affordability and high GHG emissions. Thus, I argue that we can address energy and housing burdens of Vinalhaven's downtown by moving away from thermally thin standard walls. Details of supporting data and my research process behind identification of the problem is provided in chapter 1.3 of my thesis. Focus on walls of island homes is definition of scope for my thesis.

Fig.8: Five island homes in Vinalhaven’s downtown along Main Street.
(Created by Author on GIS mapping data layer)

Chapter 1.3. Standard walls of island homes

The problem statement I tackle is that all five island homes along Main Street in Vinalhaven’s downtown have high home-heating energy burden due to their thermally weak thin standard walls. The existing homes were designed and constructed with such walls. With pressures from rapid urbanisation, new and upcoming homes along this street would have similar standard walls. My goal in this chapter is to provide supporting information on the problem statement of my thesis. With the scope of the problem defined, I studied various characteristics or features of these walls. I inquired about their designers, materiality, construction style, assembly and thermal performance. Figure 9 in this chapter shows two island homes along Main Street. The architectural style of these homes could be regarded as ‘New England Architecture’. Predominantly a wooden construction, these homes vary in size, shape and orientation. The roofs of these homes are pitched, with some having unequal sides.

Fig.9: Two island homes in Vinalhaven’s downtown.
(Data Source: Trulio website)

Section 1.3.1. Analysis of a standard wall panel

In this section, I analyze the standard walls within the scope of my thesis. In other words, I studied only those characteristics of the walls that support how they are inefficient in their thermal performance, leading to high home-heating operating energy demand. Data from local construction agents and design-build firms show that the standard walls of these homes were constructed and assembled as panels. The panelization system is a fundamental characteristic across walls of Maine’s island homes. Figure 10 below shows one such home being constructed and assembled. The photograph is from an on-site construction and assembly of the home by a design-build firm called Ecocor. It is comprehensible from the photo that these standard walls are factory-panelized and assembled on-site with cranes, under human supervision. A standard wall panel, in this case, could be defined as a system that has layers of different wall components. These components are vertically placed one behind the other. The vertically stacked components are fastened or bolted to each other using steel connectors.

Fig.10: Panelized Standard Walls for island homes in Maine – Construction and assembly as panels.
(Data Source: Retrieved from Ecocor official website)

I enlist the following characteristics of a standard wall panel, based on above-mentioned sources in Vinalhaven's downtown:

i. Materiality: A standard wall panel is a constructed system of timber studs (structural members), rigid foam insulation (performative component), agepan panels (vapor barrier), window glass and frame, and vinyl siding (external rain screen). Conventional steel fasteners keep the components from falling apart. A single-glazed glass is used for the window, held by aluminum a frame.

ii. Dimensions: A standard wall panel is 8 feet in height and 9 feet in span. Total thickness varies according to number of layers and drastically differs whenever a thicker rigid foam insulation is used.

iii. Thermal Performance: A standard wall panel has low thermal mass (from timber) and low thermal insulation properties (from rigid foam). Such walls by themselves are insufficient in providing with effective thermal properties for island homes, especially during winters. Thus, active ductless home-heating systems have high demand.

iv. Cost of construction: A standard wall panel has significantly higher cost of construction due to factory-panelization, complex shipping and on-site assembly processes. Furthermore, lack of construction workforce/ skilled labor increases the cost of construction. These invariably raise the cost of island homes. A standard wall is not affordable, as of today.

Section 1.3.2. 3D CAD model of a standard wall panel

Based on characteristics of a standard wall panel enlisted at the end of previous section, I developed a to-scale three-dimensional (3D) computer-aided design (CAD) model in AutoCAD 3D modelling software of a standard wall panel. Such a 3D modelling exercise can guide comprehension of designed artefacts and help in further research and analysis. Architects and building designers around the world make accurate 3D models in CAD environments at the initial design stage. Figure 11 in this section presents this model's isometric representation. It has an attached window and only four layers of vertically stacked components. Material representation is defined by colour coding where green is for wood stud-walls and purple is for rigid foam insulation. Additionally, the model considers material components like particle board/agepan vapor barrier and vinyl siding (rain screen). A standard wall panel is 8 ft in height, 9 ft is span and 1 ft in thickness. The 3D CAD model represents a typical thin standard wall panel that is thermally weak due to low thermal mass and low thermal insulation properties. As a result, the island homes with such walls have (i) high operating energy costs, (ii) high home-heating demands and (iii) high residential GHG emissions.

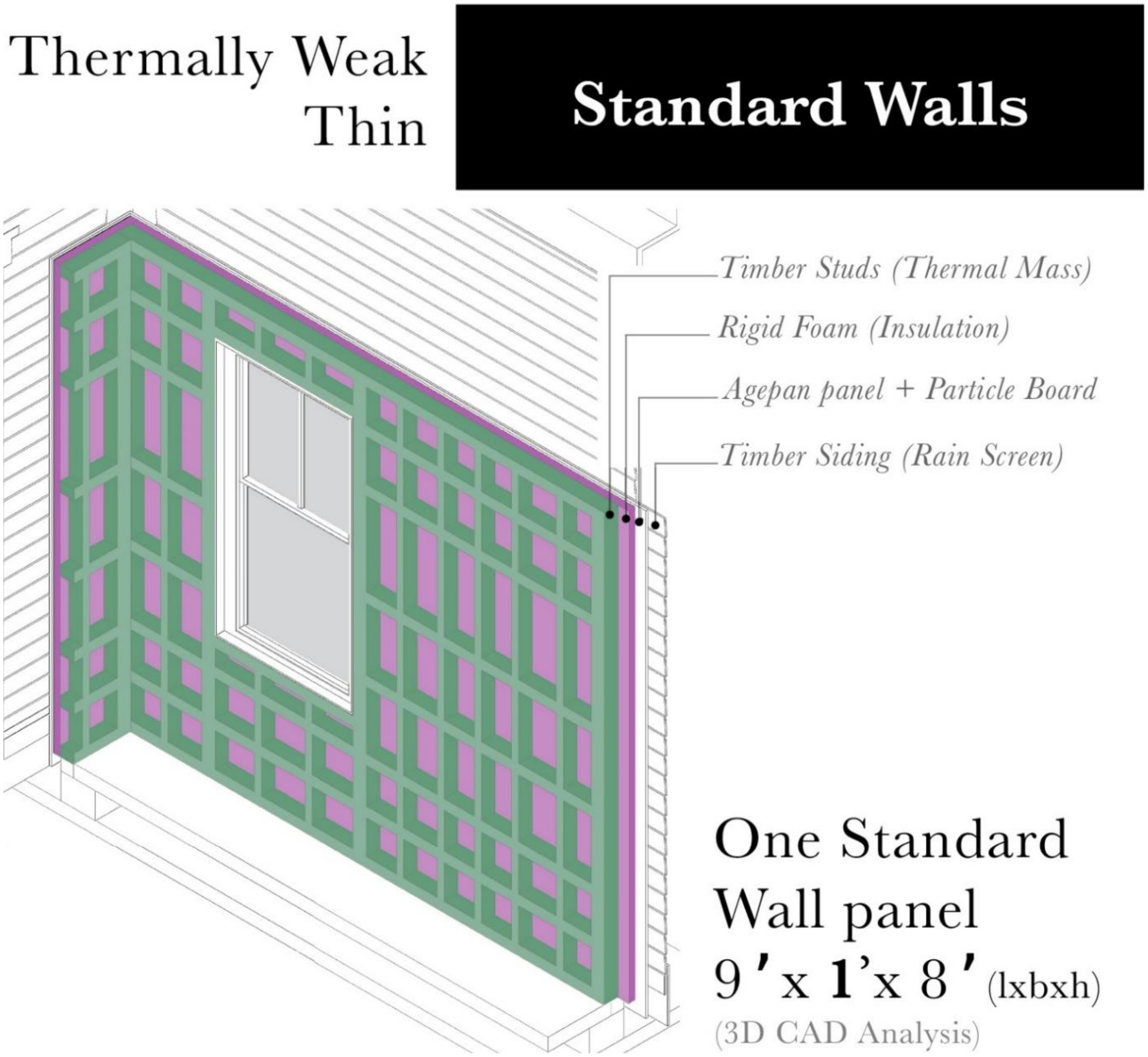


Fig.11. Thermally weak thin Standard Wall panel of 9’x1’x8’ (lxbxh) with [1] high operating energy costs, [2] high space heating demands and [3] high residential GHG emissions. (3D CAD model created by author, guided by material datasets and dimensions from Standard Wall panels designed-built by Ecocor)

Based on characteristics of a standard wall panel from 3D CAD model and GIS mapping data on Vinalhaven’s downtown, a quick analysis shows that there are 51 standard wall panels (Fig. 12.) in total, of same dimensions, that make up all exterior walls of existing five island homes. Such a neighborhood-level analysis is foundational to upcoming parts of my thesis.

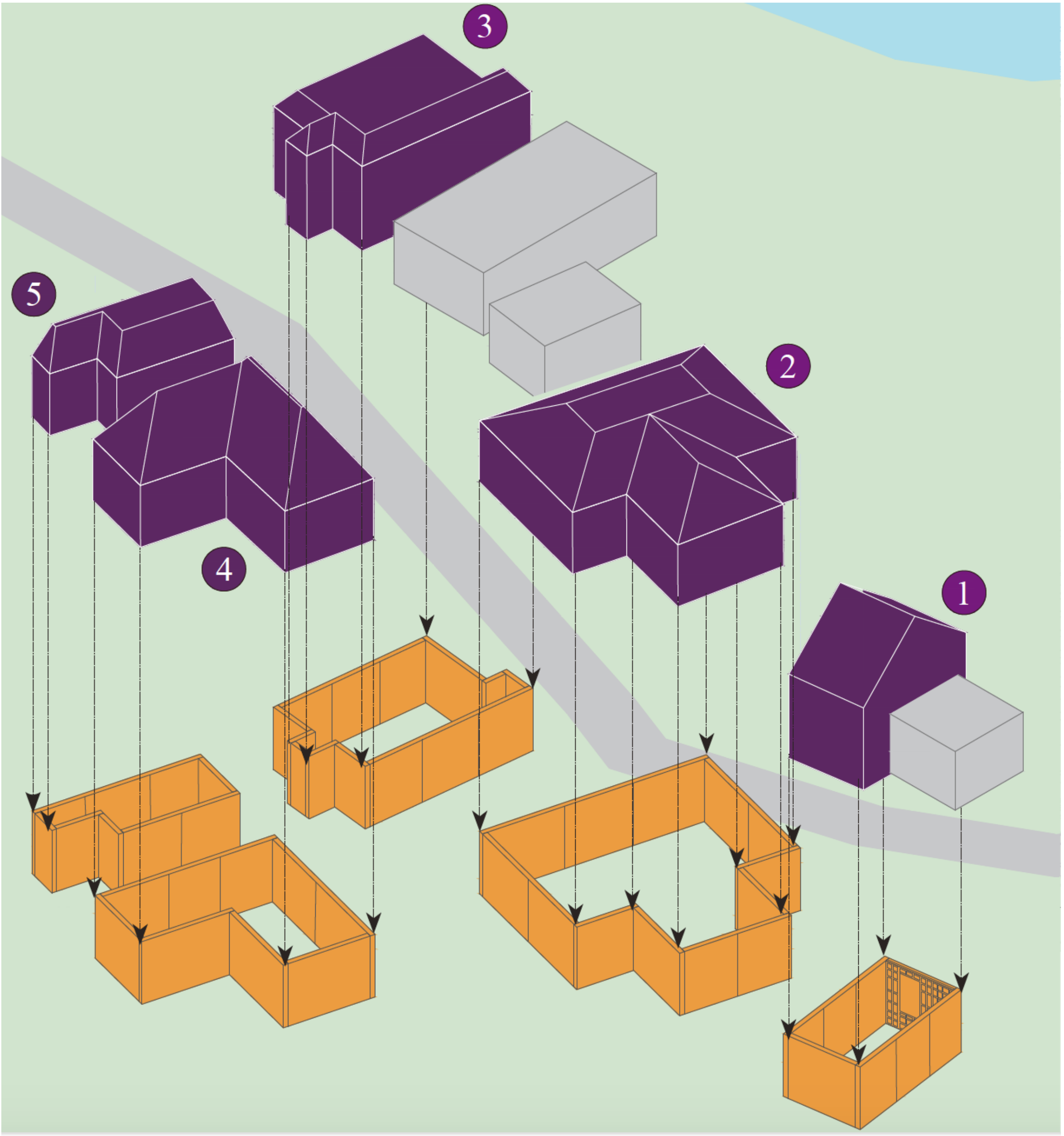


Fig.12. 51 standard wall panels extracted from 5 island homes in Vinalhaven's downtown.
(3D CAD model created by author, on GIS mapping data from the state of Maine)

Chapter 1.4. Summary

Summarizing Part I of my thesis, I introduce the problem I attempt to tackle. My thesis problematizes the walls of five existing island homes in Vinalhaven's downtown to be the root cause of their energy and housing burdens. Homes in Vinalhaven island has the highest year-round population and three times the average US energy cost for home-heating. I define the scope of my thesis by introducing the island of Vinalhaven, then its downtown and finally narrowing down to five island homes in the downtown area. Travel study in January 2019 to the island, datasets from the Island Institute and previous studies documented in the DART reports guide my understanding about the context. I highlight the importance of existing standard walls, their panelization method of construction and assemble, and the role of these wall panels in increased in energy burdens of the five island homes. I create a 3D CAD model of one standard wall panel according to data retrieved from local design-build firm and analyze it across the neighborhood based on a combination of volumetric CAD assessment and Maine's GIS mapping data. The 3D CAD analysis becomes a baseline for further assessments, especially important to support arguments in Part II.

Part II: The Argument

In this part of my thesis, I argue that even though thick passive solar walls are thermally better than thin standard walls, they are not the right solution to the given problem. My thesis becomes argumentative from this part. I provide supporting claims, data, literature and analysis. In sections of Chapter 2.1, I introduce passive solar walls, highlight previous studies on advantages of their thermal properties and create a 3D CAD model of one passive solar wall panel. In Chapter 2.2, I identify the presence of passive solar wall panels in single-family homes across Maine and the design-build firms that create them. The sections under Chapter 2.3 explain major limitations of passive solar wall panels within the scope of my thesis. Typical substituting thin wall panels with passive solar wall panels is a known solution. However, such walls would be inundated with (i) high embodied energy in non-recoverable materials, (ii) high complexity of construction, and (iii) high cost of construction and renovation. In Chapter 2.4, I analyze a standard and a passive solar wall panel, guided by respective 3D CAD models. In the first section of Chapter 2.4, I calculate and compare the total material embodied energy (MEE) in each wall panel typology, while in the second section I calculate and compare the total MEE for one island home when completely built with multiple quantities of each wall panel typology. At the end of this part, I summarize my main argument and supporting comparative analyses.

Chapter 2.1. Advantages of passive solar walls

In this chapter, I introduce passive solar walls by citing previous work and studies. According to the seminal book ‘Passive Solar Heating Analysis: A Design Manual’, “Sun-dwellings Project, New Mexico” was one of the most important passive solar heating experiments in the U.S. This project is known to officially use the term ‘passive’ for the first time. It defined ‘passive’ with respect to direct solar gain and home-heating. According to the highly cited paper ‘Heat storage and distribution inside passive solar buildings’, Dr. J. Douglas Balcomb is the father of energy modeling software that revolutionized passive solar architecture design methods. According to Balcomb’s paper ‘Passive solar heating of building’, in all passive solar heating mechanics, thermal energy flow into the house by natural means (Balcomb, 1983). The paper was one of the firsts to highlight that passive solar walls capitalize on total solar gain (direct and indirect) falling on the home’s external body (building envelope, roof, etc.) and can be utilized for home-heating energy needs (Balcomb, Hedstrom, & McFarland, 1977).

The paper ‘Study of solar walls—validating a simulation model’ defines ‘solar wall’ as “the primary exterior system” of passive solar houses. The study enlists the main components of passive solar walls. Based on this paper and scope of my thesis, a passive solar wall panel should include an efficiently built structure as thermal mass, air tightness, high-performance thermal envelope, added insulation and triple-glazed windows with efficiency frames (Zalewski et al., 2002). Figure ~ show a typical passive wall panel as provided in the paper. My further understanding of passive solar walls is from a highly cited paper titled ‘Review of passive solar heating and cooling technologies’ published in journal ‘Renewable and Sustainable Energy Reviews’. According to this paper, such walls can gain or trap heat through passive solar energy. Heat from solar radiation is absorbed, stored or used to preheat ventilation air. An important learning from the paper is that houses with such walls heat without using active mechanical devices. The passive solar system does not use or uses only small amount of external energy (Chan et al., 2010, p. 782). Another major takeaway from this paper is that building components such as facade and roofs form the passive solar system (Chan et al., 2010, p. 788).

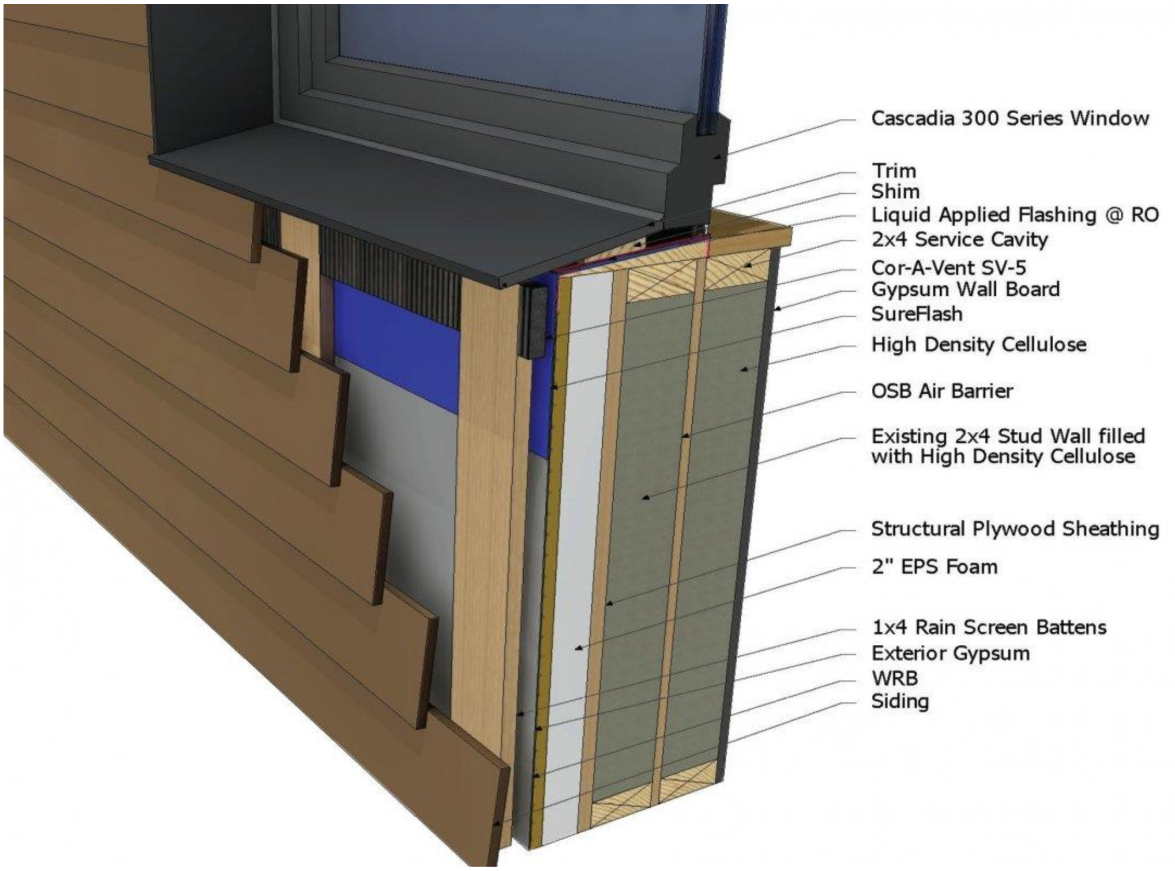


Fig.13(a). A sectional representation of typical passive solar wall with superinsulation. (Retrieved from Hammer & Hand website)

The Passive House Institute US (PHIUS), established in 2003, has the mission to “Help Make Passive Building Mainstream”. They promote passive solar homes for their long-term benefits from superinsulation, airtight construction, systems approach to modelling, design, and construction, and passive building principles as a pathway to Net-Zero Energy (NZE) buildings. PHIUS certifies and enlists building projects as passive homes along with the design-build firms that create them. One such certified house with passive solar walls has been designed and constructed by the firm called Hammer & Hand. Figure 13 (a) below shows a sectional representation of a typical passive wall with high superinsulation. Figure 13 (b) is diagrammatic representation of a section for typical passive solar house. These images have been retrieved from the official website of Hammer & Hand.

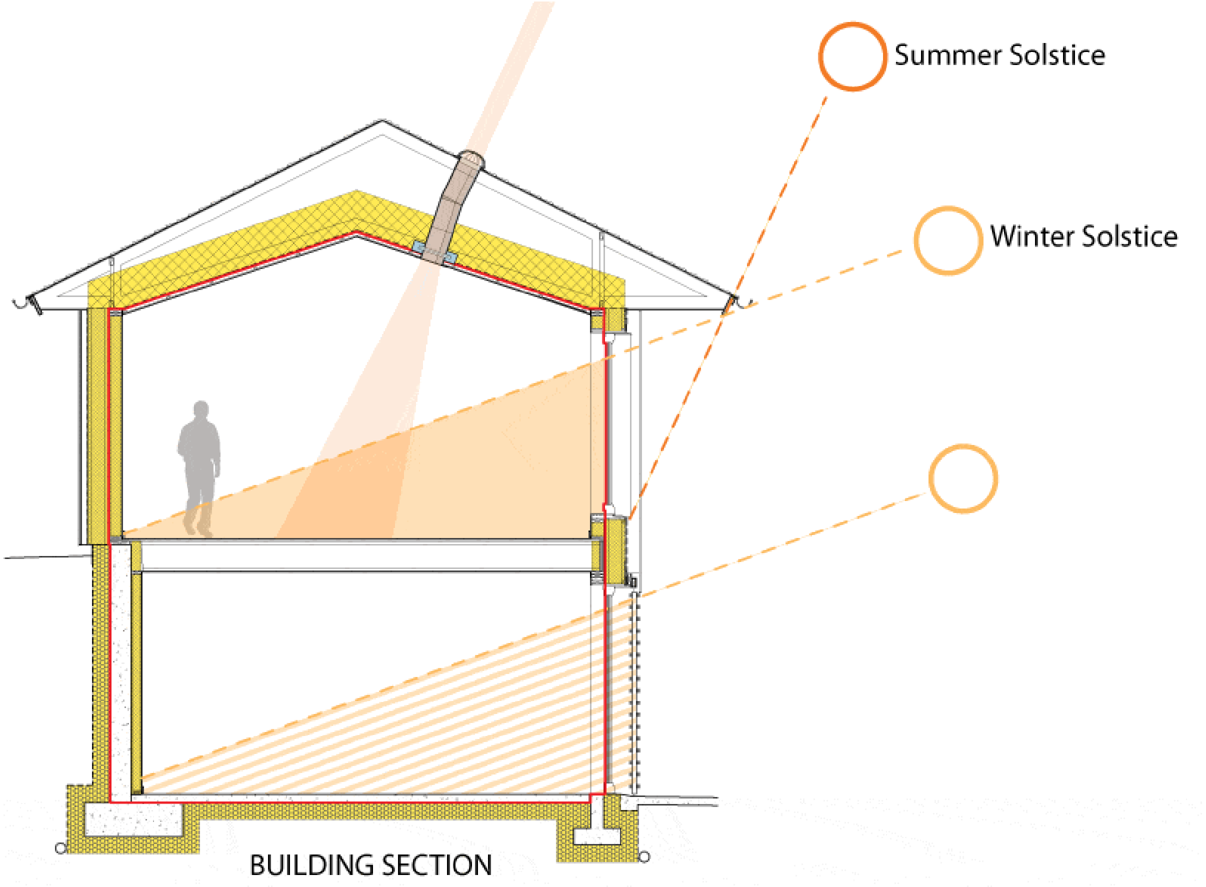


Fig.13(b). Diagrammatic representation of typical passive solar house.
(Retrieved from Hammer & Hand website)

The passive solar wall by Hammer & Hand is low on thermal mass from timber but very high in insulation from rigid foam. A set of three images from the same project by Hammer & Hand show how there are four non-negotiable systems that provide unique performative advantages to the home (Fig. 14). The four systems, according to their method of passive solar wall assembly, are air management system, heat management system, water management system and vapor management system.

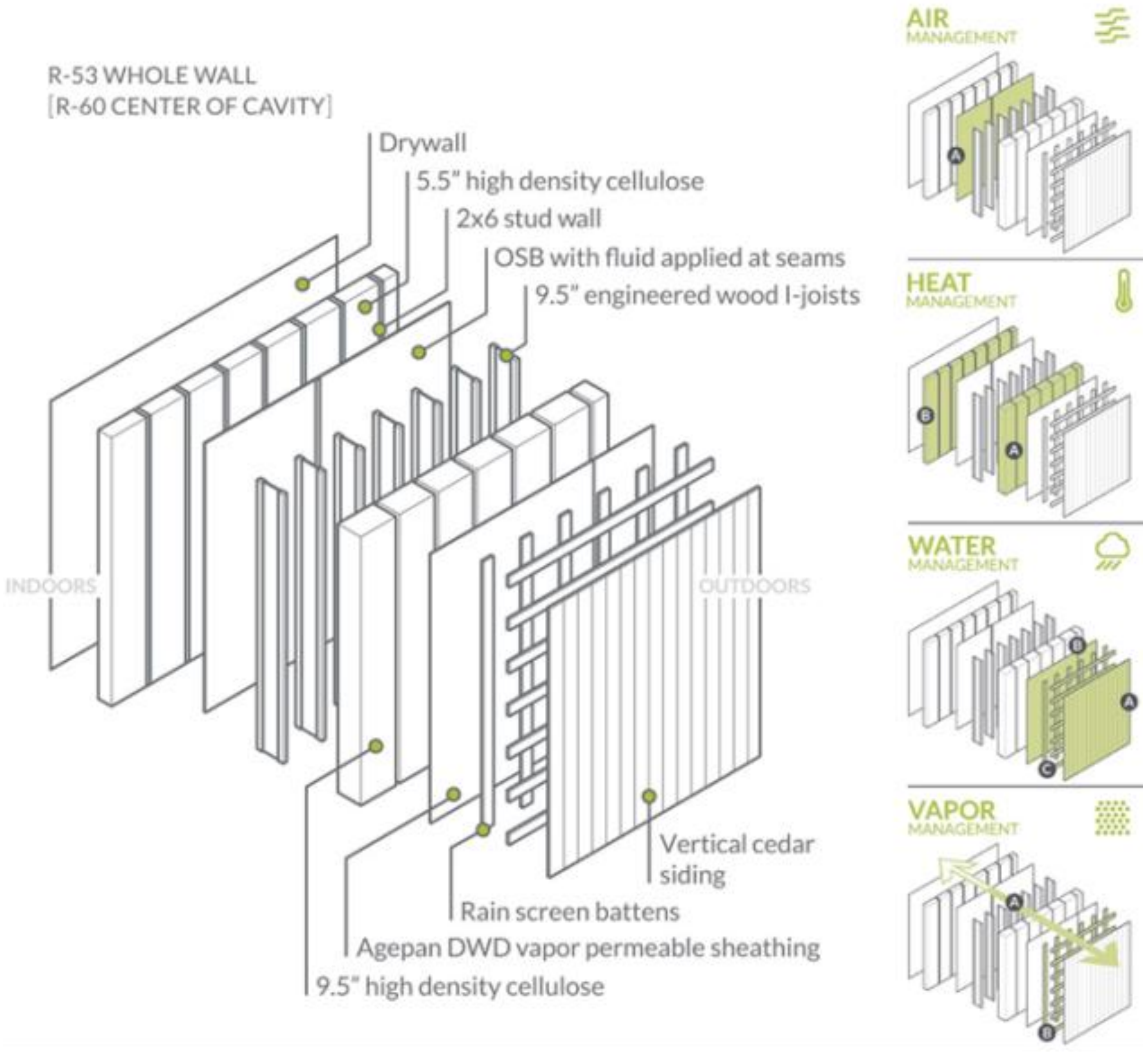


Fig.14. Four non-negotiable systems of passive solar wall assembly.
(Data Source: Retrieved from Hammer & Hand website)

Retrieved from the official website of Hammer & Hand, figure 15 shows photographs from on-site work on passive solar walls assembly. The four photographs are documentation of how some of the non-negotiable systems look in real conditions.

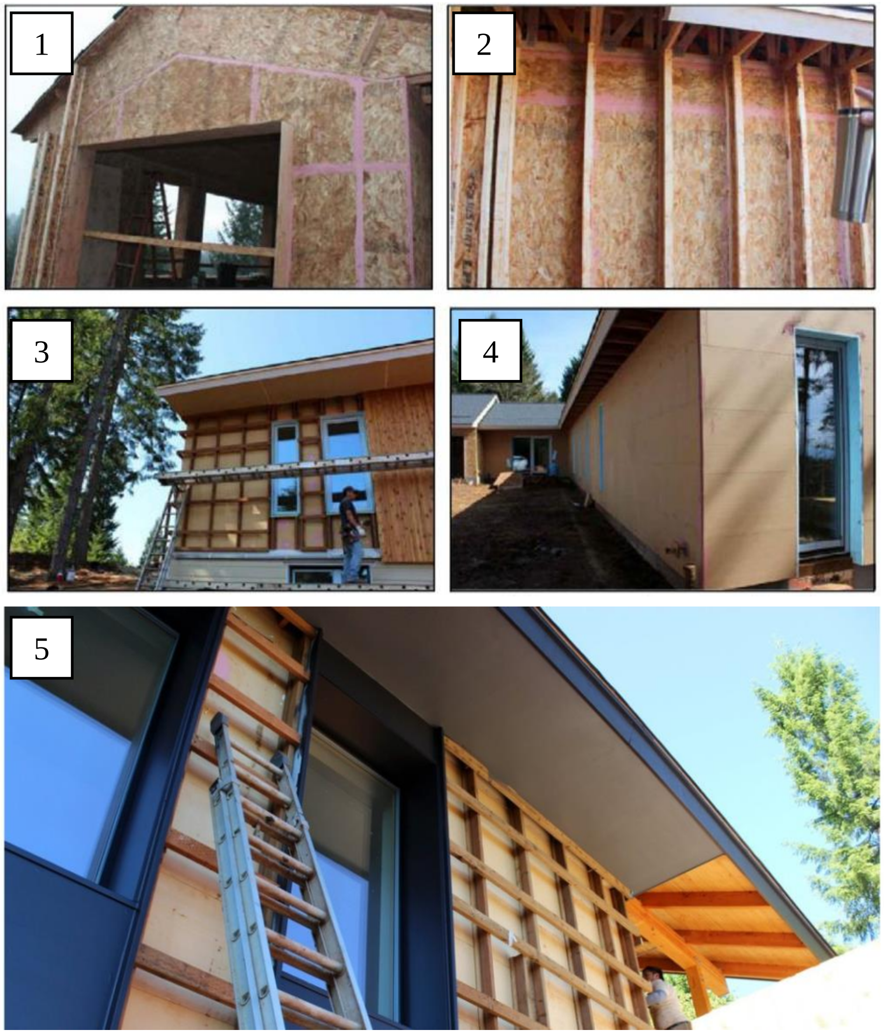


Fig.15. Thermally strong thick and super-insulated passive solar walls by Hammer & Hand. [1] Air Management – OSB with fluid applied membrane at seams, [2] Heat Management – Larsen truss system for exterior layer of high-density cellulose, [3] Water Management – Rain screen cavity lows water to drain, [4] Water Management – Agepan is final layer, [5] Vapor Management – Ventilated rain screen increases drying potential of assembly. (Date Source: Retrieved from Hammer & Hand website)

Previous studies by International Energy Agency (IEA) have also reported advantages of passive solar walls for houses in the US. These studies have been cited extensively under Section

5.2.2.1 of the book ‘Energy Transition: An Overview of the True Challenge of the 21st Century’ titled “Insulation of Buildings”. The section notes that renovation of an old building leads to savings that can amount up to 75% (Petit, 2017). According to this section, insulation works can lead to savings of up to 60% of the energy used for space heating. In the same section, the author cites the “Passivhaus” concept launched in Germany in the 1990s that claims of new buildings reaching insulation performances amounting to 90% of savings in heating (Petit, 2017, p.135).

Section 2.1.1. Passive solar walls in Maine’s homes

In this section, I study existing certified buildings by PHIUS in the entire state of Maine. The “Passive House Map for Maine” suggests that there is a total of sixty buildings in Maine with passive solar walls. Nine of these are single-family homes along Maine’s coast and other islands, as indicated in Figure 16. This map has been created using data from GIS and overlaying data retrieved from passivhausMAINE website (retrieved from www. passivhausmaine. org/passivhausmapofmaine). As of today, there are no homes with passive solar walls in Vinalhaven island. However, the data clearly suggests that homes with passive solar walls are a locally known solution to energy burden in Maine.

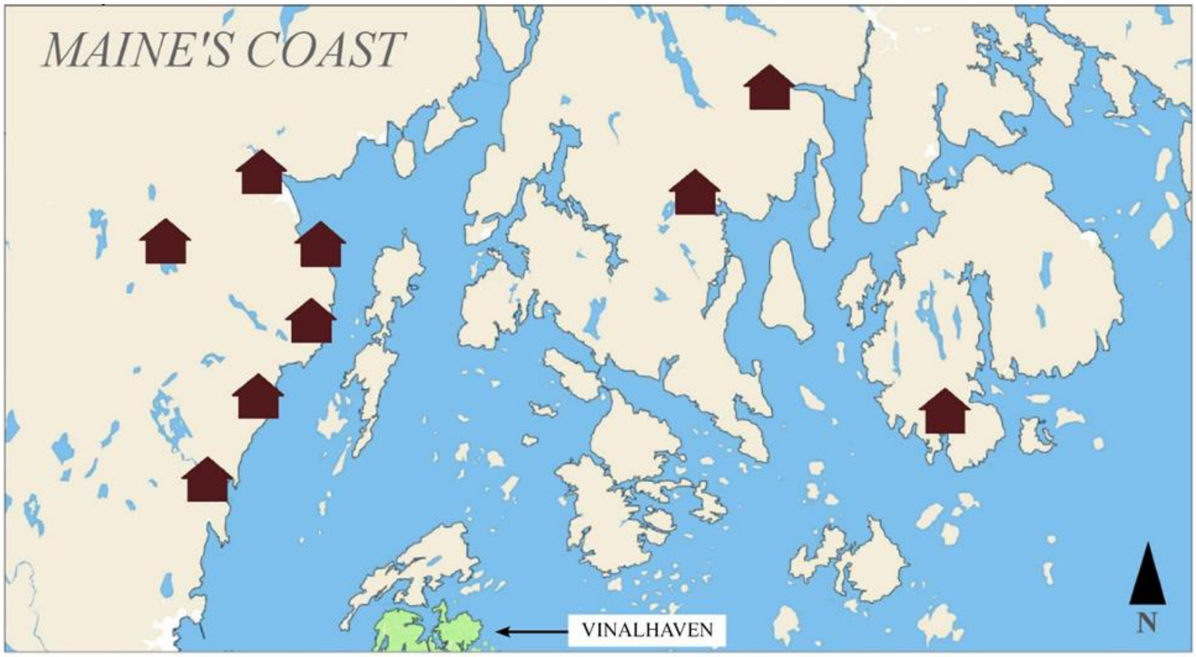


Fig. 16. Maine’s houses with passive solar walls (Data Source: Retrieved from passivehausMAINE website)

I studied a few examples of homes with passive solar walls in Maine. ‘The Maine Solar House’ in Cape Porpoise, Maine has been a good example of the possibilities of solar without compromising quality of lifestyle (Curtis-McLane, Keltz, Trattner, & Widay, 2000). The ‘Small House’ concept by Maine Sunworks ("Small House", 2019) is another example where the walls can be regarded as passive. Figure 17 shows photographs of two homes in Maine with passive solar walls. According to The Island Institute, Maine’s design-build firms like ‘Bungalow in a Box’. design, construct and deliver passive solar homes for Maine’s islands. An island home in Chebeague Island, Maine was prefabricated with ready-to-assemble methods to lower overall energy, costs and need for on-site labor (“Bungalow in a Box offers energy efficiency, ease of construction", 2019). Other firms like Hammer & Hand, Ecocor and Go Logic have developed design-build expertise in this field.

Fig.17. [1] Maine Sunworks, Burnswick, ME. (Data Source: Retrieved from Maine Sunworks website),
[2] House in Cascobay, ME by Bungalow-in-a-Box. (Data Source: Retrieved from Bungalow-in-a-Box website)

Design-production of homes with passive solar walls in other parts of Maine is clearly happening today. It could be seemingly assumed that doing the same for five island homes in Vinalhaven’s downtown will be an obvious solution to my problem statement. Business as usual would be if we substitute existing thermally weak thin standard wall panels with thermally better thick passive solar wall panels. The new and upcoming island homes would follow suite as rapid urbanisation occurs along Main Street. However, in section 2.3. of this chapter, I provide with limitations of today's passive solar walls to support my argument. I argue for the need of a better approach, not business as usual.

Section 2.1.2. 3D CAD model of a passive solar wall panel

Based on datasets from design documentation on passive solar walls publicized by PHIUS and Hammer & Hand, I developed a 3D CAD model of one passive solar wall panel. Figure 18 is isometric representation of a typical passive solar wall-panel developed in AutoCAD 3D modelling software. Such a 3D modelling exercise can guide comprehension of designed artefacts and help in further research and analysis. It has an attached window and multiple layers of components in complex interactions with each other through various connection qualities. Material representation is defined by colour coding where green is for timber (I-joists and studs) and purple is for rigid foam insulation. Additionally, the model considers material components like particle board/agepan vapour barrier, siding (rain screen) and smaller components like steel fasteners. The island homes with such walls have (i) high demand for new thermally performative materials, (ii) high complexity of construction and (iii) highly skilled labour for construction, renovation and assembly.

I enlist the following characteristics of a standard wall panel, based on above-mentioned sources in Vinalhaven’s downtown:

i. Materiality: A typical passive solar wall panel is a complex constructed system of timber studs and I-joists (structural members), rigid foam insulation (performative component), agepan panels (vapor barrier), window glass and frame, and vinyl siding (external rain screen). Conventional steel fasteners keep the components from falling apart. A single-glazed glass is used for the window, held by aluminum a frame.

ii. Dimensions: A passive solar wall panel is 8 feet in height and 9 feet in span. Though the thickness varies depending mostly on amount of insulation, to achieve a whole wall insulation rating of R-53 (suitable for Vinalhaven’s climatic conditions), the optimum total thickness is 2 ft.

iii. Thermal Performance: A typical passive solar wall panel has high thermal mass (from timber) and very high insulation properties (from rigid foam with total R-53).

iv. Cost of construction: The complex set of assembly processes require highly skilled labour and different set of analog tools to build an effective passive solar wall.

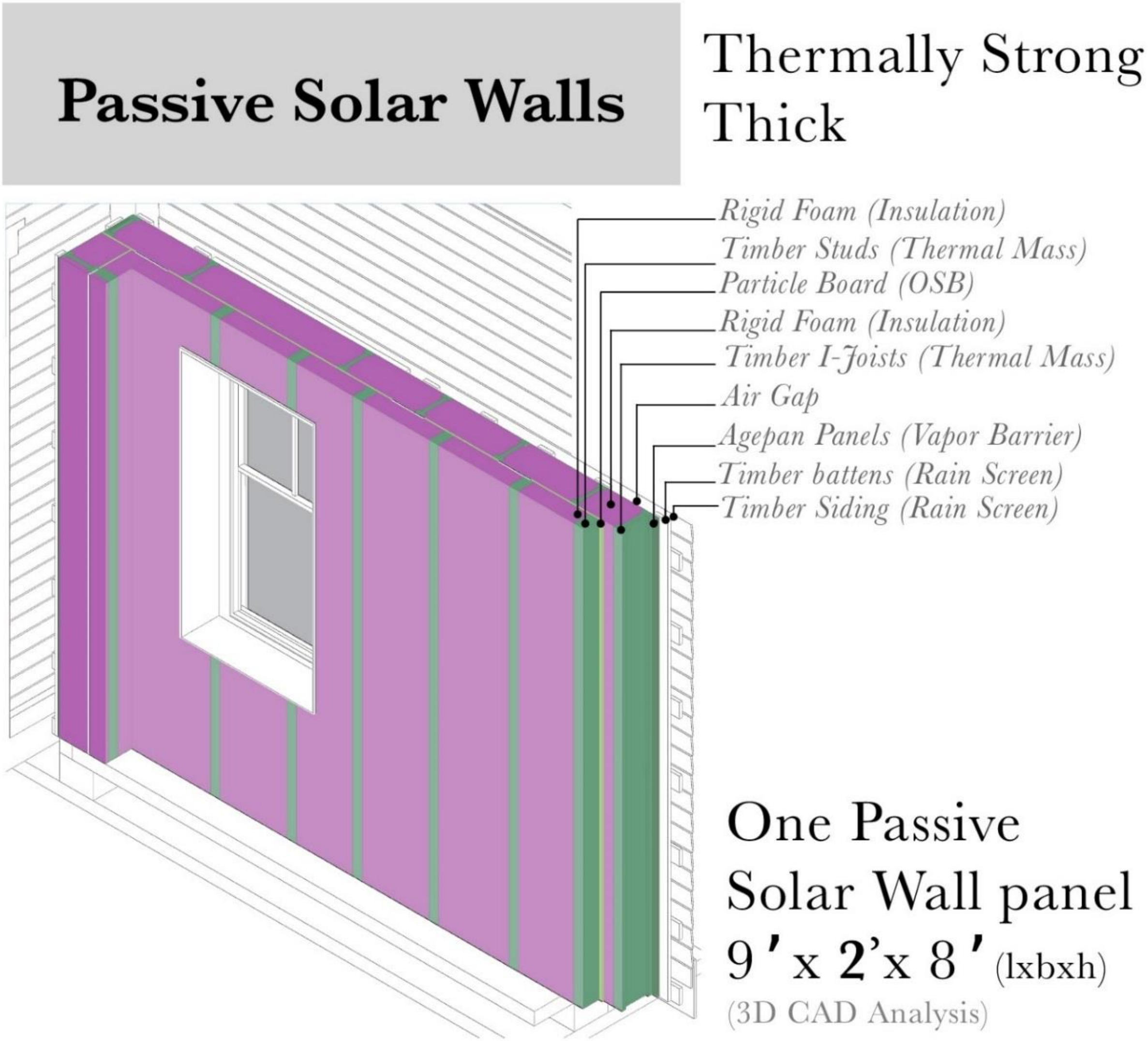


Fig.18. Thermally strong thick Passive Solar Wall panel of 9’x2’x8’ (lxbxh) with have [1] high demand for new thermally performative materials, [2] high complexity of construction and [3] highly skilled labour for construction, renovation and assembly. (3D CAD model created by author, guided by material datasets and dimensions from Passive Solar Wall panels designed-built by Hammer & Hand)

Chapter 2.2. Limitations of passive solar walls

This chapter highlights the shortcomings of passive solar walls in general. My argument that typical passive solar walls are not the appropriate solution to lower energy burden of the five island homes of Vinalhaven's downtown is supported by previous studies and projects that put forth datasets on limitations of such walls. Firstly, passive solar walls have high embodied energy of materials that are non-recoverable due to its complex connection qualities. Passive solar walls have high complexity in construction. For certified-level passive houses, highly skilled labor is required. Since there is an ongoing lack of locally available skilled labor, this solution is not favored. Cost of construction and renovation of passive solar walls is very high, especially due to the need to ship in newly processed materials/components and highly skilled labor. Given the current burden of housing costs and weatherization efforts, this solution will be highly unlikeable. I conclude this chapter of my thesis by asserting that even though thermal performative properties of the walls will increase significantly with intervention of passive solar walls, business as usual will lead to newer burdens. Substituting standard wall panels is a solution but substituting them with typical passive solar walls is not the ideal solution. The sections of this chapter expand on each of these limitations, supported by cited datasets, previous studies and design-build projects.

Section 2.2.1. Non-recoverable material embodied energy

Within the scope of my thesis, the first limitation of passive solar wall is the non-recoverability of the material embodied energy locked in. The huge amount of insulation and the triple-glazed high efficiency windows require a significant amount of energy for manufacture (Crawford & Stephan, 2013). My inquiry into 'embodied energy' benefits from U.S. Department of Energy datasets titled '2011 Buildings Energy Data Book' prepared for the 'Buildings Technologies Program Energy Efficiency and Renewable Energy' in March 2012. A major takeaway from the document is that the Book defines 'embodied energy' as 'energy use includes extraction, processing, transportation, construction, and disposal of each material' (DOE, 2012, p. 1-32). Under the Book's Chapter 1, section 1.6. titled 'Embodied Energy of Building Assemblies', many datasets provide quantified assessments of embodied energy for various building materials and components. The energy embodied in materials of the building components will be regarded as ‘material embodied energy’ throughout the rest of my thesis.

According to the highly-cited international journal paper ‘The Significance of Embodied Energy in Certified Passive Houses’, various case studies conclude that ‘compared to a standard house with the same geometry, structure, finishes and number of people, a passive house can use more energy over 80 years, mainly due to the additional materials required”. This is clearly shown in the paper, cited in this section of my thesis as Fig.19. (Crawford & Stephan, 2013, p. 478). Furthermore, this paper explores a quantitative correlation between price and embodied energy for certified passive houses noting that “the standard house uses less materials overall and costs less to construct”. The same paper compares the contributions of each building element towards the life cycle embodied energy of the case study passive house (Crawford & Stephan, 2013, p. 477). Results show that skin and structure of the passive house contributes the most total initial embodied energy, thereby supporting the focus of my thesis on walls of island homes in Vinalhaven’s downtown.

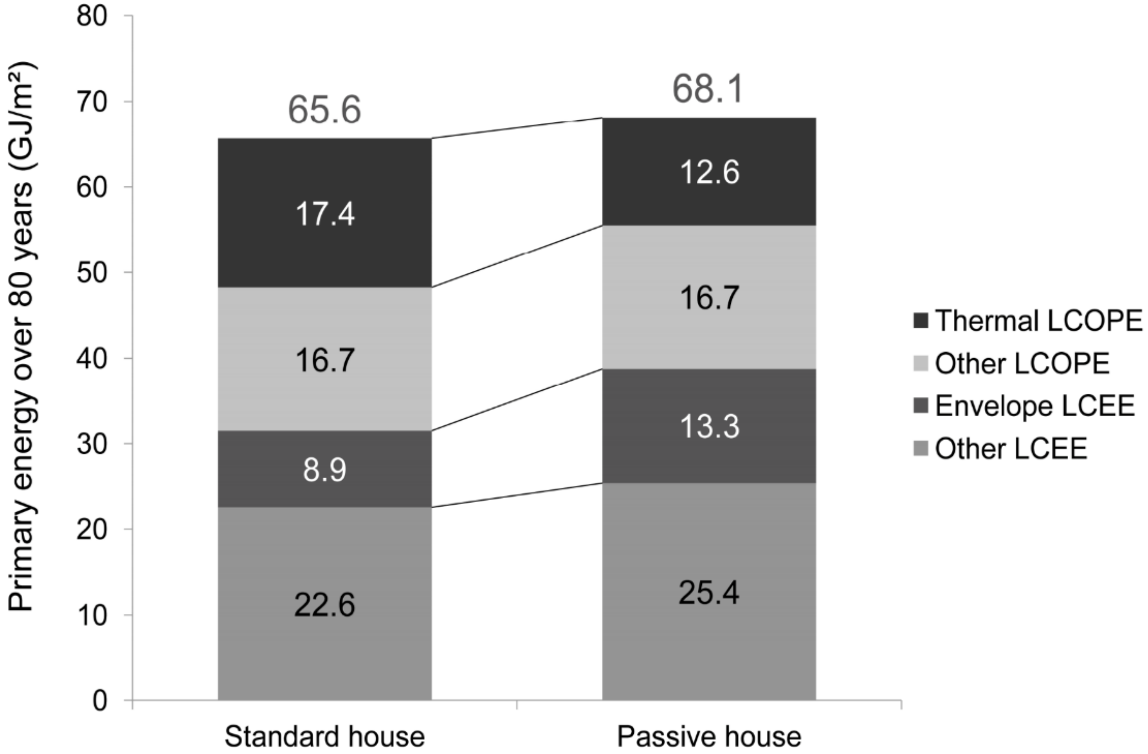


Fig.19. Life cycle energy demand of the case study passive house and a standard house alternative, per m² of usable floor area. Note: LCOPE = life cycle operational energy and LCEE = life cycle embodied energy (Source: Crawford & Stephan, 2013).

Section 2.2.2. Complex construction and renovation

Within the scope of my thesis, the third limitation that passive solar walls pose for Vinalhaven's island homes are non-availability of a complex set of newly processed functional materials (even for conventional passive solar walls), lack of skilled labor for construction and builders' disinterest and economic presumptions on such projects. 'Energizing Maine Households' report by The Island Institute supports this need, describing that the residential energy demands and expenditures escalate just before harsh winters in Maine's islands. 'The Island Institute', based at Maine, has helped these households through projects like weatherization weeks. The Institute observes that apart from being unaffordable, weatherization efforts for these houses face other challenges like lack of skilled labor, lack of interest from contractors to serve island households that have unprofitable returns and lack of newly processed functional materials (Energizing Maine Households, 2017). According to another report by The Island Institute titled 'Save Like an Islander', costly weatherization renovations are needed before extreme winters in Maine's islands. These are in form of increased insulation (Save Like an Islander: Insulation Options for Maine Island Homes, 2015).

Fig.21. Complex construction in Maine's islands (Source: Retrieved from Bungalow in a Box website - http://www.bungalowinabox.com/cascobay.html)

Section 2.2.3. Costly construction and renovation

The third limitation of with today's houses with passive solar walls is of affordability. The statement is supported by the paper 'Economic analysis of passive houses and low-energy houses compared with standard houses'. This paper explores eleven different houses divided into categories of standard house, low-energy house and passive houses. The analysis and study conclude that "the extra cost of ... the passive house is 16% in comparison with the standard house" (Audenaert, De Cleyn, & Vankerckhove, 2008). The paper uses a typical cost-benefit analysis methodology. This paper is important for my dissertation as the analysis questions the economic viability of passive houses. Under section 4.1. 'Specific additional costs', it notes that "the specific extra costs related to passive houses compared with low-energy houses and standard houses can be broken up into seven categories, e.g., costs for heating, ventilation, isolation, air tightness, ground works, differentiation in net floor surface and miscellaneous costs. There is a difference in net surface of the building because of the thicker walls in a passive house and the low-energy" (Audenaert, De Cleyn, & Vankerckhove, 2008, p. 49). Fig. 2. captioned 'Analysis of the specific additional costs of three building types' clearly diagrams that "additional costs for isolation and ventilation result in the biggest surplus cost for the passive house of, respectively, 64% and 27% of total costs". The paper summarizes that "extra costs of the passive house are not in proportion to the savings in energy costs" and "only after 47 years the passive house is more rentable than the low-energy house" (Audenaert, De Cleyn, & Vankerckhove, 2008, p. 50).

Higher cost of designing and building passive solar walls is evident from the documentation of a recent project called 'Cost Efficient Passive Houses as EUropean Standards' (CEPHEUS). The project has been documented in the paper 'CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building' which notes that "passive houses offer a viable option to meet the remaining energy demand only with renewable sources, within the boundaries of availability of renewable energy and affordability". According to the paper, "the improved construction quality of the building envelope and the highly efficient ventilation systems in Passive Houses require extra investment" and "the extra construction and engineering system investment was found to be between 0% and 17% of the pure construction costs" (Schnieders and Hermelink, 2006). The paper notes that the project's "approach is cost-efficient because, following the principle of simplicity, it relies on optimizing those components of a building which are necessary in any case: the building envelope, the windows and the automatic ventilation system" ... "Improving the efficiency of these components to the point at which a separate heat distribution system is no longer needed yields savings which contribute to financing the extra costs of improvement" (Schnieders and Hermelink, 2006, p. 152).

The paper 'Exploring transaction costs in passive house-oriented retrofitting' expands on salient aspects around the cost of renovation of passive solar walls. While this paper too notes that *"the additional investment cost of newly built passive houses can go up to 17% of the total construction costs",* it presents approaches of overall cost reduction that is not tied solely to design optimization. One approach, according to the paper, is that the average additional cost of building a passive house could go down to 5-8% of the conventional construction cost, due to increase in scale (Kiss, 2016, p. 66).

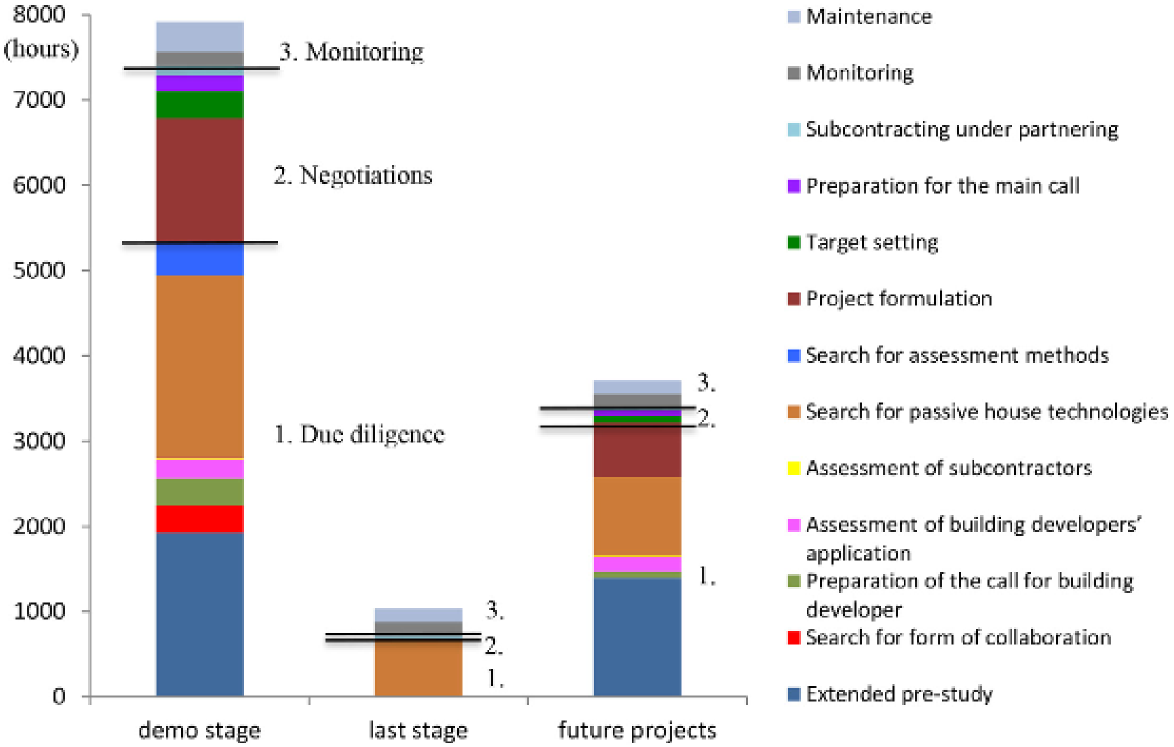


Fig.22. Opportunities to lower transaction costs for passive solar houses (Source: Kiss, 2016)

Chapter 2.3. Comparative CAD Analysis

This chapter provides with supporting studies and framework on using 3D CAD environment for embodied energy calculations. According to the paper "A 3D CAD model of embodied energy for assessment of sustainable construction", the embodied energy module in 3D CAD is an example of integration of a new analysis need (embodied energy) with an existing need (quantities of materials) based on an object-oriented approach to specification of building items. The paper presents a methodology of volumetric analysis for CAD that guides accurate calculation of material embodied energy at the design stage. The provision of fast environmental evaluations of embodied and operating energies and CO2 of whole buildings is a major benefit in evaluation of alternative designs. It requires little additional effort by designers, architects and quantity surveyors to perform embodied energy and CO2 calculations. The 3D CAD model also allows users to compare the embodied energy and CO2 for parts of a building, if required.

Section 2.3.1. Total MEE of one wall panel

This section benefits from the existing CAD-based quantification framework of embodied energy. Material Embodied Energy (MEE), within the scope of my thesis, **is the total initial embodied energy locked in the components/parts of the walls in houses** of Vinalhaven's downtown. The primary material components of the wall to be considered here are:

i. Structural members
ii. Insulation barriers (performative component)
iii. Vapor barriers (performative component)
iv. External siding (rain screen)
v. Window glass
vi. Window frame
vii. Fasteners/connectors

It is to be noted that material embodied energy is purely dependent on factors like volume, weight and the material's embodied energy coefficient (Fig. 23). Thus, for quantification purposes, the initial embodied energy contribution from transportation and assembly of these components and their materials is beyond the scope of my thesis.

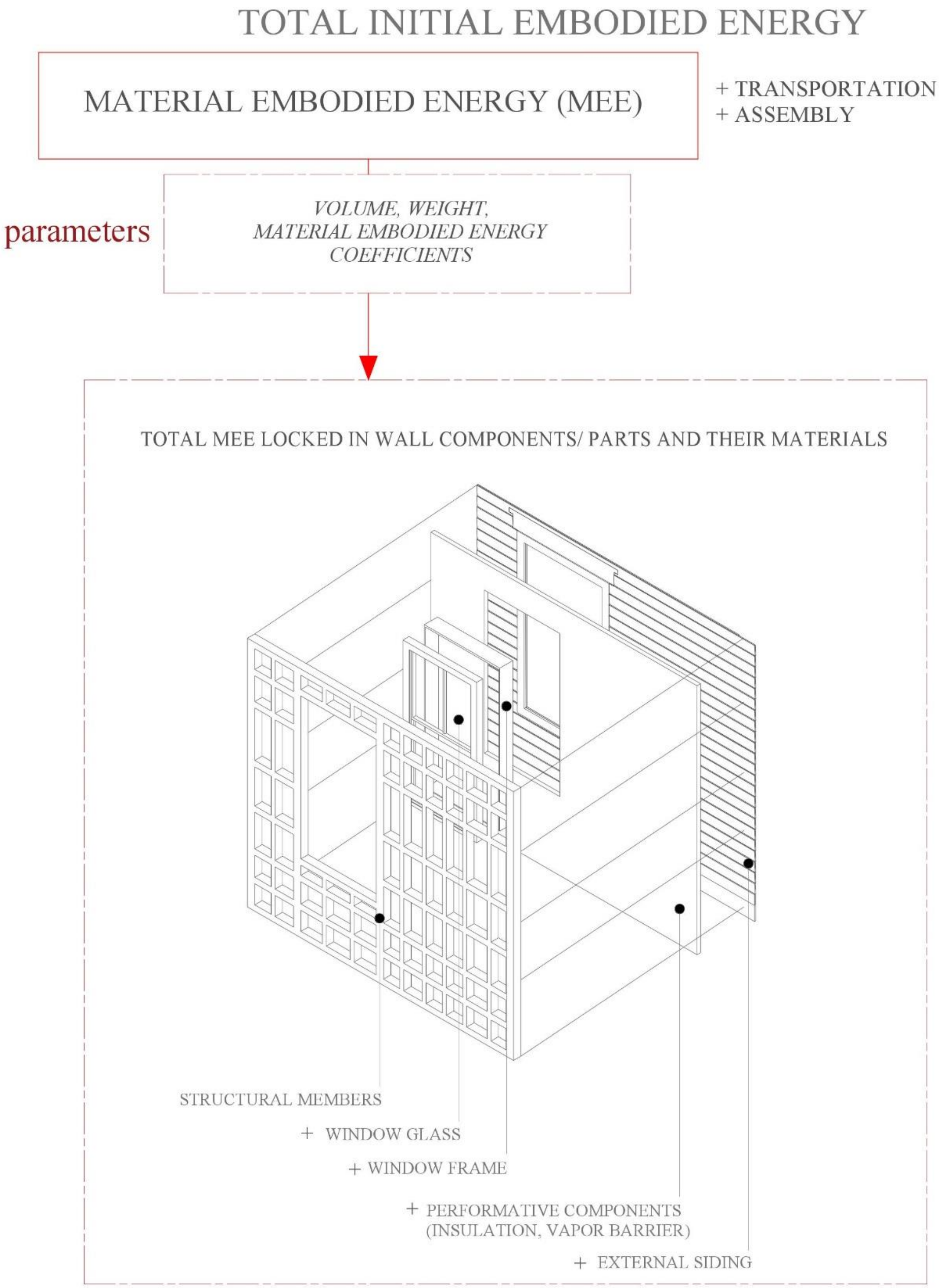
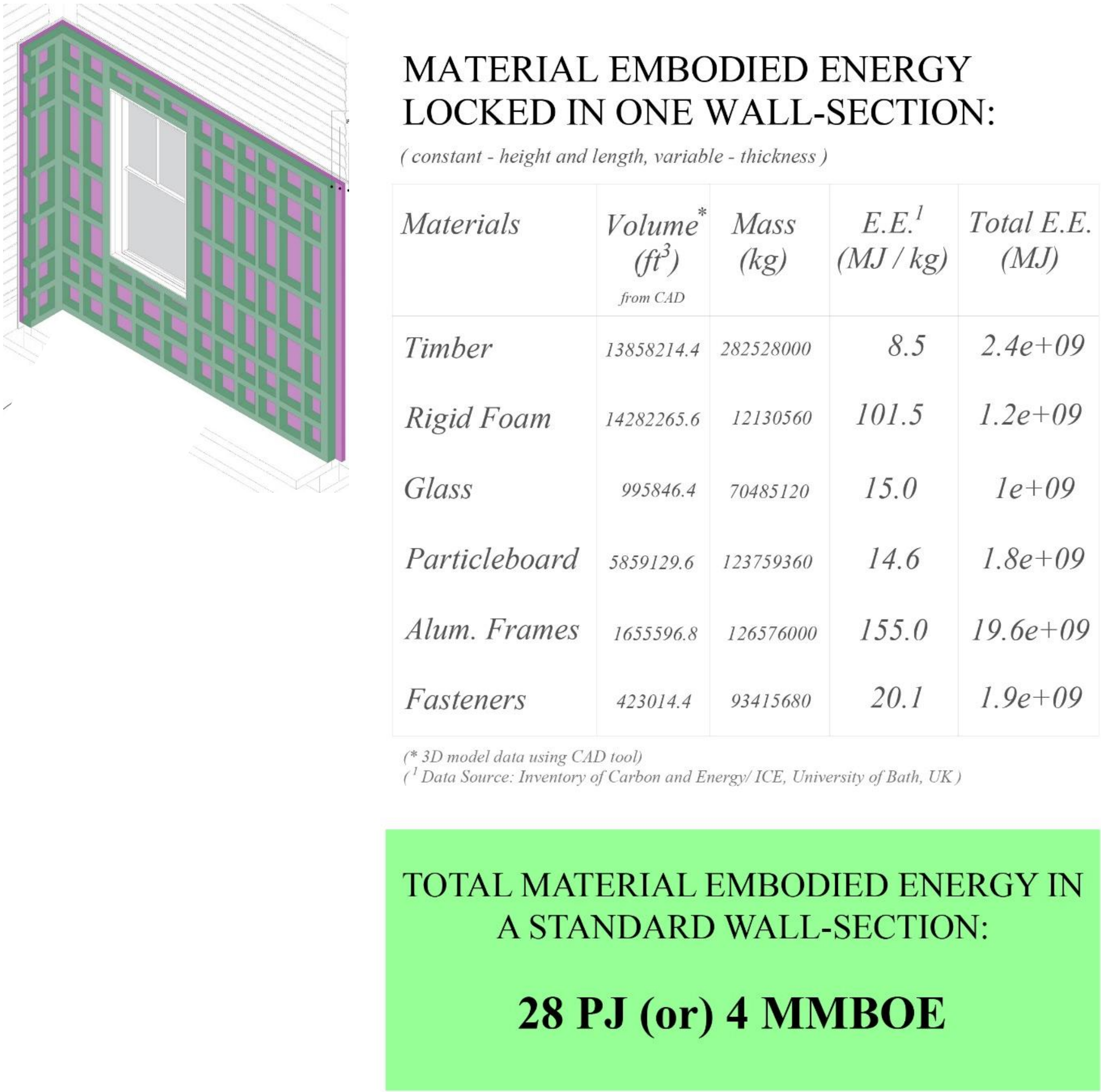


Fig.23. Material Embodied Energy as significant constituent of Total Initial Embodied Energy
(Created by Author)

This section benefits from a CAD-sourced calculation method for quantification of MEE. Following the steps and sourcing initial input data from the 3D CAD models of standard and passive solar wall panels presented in previous section of my thesis, I have documented the results as presented in Fig. 24. and Fig. 25. of this section.

The process involves the following step-by-step process, leading to accurate calculation of material embodied energy from 3D CAD model of any artefact:

1. **Step 1: VOLUME CALCULATION**
   1.1. Input: 3D CAD model with material representation from designer
   1.2. Operation: Volumetric Analysis (geometric approximation)
   1.3. Output: Volume of product/ components (in cu ft or cu m)
2. **Step 2: WEIGHT CALCULATION**
   2.1. Input: Volume of product/ components (in cu ft or cu m) from step 1 and Density constant (in kg/cu ft or kg/ cu m) from scientific data
   2.2. Operation: Weight calculation (mathematical equation: Density x Volume)
   2.3. Output: Weight of product/components (in kg)
3. **Step 3: MATERIAL EMBODIED ENERGY (MEE) CALCULATION**
   3.1. Input: Weight of product/components (in kg) from step 2 and Material Embodied Energy Coefficient (in MJ/Kg) from “Inventory of Carbon and Energy/ ICE, University of Bath, UK” dataset (Hammond & Jones, 2008).
   3.2. Operation: Total Material Embodied Energy calculation (mathematical equation: Coefficient x Weight)
   3.3. Output: Total Material Embodied Energy of product/components (in MJ)
4. **Step 4:** Conversion of quantification of Total Material Embodied Energy of product/components from Megajoules (MJ) to Petajoules (PJ) or Barrels of Oil Equivalent (BOE) or Million Barrels of Oil Equivalent (MMBOE). Barrels of Oil Equivalent (BOE) is an intuitive metric that equates the material embodied energy to the amount of oil / fossil fuel that was burnt in order to produce the material.



MATERIAL EMBODIED ENERGY LOCKED IN ONE WALL-SECTION:

(constant - height and length, variable - thickness)

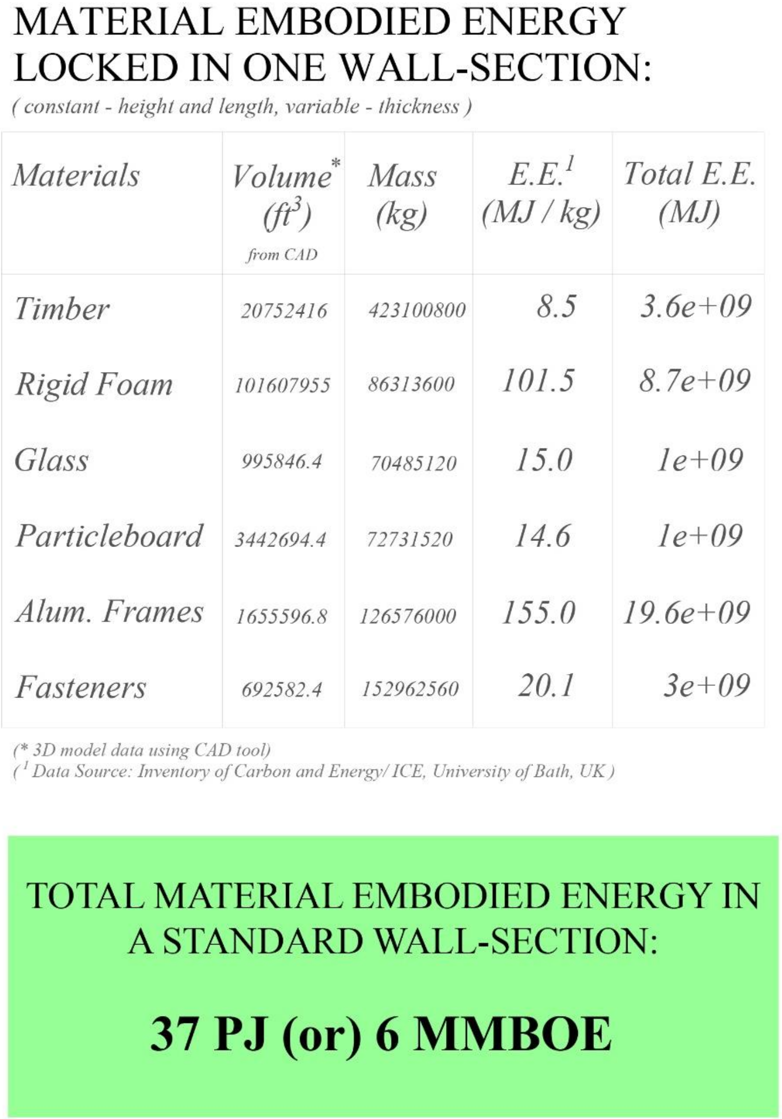
Materials	*Volume* * *(ft^3)* *from CAD*	*Mass (kg)*	*E.E.* [1] *(MJ / kg)*	*Total E.E. (MJ)*
Timber	*13858214.4*	*282528000*	*8.5*	*2.4e+09*
Rigid Foam	*14282265.6*	*12130560*	*101.5*	*1.2e+09*
Glass	*995846.4*	*70485120*	*15.0*	*1e+09*
Particleboard	*5859129.6*	*123759360*	*14.6*	*1.8e+09*
Alum. Frames	*1655596.8*	*126576000*	*155.0*	*19.6e+09*
Fasteners	*423014.4*	*93415680*	*20.1*	*1.9e+09*

(3D model data using CAD tool)*
([1] Data Source: Inventory of Carbon and Energy/ ICE, University of Bath, UK)

TOTAL MATERIAL EMBODIED ENERGY IN A STANDARD WALL-SECTION:

28 PJ (or) 4 MMBOE

Fig.24. CAD-based calculation of Material Embodied Energy locked in one standard wall panel.
(Created by Author, based on data from ICE)



MATERIAL EMBODIED ENERGY LOCKED IN ONE WALL-SECTION:

(constant - height and length, variable - thickness)

Materials	*Volume** *(ft^3)* *from CAD*	*Mass (kg)*	*E.E.*[1] *(MJ / kg)*	*Total E.E. (MJ)*
Timber	*20752416*	*423100800*	*8.5*	*3.6e+09*
Rigid Foam	*101607955*	*86313600*	*101.5*	*8.7e+09*
Glass	*995846.4*	*70485120*	*15.0*	*1e+09*
Particleboard	*3442694.4*	*72731520*	*14.6*	*1e+09*
Alum. Frames	*1655596.8*	*126576000*	*155.0*	*19.6e+09*
Fasteners	*692582.4*	*152962560*	*20.1*	*3e+09*

(3D model data using CAD tool)*
([1] Data Source: Inventory of Carbon and Energy/ ICE, University of Bath, UK)

TOTAL MATERIAL EMBODIED ENERGY IN A STANDARD WALL-SECTION:

37 PJ (or) 6 MMBOE

Fig.25. CAD-based calculation of Material Embodied Energy locked in one passive solar wall panel.
(Created by Author, based on data from ICE)

As per results from calculation of material embodied energy (MEE) locked in the two typologies of wall panels with a window (9ft x 8ft) but varying thickness, the following conclusions are drawn:

1. For a passive solar wall panel, the amount of MEE is significantly higher (additional two million barrels of oil) compared to a standard wall panel with same height and span.
2. The significant contribution towards MEE in both the typologies is from materials like aluminum which is used for window frames. This calls for alternative materials that can perform the same function (Fig. 26.a. i).
3. For a wall panel without any window, the top two contributors to MEE is timber (for structure) and steel (for fasteners). This calls for reimagination of how structural materials and fastening/ connecting materials should be used (Fig. 26.a. ii).
4. Both the wall panels are assembled using metal fasteners that lead to destructive disassembly or demolition during its removal. This is not only an end-of-life issue, since renovation of passive solar walls is a recurring event and the method of assembly makes non-destructive recovery of the high material embodied energy almost next to impossible. Destructive recovery or demolition would mean that the material embodied energy is lost and rendered useless (Fig. 26.b. i).
5. The quantity of materials varies drastically. Aluminum can be replaced with another material of low MEE coefficient since its contribution is only through window frames. However, replacing rigid foam insulation material is not feasible due to its performative advantages. Thus, such non-replaceable high MEE materials could be made more recoverable. Though steel fasteners are in massive quantities, they could be reduced to negligible quantities by designing the other components such that they would not need external fasteners to stay together. This opportunity is explored in detail in the next chapter of my thesis (Fig. 26.b. ii).

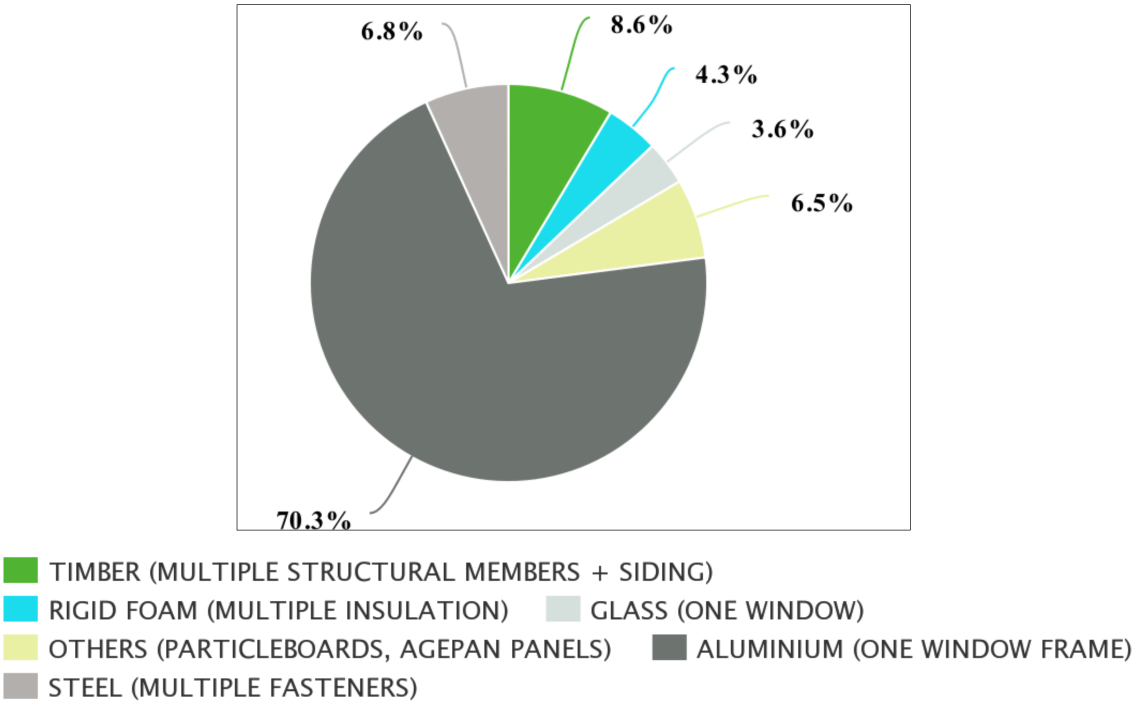


Fig.26. a (i). Pie-chart displaying MEE contribution from different materials in wall components

- One Standard wall panel

(Created by Author, through CAD analysis, based on data from ICE)

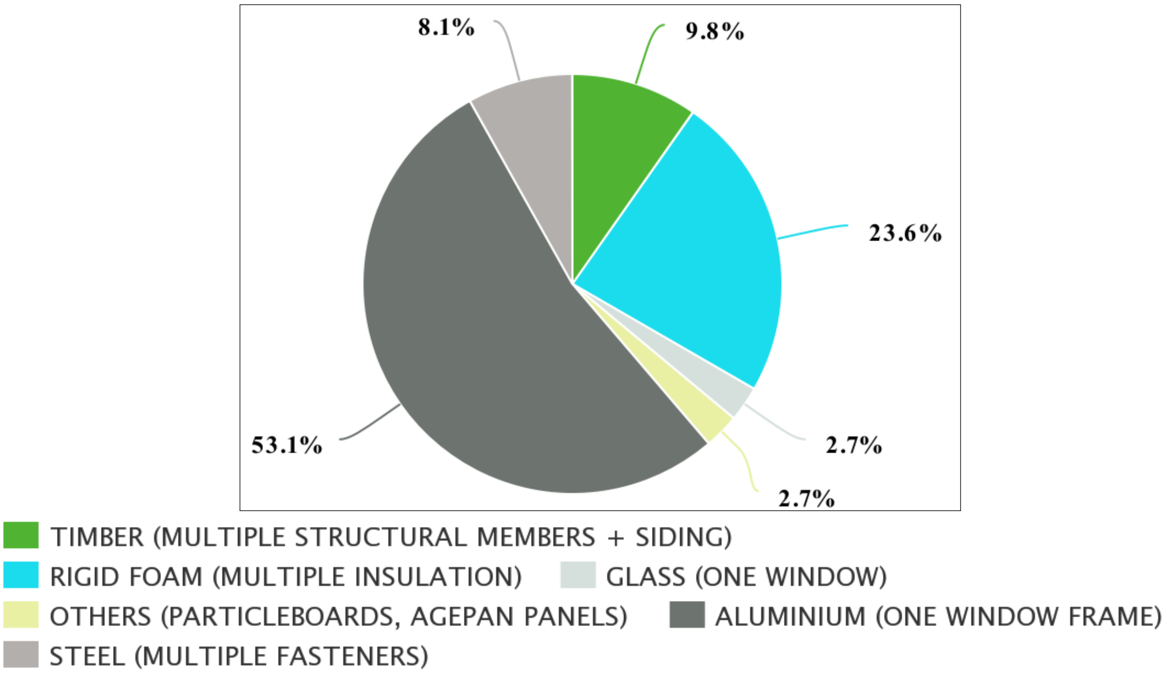


Fig.26. a (ii). Pie-chart displaying MEE contribution from different materials in wall components
– One Passive solar wall panel
(Created by Author, through CAD analysis, based on data from ICE)

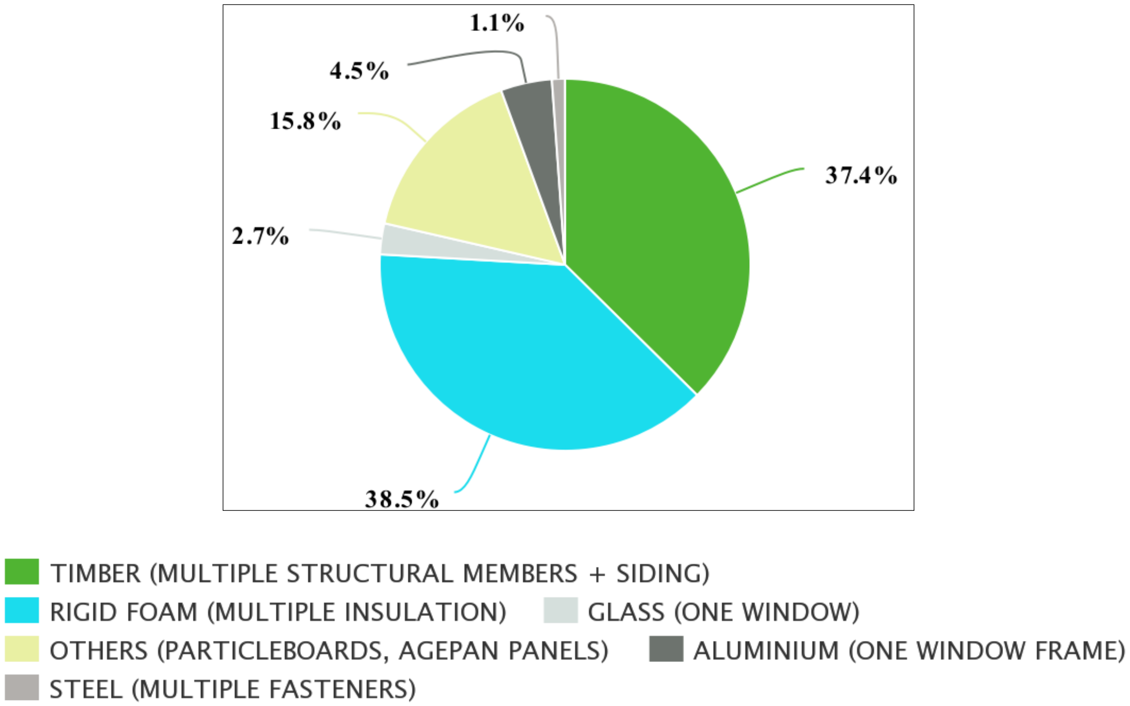


Fig.26. b (i). Volumetric Quantity of different materials in one standard wall panel
(Created by Author, through CAD analysis, based on data from ICE)

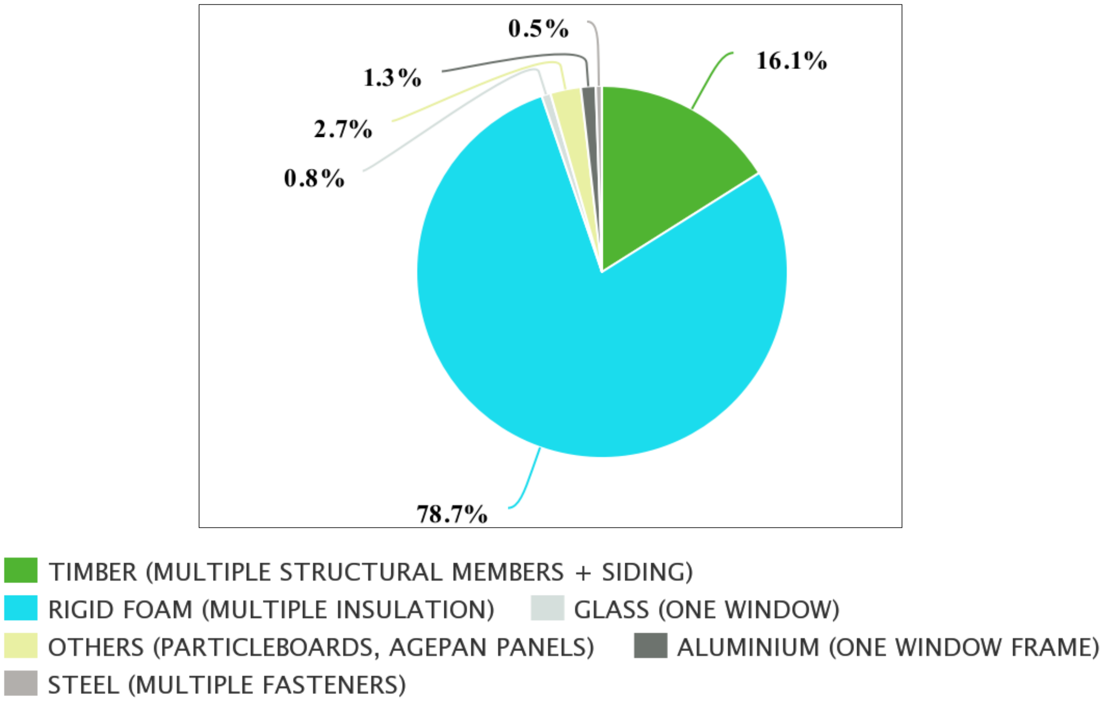


Fig.26. b (ii). Volumetric Quantity of different materials in one standard wall panel
(Created by Author, through CAD analysis, based on data from ICE)

Section 2.3.2. Total MEE of one island home

This section highlights how significant the limitations of substitution with typical passive solar wall panels would be in the scale of one island home. Through a set of speculative diagrams presented as Fig. 27, my thesis showcases the increase in amount of material embodied energy (MEE) that will be needed for successful substitution of all 8 wall panels (as per CAD analysis) belonging to one island home of Vinalhaven’s downtown with passive solar wall panels in order to transition them into passive island homes, thereby seemingly solving their energy burdens. The increased MEE is an edge case scenario which will bloat up further due to addition of embodied energy from shipping in the materials, highly skilled labor and assembly. Quantifying the other factors is beyond the scope of my thesis but recognizing their involvement has been an honest attempt. Substituting typical passive solar wall panels across Vinalhaven’s downtown (Fig. 27), the following conclusions are drawn:

1. Destructive disassembly or demolition leads to material wastes, thus necessitating more newer processed materials. Materials are not easily recovered from standard walls and so have limitation in further reuse. Accurate material embodied energy of wall panels for one island home in Vinalhaven’s downtown is computed in CAD environment.
2. Newer processed materials, skilled labor for complex construction and higher funds for construction are sourced from mainland Maine.
3. Passive solar walls have significantly higher embodied energy in materials than standard walls. Complex construction follows conventional assembly methods.
4. If substitution of one standard wall panel is to occur in Vinalhaven’s downtown with one passive solar wall panel, then it will call for high amount of additional processed materials shipped from mainland Maine and highly skilled labor to perform the complex construction. This would have been ideal given that the material embodied energy could have been recovered significantly.
5. Due to requirement of high amount of materials, complexity of construction and highly skilled labor, the cost of construction and renovation of a passive solar wall panel would be significantly higher than that of a standard wall panel of the same height and span. According to Figure 27, there is a 32% increase in total material embodied energy.

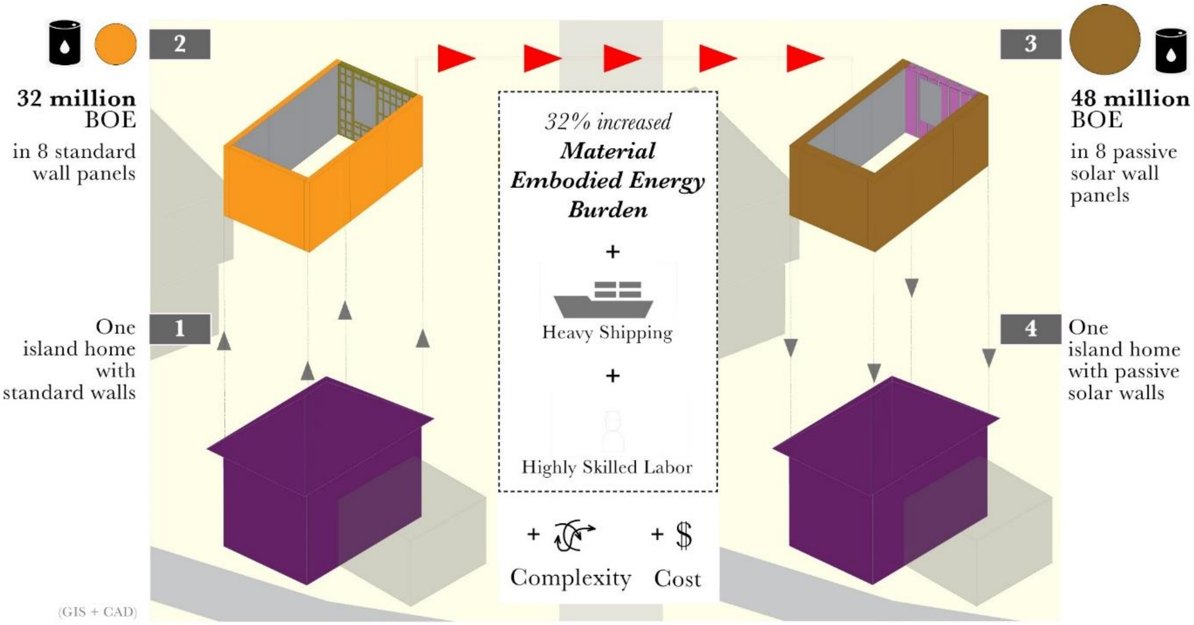


Fig. 27. Increase in initial embodied energy
In case of substitution with typical passive solar walls
(Created by Author, through CAD analysis, based on ICE data)

Chapter 2.4. Summary

More precisely, the problem that my thesis sheds light upon is that even though passive solar walls are regarded as a known solution to substitute standard walls in island homes with high home heating energy and its cost burden, the MEE of typical passive solar walls remain high and non-recoverable. The complexity of construction and high cost of construction and renovation would further hinder large-scale acceptance by low-income islanders of Vinalhaven in Maine. The problem is visibly much bigger when we move from one wall panel to substitution of all 51 wall panels across Vinalhaven's downtown. My thesis attempts to solve for this problem as till date there exists no digital design-production system that can effectively guide designers and builders of these passive solar wall panels to recover its material embodied energy, lower complexity and cost.

Part III: The Research Questions

My thesis addresses two research questions stemming out of the problem statement explained in Part I. The two research questions cater to two different scales of inquiry. The scales are: (1) Study Scale and (2) Island scale. My two research questions pertaining to respective scales are as follows:

1. Study Scale: **How can we digitally design-produce a passive solar wall to easily recover its panels and components?**
2. Island scale: **What are the urban implications when Vinalhaven homes have recoverable wall panels and components?**

In this section, I expand upon the two research questions and the motivation behind them. Figure 28 shows the first goal of materializing a novel passive solar wall through digital systems that has (i) highly recoverable low material embodied energy, (ii) low complexity and (iii) low cost. Figure 29 shows graphically how the two scales perform throughout my thesis as a linear inquiry. In such a method, the answer to my first question would present cues towards formulation of the answer to my second research question.

Addressing these two questions at its respective scales will lead to a comprehensive contribution from my thesis to the field of both design and energetics. The professionals of the building industry like architects, construction agents and urbanists can accelerate global equitable energy transition by 2050 without further contributing to Climate Change, design, construction and delivery are embraced fully by 2030. Materials are what presuppose architecture and thus a digital design-production system that guides recovery of MEE can be crucial in the sustainable way forward. Successful initiatives such as the Architecture 2030 Challenge and the American Institute of Architects' 2030 Commitment strongly justifies the need of a novel system with the pledge to make all new buildings and renovations carbon-neutral by 2030 (“Architecture 2030”, 2019; “AIA 2030”, 2019), exploring ways for architects to lower operational energy in buildings by 2030.

Further motivation for responding to both scales comes from reading about the ‘Embodied Energy Pilot Project’ (EEPP) at Columbia University’s GSAPP with importance of embodied energy in architecture at its core. The project was “an open-ended research initiative aiming to unveil key questions, issues, and opportunities for architectural design in the context of embodied energy” (Benjamin, 2017), documented into a compendium book titled ‘Embodied

Energy and Design'. The book highlights ideas surrounding design and embodied energy in both small iterative experimental scale and large urban and infrastructural scale. Through my thesis, I aim to encourage the building industry professionals to identify digital design-production system as a tool to lower and recover MEE in their upcoming designed buildings.

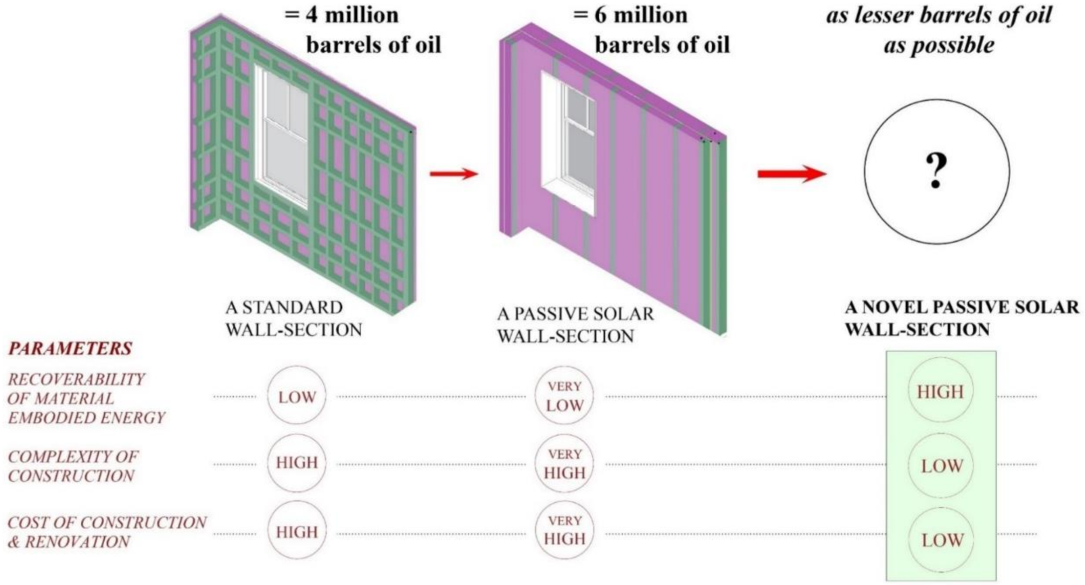


Fig.28. Comparison of wall typologies; need of a novel approach to achieve targets. (Created by Author)

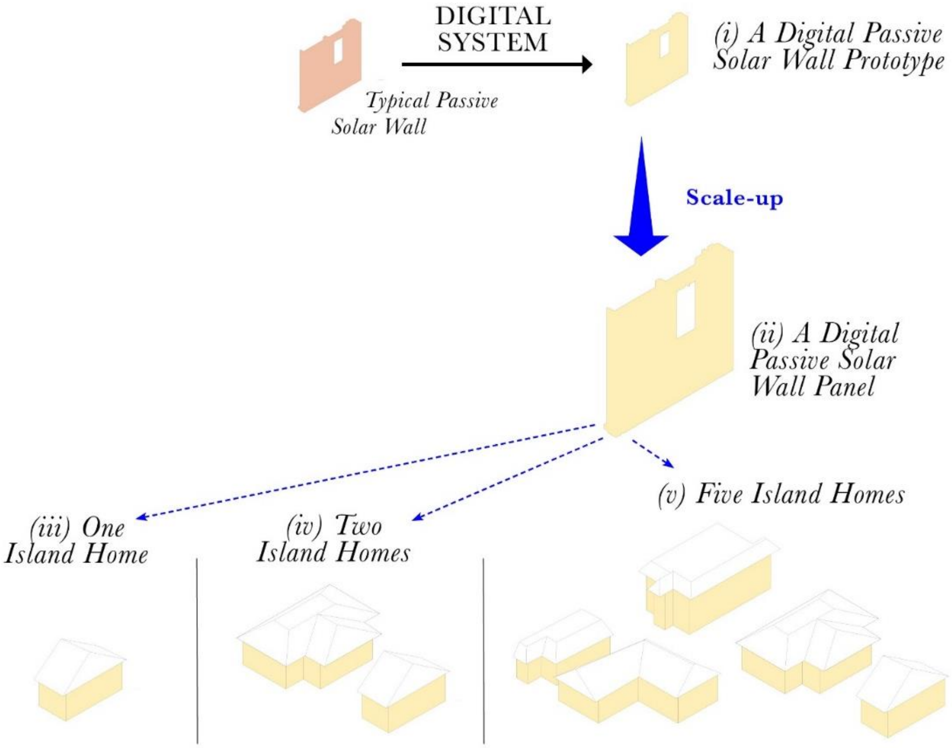


Fig.29. Graphical representation of research goals across two scales. (Created by Author)

Part IV: The Conceptual Framework

This part of my thesis presents a conceptual framework that ties together previous studies the study scale and the island scale in two distinct concepts. The first concept is that successful recovery of material embodied energy (MEE) in a non-destructive way will lead to significant decrease in environmental impacts, cost of construction and renovation and ensure a circular system. I have expanded upon it in chapter 4.1. The second concept is that digital design-production (on-site production of buildings directly from computer models) can guide recovery of MEE, decrease complexity of construction and lower the cost of construction and renovation significantly. This concept has been further expanded in chapter 4.2. supported by previous studies on advantages of digital systems like CAD-CAM interface.

Chapter 4.1. Recovery of material embodied energy

In this first section of conceptual framework for my thesis, I claim that developing a system that guides successful recovery of material embodied energy in a non-destructive way will lead to significant decrease in environmental impacts, cost of construction and renovation and ensure a circular system. My claim is supported by Philip Crowther's paper on 'Design for Disassembly to Recover Embodied Energy'. According to the paper, there have been examples of buildings throughout history that have been designed for disassembly, from primitive nomad tents, through the nineteenth century Crystal Palace and portable colonial cottages, to visionary works of Buckminster Fuller, Archigram and the Metabolism group (Crowther, 1999). Under section 5, 'Disassembly to Reduce Energy Consumption', the paper asks the research question 'What then can be done to reduce this large energy burden?'. Answer is presented in three ways: to reduce energy consumption in operation by designing buildings that maintain an internal environment through the more efficient use of energy and the use of passive energy design, to reduce embodied energy consumption through the use of low energy content building materials and to reduce embodied energy consumption through the reuse, recycling and remanufacturing of building materials. Crowther postulates certain guidelines for DFD, considering issues like the use of mechanical connection rather than chemical ones, separating structure, enclosure and services, creating components to a size suitable for handling during disassembly, standardization and compatibility with other systems, aiding permanent identification of materials, components and procedures, employing common building practice and user participation, providing access for the disassembly process, allowing for concurrent or parallel disassembly of components.

Another paper by Crowther titled 'Developing an inclusive model for Design for Deconstruction' points to the lack of understanding or knowledge of design for deconstruction in architecture. The required knowledge can be attained by asking questions like why deconstruct, when to deconstruct, where to deconstruct, what to deconstruct and how to deconstruct. The paper presents a major hindrance in successful deconstruction, which is non-destructive recovery (the difficulty in recovering items in good condition). If buildings were initially designed for deconstruction, it would be possible to successfully recover much more material for reuse. This would have significant advantages both economically and environmentally. Under the section 'The Theory of Layers', the paper cross-references two crucial terminologies related to buildings i.e. 'structure' and 'skin' from a seminal book 'How buildings learn: What happens after they're built' on exploring the process involved in the evolution of buildings. The central concept of the book is where author outlines what he terms the generic "six S's" as the core to understanding the nature of how buildings change. My work benefits from two that author characterizes as Structure and Skin. Structure, in the paper, is regarded as having life-cycle of 30 to 300 years and costly to change. Skin, in the paper, is regarded as having life of 20 years and needs renovation more frequently.

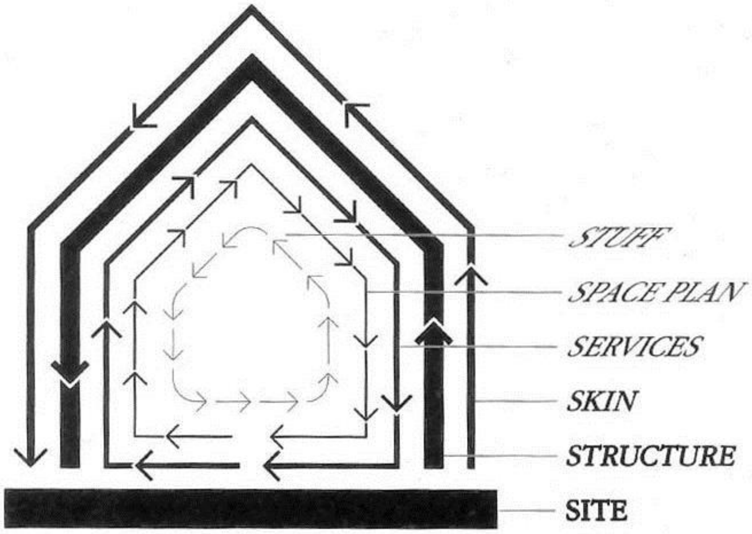


Fig. 30. Skin and Structure as two of Brand's S's (Brand, 1994, p.13)

My thesis benefits from the study of these layers that are useful in physically determining the places within a building that deconstruction might most usefully occur, and at what time deconstruction might occur. Under section titled ‘Building Layers and Deconstruction’, the paper notes that “theories of building layers can have a major impact on the design of, or analysis of, buildings for deconstruction. The interfaces between the layers can obviously become primary points of deconstruction for the building. The argument is not just however that they can become points of deconstruction, but that they should become points of deconstruction”. (Crowther, 2001). Another crucial input for my thesis is derived from section ‘Recycling Hierarchy in the Built Environment’ mentioning the end-of-life scenarios identified by industrial ecologists; reuse, repair, reconditioning, and recycling of materials. The model is then simplified by separating the scenarios into two levels; the product level, and the material level. The scenarios of reuse, repair, and reconditioning are placed in the product level since they are concerned with product components or subassemblies, while the recycling scenario is placed in the material level since it is concerned with base materials. (Crowther, 2001).

Based on above studies and conclusions from previous sections, for a passive solar wall panel with high MEE locked in the timber thermal mass and in the metallic fasteners or connectors, the following decision can be taken:

- Non-destructive disassembly of timber from walls
- Complete reduction of metallic fasteners or connectors for assembling walls

Chapter 4.2. Digital Design-Production

Within the scope of my thesis, my second concept is a digital system that enables on-site production of buildings directly from computer models. The CAM-Oriented CAD model aims to simplify the design process and lay foundation for future development in automatic extraction of data required for the construction stage. As per this methodology, first the designer adapts a component-oriented library to cast or recast the building model. The model resultantly leads to high design productivity in both the (recast) traditional model and especially in its automatic version. CAD-CAM machinery for fabrication is on a rise in current architectural construction as an intermediary between design concepts and real-world construction. Contemporary designers attempt to identify their concepts in construction using CAD-CAM technologies applied to digital designs in the finishing stages of design process, an extraordinary example being the work of Gehry Partners with their complex shapes as physical models made traditionally of paper, cardboard and wood. Designs are later created using parametrically based software and CAD-CAM manufacturing techniques.

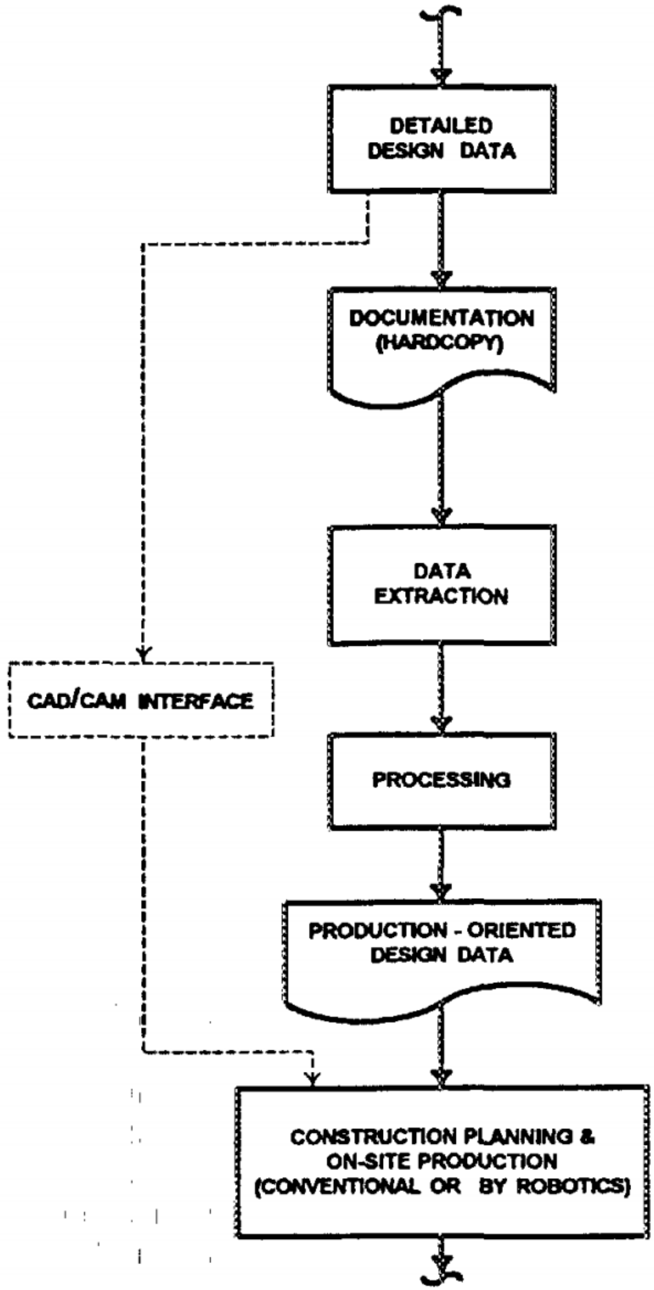


Fig. 31. CAD-CAM interface methodology (Navon, 1995, p. 237)

According to the paper ‘Materializing design: the implications of rapid prototyping in digital design’, CAD-CAM machinery for fabrication is on a rise in current architectural construction as an intermediary between design concepts and real-world construction. Also common is large CAD-CAM machinery employed in bending and cutting metals from CAD files in form of G-Code. Apart from being a way of building, the CAD-CAM building fabrication process can be considered a mode of thinking about construction through machine-interaction. Contemporary designers attempt to identify their concepts in construction using CAD-CAM technologies applied to digital designs in the finishing stages of design process, an extraordinary example being the work of Gehry Partners with their complex shapes as physical models made traditionally of paper, cardboard and wood. Designs are later created using parametrically based software and CAD-CAM manufacturing techniques. Digital fabrication is a large field partly comprising of rapid prototyping (RP), using the application of RP for design and CAD-CAM for construction.

Various aspects of production of buildings directly from computer models is explained by the recent paper ‘Housing Prototypes, Timber Tectonic Culture and the Digital Age: Innovative Techniques of Representation in Architectural Design’. In this paper, three recent residential architecture prototypes have been discussed which embrace digital design to fabrication. The projects could be held as exemplars of the capacity potential of digital design to file-to-factory. The paper presents growing role of timber-based products, in a digitally enabled domestic construction industry.

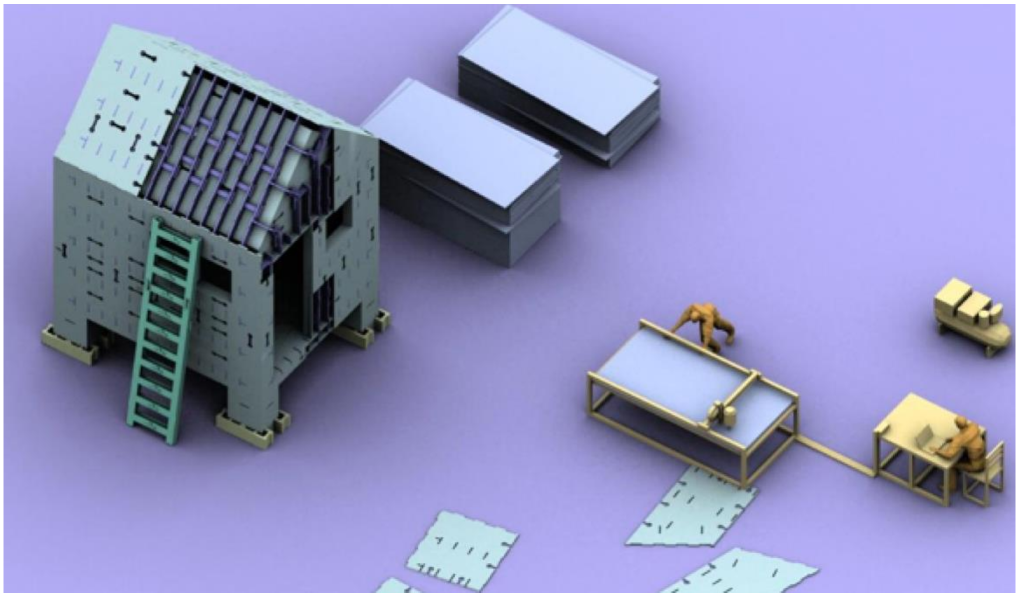


Fig. 32. On-site production of buildings directly from computer models. Retrieved from website of Digital Design Fabrication Lab, discussed in paper Sofia & Blair (2019)

My thesis identifies digital fabrication tools as a viable technology to recover MEE. Its relevance is supported by the paper ‘Environmental design guidelines for digital fabrication’ that presents “environmental guidelines to be considered during the design of digitally fabricated architecture.” There are three case studies presented in the paper, each establishing a comparison between three digital fabrication projects and three classic building elements with the same function. Environmental impact of their respective wall, floor and roof is compared from the perspective of building material use. The major takeaways from the paper are expanded under section 5 titled ‘Synthesis and guidelines. The section states that “the results of the evaluation indicated that the energy and resource consumption of the robotic fabrication processes contributed minimally in terms of energy and environmental impacts. The first and third case studies highlighted the low relative impact of digital fabrication compared with materials production. Specifically, the production of digital fabrication technologies had a negligible impact on all midpoint categories from both case studies. Additionally, the relative contribution to environmental impacts of the robotic construction process was low.” (Agustí-Juan & Habert, 2017, p. 2789).

Part V: The Methodology

This part of my thesis presents the methodology that guides development of the digital design-production system as well as informs speculation of urban implications of the wall substitution process in Vinalhaven's downtown. Methodology for my thesis is divided into three chapters. The first chapter is literature study, that presents supporting literature and data sources in both study scale and island scale in respective sections. The study scale highlighs relevant studies on disassembly theory that involves learning terminologies of the field. The island scale focusses on data collection from community partners like The Island Institute reports. The other two chapters are Design for Assembly, Disassembly & Reassembly (DfADR) Framework (chapter 5.2.) and Rapid Prototyping (chapter 5.3.).

Chapter 5.1. Literature study

The first methodology is search & review of previous literature on current methods and ideas around recovery of material embodied energy. Literature search needs to incorporate a combination of protocol driven, snowballing and personal knowledge approaches. A search that is restricted to database searching alone is likely to locate a very small percentage of relevant articles. A combination of following steps was carried out under this methodology:

1. Snowballing (emerging as the study unfolds)
2. Reference tracking (scanning the reference lists of all full text papers)
3. Citation tracking (using special citation tracking databases to identify articles that had subsequently cited those papers)
4. Serendipitous discovery (such as finding a relevant paper when looking for something else).

My literature search & review employs majorly the snowballing technique that involves two approaches. First, scouring references sections of articles already included in the review. Second, using certain citation tracking databases to identify articles that had subsequently cited papers that are included in the review. The first approach works back in time from an article, whilst the second approach works forward in time from that article.

The parameters or phrases for literature study are: ‘recover material embodied energy / embodied energy’. The major techniques used in the methodology are snowballing, reference tracking and citation tracking. As a result of literature search & review, the seminal works pertaining solely to ‘recovery of MEE’ are enlisted chronologically as follows:

1. ‘Design for Assembly and Disassembly’ (Boothroyd & Alting, 1992)
2. ‘Design for disassembly to reuse embodied energy’ (Crowther, 1999)
3. ‘Developing an inclusive model for Design for Deconstruction’ (Crowther, 2001)
4. ‘Disassembly modeling for assembly, maintenance, reuse and recycling’ (Lambert & Gupta, 2004).
5. ‘Re-Valuing Construction Materials and Components through Design for Disassembly’ (Crowther, 2015)
6. ‘Disassembly Sequencing: a survey’ (Lambert, 2003)
7. ‘Application of Cognitive Robotics in Disassembly of Products’ (Vongbunyong, Kara & Pagnucco, 2013)
8. ‘Concept of an autonomous disassembly system using behavior-based robotics’ (Tani & Guner, 2012)
9. ‘Recycling potential and design for Disassembly in Buildings’ (Thormark, 2001)
10. ‘Designing for Disassembly (DfD)’ (Durmisevic & Yeang, 2009)

The enlisted ten studies and works form the library of literature upon which I build my own conceptual framework. The significant learns and theoretical derivations from these studies has been explained further in sub-section 4.1.1. of this section.

Section 5.1.1. Study Scale : Disassembly Theory

Based on initial literature study, ten works have been enlisted for their contribution towards ‘recovery of MEE’. All of these works have a common strategic thread based on what is called ‘Disassembly’. The following table presents extracted content from the studies that guide my understanding of the term ‘disassembly’, within the scope of my thesis.

S. No.	NAME OF PAPER / LITERATURE	THEME	DISASSEMBLY CONTENT
1.	‘Design for Assembly and Disassembly’ (Boothroyd & Alting, 1992)	Product/engineering	“More recently, environmental concerns are requiring that **disassembly** for service and recycling be considered during product design - in fact, total life cycle costs for a product are becoming an essential part of simultaneous engineering.”

2.	‘Design for disassembly to reuse embodied energy’ (Crowther, 1999)	Architecture/construction	“If buildings were designed for **disassembly**, rather than demolition, greater proportions of building materials could be salvaged for reuse.”
3.	‘Developing an inclusive model for Design for Deconstruction’ (Crowther, 2001)	Architecture/construction	“The issues of design for **disassembly** need to be located within a general model for sustainable construction so that the external consequences of a design for deconstruction strategy might be highlighted and considered.”
4.	‘Disassembly modeling for assembly, maintenance, reuse and recycling’ (Lambert & Gupta, 2004)	Product/engineering	“**Disassembly** is a process in which a product is separated into its components and/or subcomponents by nondestructive operations.”
5.	‘Re-Valuing Construction Materials and Components through Design for Disassembly’ (Crowther, 2015)	Architecture/construction	“Analysis at material, component, and whole-of-building levels shows the potential benefits of strategically designing buildings for future **disassembly** to recover this embodied energy.”
6.	‘Disassembly Sequencing: a survey’ (Lambert, 2003)	Product/engineering	“Usually, end-of-life **disassembly** is a process in which uncertainty is encountered, both in quantitative and qualitative product”
7.	‘Application of Cognitive Robotics in Disassembly of Products’ (Vongbunyong, Kara & Pagnucco, 2013)	Automation/robotics	“...**disassembly** is still performed manually due to the uncertainty associated with the quality and the quantity of the returned EOL products. In this paper, a cognitive robotics-based system is proposed to address this problem.”
8.	‘Concept of an autonomous disassembly system using behavior-based robotics’ (Tani 2012)	Automation/robotics	“Automatic **disassembly** of disused products into parts is important for high-level recycling.”
9.	‘Recycling potential and design for Disassembly in Buildings’ (Thormark, 2001)	Architecture/construction	“Design for **disassembly** is a design aiming at a construction which is as easy as possible to dismantle, i.e. a design which facilitates future reuse or recycling of included materials or components.”
10.	‘Designing for Disassembly (DfD)’ (Durmisevic & Yeang, 2009)	Architecture/construction	“…replaced components in the building lifetime, nonetheless partitions, as other building components, are still frequently built with construction methods...that don't cater for reuse or **disassembly**.”

Table 2. Review of previous study on ‘disassembly’ from the perspective of products, engineering, architecture and construction.

The table shows the prevalence of the idea of disassembly and the body of work that already exists on the same. I am deriving the fundamental notions of the term from such existing literature which form the core of my research. My thesis extensively draws inspiration from assembly, disassembly & reassembly methodology explained in the seminal journal book published by ***CRC Press titled 'Disassembly modeling for assembly, maintenance, reuse and recycling', written by A.J.D. Lambert & Surendra M. Gupta.***

The book highlights 'disassembly theory' for artefacts, and that the theory is not confined to studying the disassembly process of a given product, but it also addresses the design issues. Design for disassembly (DfD), as an extension of design for assembly, has been popular since the early 1990s. Simultaneously considering in the design all phases of the product life, including production, consumption, maintenance, and the end-of-life, is called design for life cycle. This implies that, even in the conceptual phase of a product, the design of appropriate production systems and dismantling systems should be considered, because these systems depend strongly on the design of the product itself and vice versa. According to the book, *"Disassembly is a process in which a product is separated into its components and/or subcomponents by nondestructive operations."* A useful division in aggregation levels has been presented in the book that suggests the following hierarchy: Primitive level, Component level, Product level and Batch level.

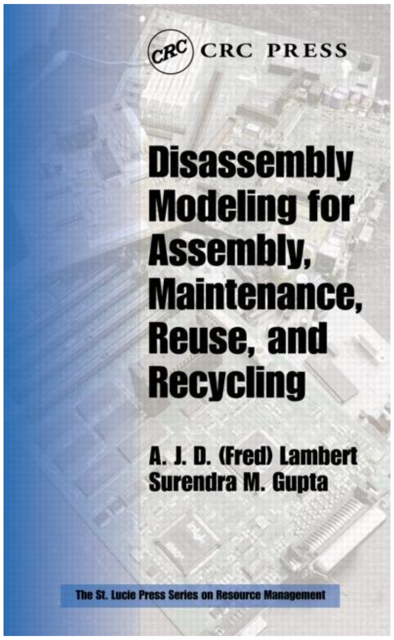


Fig. 33. Comprehensive literature explaining disassembly theory, sequencing and planning

For my thesis, the component level is significant. This level deals with the movement of components in the course of disassembly operations and their possible interaction with other components. It deals with topics such as geometric and topological constraints and, consequently, precedence relationships. According to the book, the product level is applied if the analysis of a product is required, for studying the relationships between the disassembly operations and the sequence of those operations. A distinction can also be made between the product and the system approaches, also known as the product-oriented and process-oriented approaches. The product-oriented approach focuses on how components interact, and the process-oriented approach deals with how workstations and tasks interact. Both approaches are tightly intertwined.

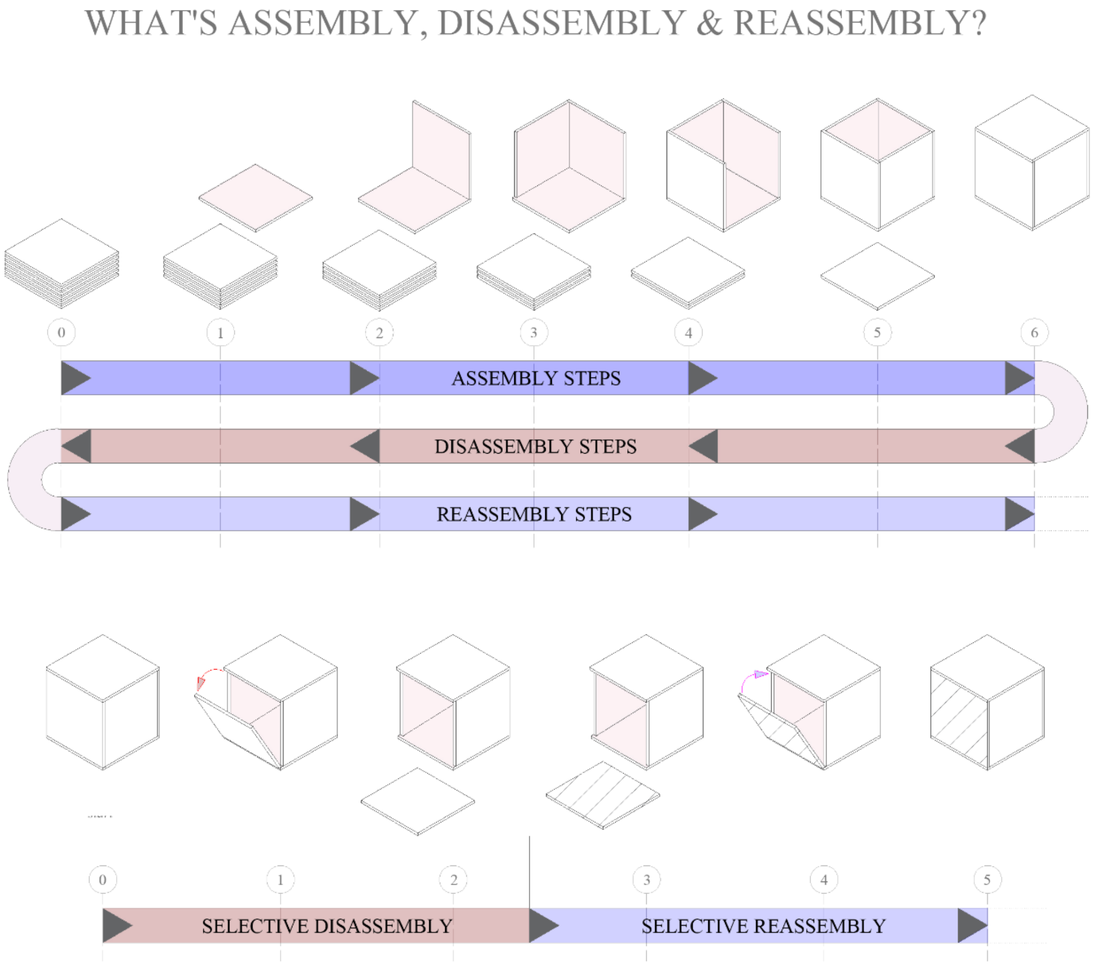


Fig. 34. Steps involved in assembly, disassembly & reassembly of artefacts. (Created by Author)

Current systems to recover embodied energy in form of building materials and components lack specificity in methodologies. Geoffrey Boothroyd's seminal paper titled 'Design for Assembly and Disassembly' expands on specific methods in design-build process like reduction of number of parts, reduction of number of assembly processes, etc. The paper defines "design for assembly" as "the design of the product for ease of assembly". The paper explains the term "disassembly" as "the disassembly of certain parts from a product in order to replace a service item would mean the careful unscrewing of screws, removal of parts, and placing them in accessible locations for subsequent reassembly" (Boothroyd & Alting, 1992, p. 625).

A prime part of the methodology is 'Disassembly sequencing' that addresses the question, "How to disassemble?" and 'Disassembly planning' that delineates "How much to disassemble?". The disassembly process starts with the product. The product represents a functionality (ability to provide services). The product consists of several discrete parts, which are called the components. A component cannot be further disassembled and is sometimes called an atomic part for this reason. Components can be grouped in subassemblies. A subassembly is a connected set of components. A subset is also a set of components of the product that is not necessarily connected. Yet another way of grouping of the components is in modules, which are functional units, composed of components. If components are physically linked, such a link is called a connection. The terms liaison and joint are also used by several authors.

If the components are nearly in touch with each other, this can be considered a virtual connection in some cases. Connections restrict the freedom of motion of the components involved. This can be established in different ways, the most uncomplicated way of which is mating.

In many cases, specialised components, or parts of components, called fasteners, are used for connections. Fasteners can be discrete components such as screws, or non-discrete material objects such as snap fits. If the fastener is a component, but not considered as such in modelling, it is considered a quasi-component.

Disassembly operations accomplish the basic transformations in the disassembly process. These can be defined according to two different approaches:

1. The disestablishment of connections (other than mating surfaces)
2. The detachment of components or subassemblies

These steps can be generalized by defining the disassembly operation as the removal of quasi-components, components, or subassemblies. Disassembly operations are subdivided into disassembly tasks, which are unit operations on a lower level of aggregation. These involve preparatory tasks such as the establishment of a fixture, changing tools, repositioning the product, etc. Apart from this, there are proper disassembly tasks, which include:

1. Getting access to a component/subassembly
2. Moving a component
3. Removing a component
4. Collecting a component

According to the book, *"nondestructive disassembly operations are disassembly operations that do not impair the components"*. The book further defines complete disassembly as the separation of a product into all its components. Incomplete disassembly also involves the separation of a product but not all the components are separated from each other. The disassembly depth is the extent to which the disassembly process is carried out. A term significant to my thesis is selective disassembly which is a disassembly process that has to meet some specific criteria. It should be stressed that incomplete disassembly does not have a counterpart in assembly and hence is different from reverse of assembly, because assembly is aimed at obtaining a complete product and not just a partly complete product. Selective disassembly is generally used either for repair and maintenance of a product or for end-of-life disassembly. Here selective disassembly is always followed by reassembly implying that damage to any disassembled component or module must be prevented. Modules can normally be further disassembled, but sometimes are not as they possess their own functionality and thus may be reusable as such. The book also highlights significance of such a methodology in end-of-life selective disassembly as follows:

1. Recovery of modules and components used for remanufacturing, spare parts, and secondary ("as new") modules and components for new products.
2. Removal of components that obstruct the removal of the components of interest.
3. Recovery of valuable materials.

Section 5.1.2. Island scale : Data collection

A significant portion of datasets cited in my thesis was retrieved from the community organization called ‘The Island Institute’ in Maine. The Island Institute’s mission is to sustain Maine’s island communities, working alongside Maine's island and coastal leaders to catalyze community sustainability in the state's 120 island and coastal communities and sharing what works among these diverse communities and beyond. The data-collection initiates with studying the second edition, ‘Waypoints: Livelihoods on Maine’s Coast and Islands’ that is dedicated to quantifying the way coastal Mainers make a living and presents new data that tells the story of how income levels, prevalence of self-employment, impacts of fisheries, and seasonality of the labor force define the economic and cultural landscape of our region. According to the document, 120 communities are included in these data—105 coastal and 15 unbridged, year-round islands—with population of 454,000. With more than 3,500 miles of coastline there is much variability in the size of communities. (The Island Institute, 2018, p. 5).

The data-collection methodology benefits from focusing on datasets for two community indicators are ‘Energy and Home Heating’ and ‘Housing Availability and Affordability’ (derived from work focus of The Island Institute, referred in the document ‘Waypoints: Community Indicators for Maine’s Coast and Islands’). My thesis extensively cites the following three comprehensive documents published by The Island Institute:

1. ‘2018 Annual Report’
2. ‘Waypoints: Community Indicators for Maine’s Coast and Islands’ (First Edition of Waypoint report), published in 2017
3. ‘Waypoints: Livelihoods on Maine’s Coast and Islands’ (Second Edition of Waypoint report), published in 2018

The data-collection initiates with studying the second edition, ‘Waypoints: Livelihoods on Maine’s Coast and Islands’ that is dedicated to quantifying the way coastal Mainers make a living and presents new data that tells narrates how income levels, prevalence of self-employment, impacts of fisheries, and seasonality of the labor force define the economic and cultural landscape of our region. According to the document, Two-thirds of the coastal population lives around the Portland region and south and the other third is scattered along the rest of the coast, down long peninsulas and islands. The varying distances to service-center hubs are expensive for many residents, with the smaller communities having difficulty supporting quality essential services like childcare, eldercare, healthcare, and local economic development. The size of communities determines how well residents are supported in their ability to make a living. Smaller communities have human and economic challenges that can limit investments in local infrastructure or economic development projects. It can be tough for these communities to change these dynamics themselves and challenging for private sector companies that provide economic development services (e.g., broadband internet) to construct business models viable for small, remote locations. (The Island Institute, 2018, p. 5).

Fig. 35. Referred literature, reports and dataset sources from The Island Institute on Maine's islands (Source: The Island Institute reports)

Chapter 5.2. Design for Assembly, Disassembly & Reassembly

In this section, I develop an end-to-end methodological framework that best suits further exploration in laboratory environment to design and produce products whose MEE can be recovered easily, founded on my learnings from existing body of work on 'Disassembly'. A step-by-step framework, to be termed as Design for Assembly, Disassembly & Reassembly (DfADR), is explained graphically in this section. Figures 37 (a), 37 (b), 38, 39 and 40 detail out the four-stage process. More precisely, DfADR begins with a basic 3D CAD model and ends into a scaled physical artefact whose MEE can be easily recovered. The same four stages will be followed to digitally design and produce a novel passive solar wall panel in Part VI of my thesis.

In this section, my thesis details the following salient stages that establish how to design for assembly, disassembly & reassembly :

Stage 1 : CAD ENVIRONMENT

1.1. PRE-DfADR IN CAD *:* Fig.37 (a) show primary inputs are geometric primitives: 05 (A, B, C, D, E) and no. of unique geometry-geometry and connections: 06 in Primitive Level from the designer. The component level shows no. of unique material representations: 03 (A-C, D-E, B) ; no. of unique component-component connections: 06. The important data here are Material compatibilities: A-C-D-E, B and No. of unique material families: 02 (A-C-D-E, B). At subcomponent level, the designer creates design development models with real world representations. At this stage no. of unique subcomponents: 23 (A:6, C:6, D:6, E:5), no. of unique modules: 01 (B), No. of subcomponent-module connections: 8 and No. of subcomponent-subcomponent connections: 53 (Mutually orthogonal: 43, Mutually planar: 10). The connection diagram ends up looking messy which means it is a complex product now.

1.2. DESIGN CLUSTERING IN CAD : Fig. 37 (b) shows creation of a supercomponent by clustering smaller components based on three main factors that make this process possible – i) material compatibilities, ii) component typologies and iii) connection qualities. The components not undergoing clustering are modules like B, which cannot be disassembled into its constituents. It is the supercomponent X that goes through transformation in next stages.

Stage 2 : CAD-CAM INTERFACE

This is the Method Level, shown in Fig.38, where two methods of geometric decomposition to make the designed arteface CAM-ready is explored. Since we want easy assembly and disassembly, the method of ‘plate’ looks disadvantageous, primarily due to multi-axial assembly. Instead, the method of ‘contour’ has only z-axis assembly and disassembly process which makes the method highly lucrative. The stage ends with exporting the geometric data into CAM-ready file.

1. **Stage 3 : CAM ENVIRONMENT**

This stage, graphically represented in Fig. 39, takes the process out of digital design space and into digital production space where feedstock (here : HDF/masonite) get cut through subtractive manufacturing (here : laser cutter) and results in all the cut-parts for further assembly

2. **Stage 4 : EASY ASSEMBLY, SELECTIVE DISASSEMBLY & REASSEMBLY**

In this section, Figure 40 presents end-to-end process that materializes the final product. This is the final stage where the cut-parts are first stacked on top of each other creating the supercomponent. After this, the module gets assembled without any obstruction. A module can be selective disassembled without obstruction and replaced by another module in future. This leads to a reassembled overall product.

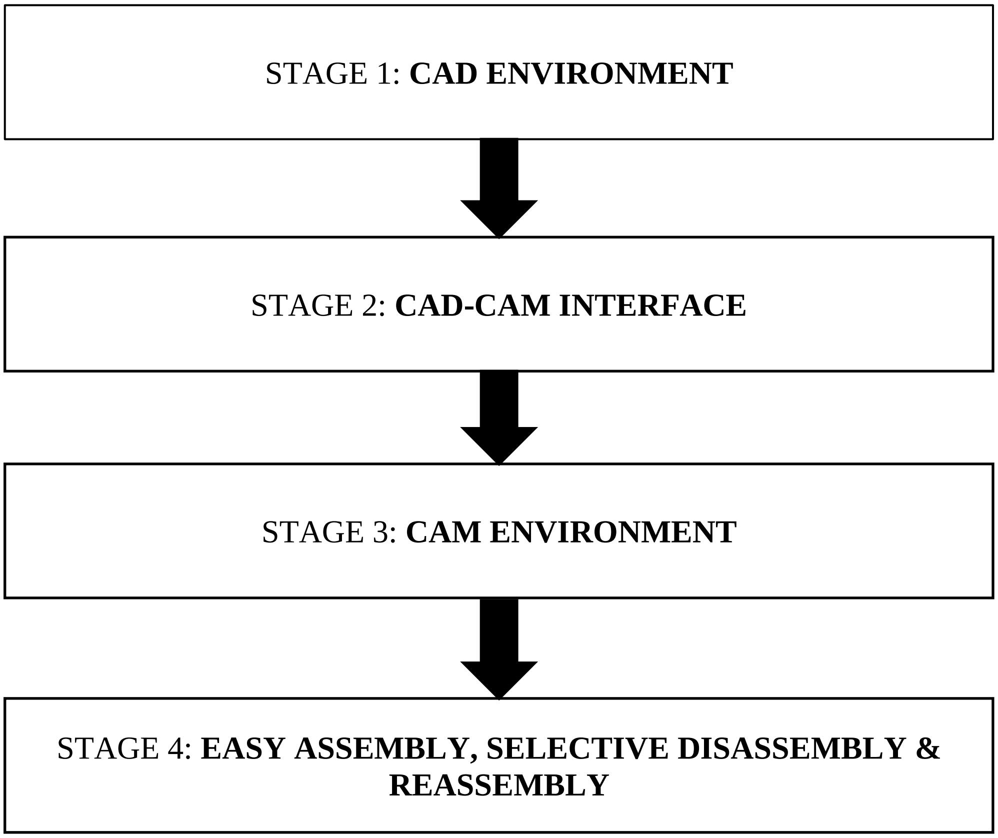


Fig. 36. Design for Assembly, Disassembly & Reassembly – Four stages.

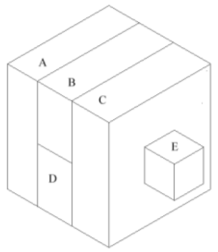
(Created by Author)

STAGE 1

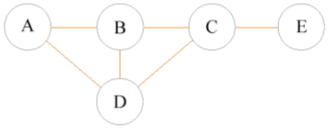
> PRE-DfADR IN CAD

PRIMITIVE LEVEL

DESIGN
DEVELOPMENT
AS USUAL



Connection Diagram



DfADR
INPUTS

1. GEOMETRIC PRIMITIVES
2. CONCEPTUAL STAGE

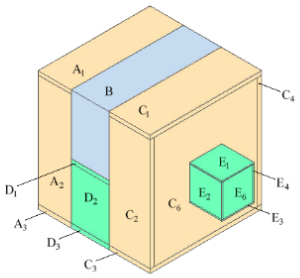
Fig.37 (a). STAGE 1: Typical feature-based design and modelling in CAD by digital designers (Created by Author)

STAGE 1

> CLUSTERING IN CAD

SUBCOMPONENT
LEVEL

DESIGN
CLUSTERING



Connection Diagram

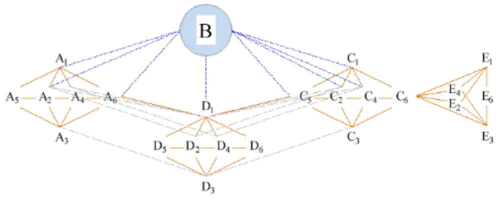
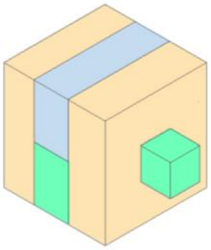
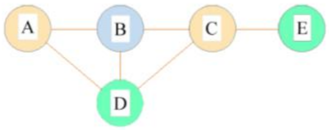


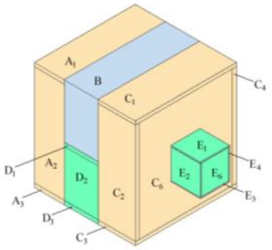
Fig.37. (b). STAGE 1: Design Clustering in CAD based on i) component types ii) material compatibilities and iii) kinds of connections (Created by Author)

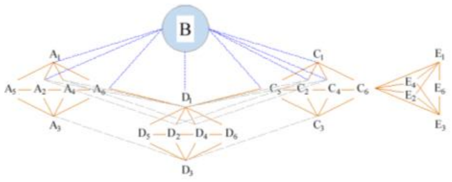
COMPONENT
LEVEL





SUBCOMPONENT
LEVEL





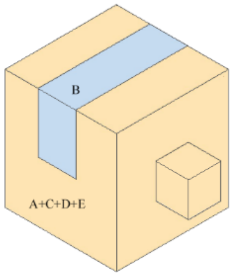
- UNIQUE COMPONENTS
- MATERIAL REPRESENTATIONS
- MATERIAL FAMILIES

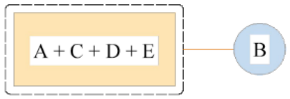
- COMPLEX CONNECTIONS
- FEATURE-BASED DESIGN
- CONVENTIONAL ASSEMBLY

1. COMPONENT TYPOLOGIES
2. MATERIAL COMPATIBILITIES
3. CONNECTION QUALITIES

CAD

SUPERCOMPONENT
LEVEL





STAGE 2

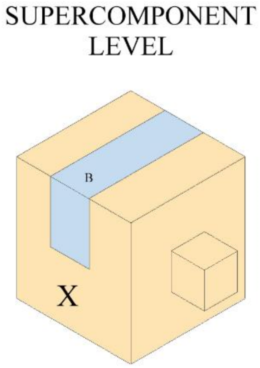


Fig.38. STAGE 2: CAD-CAM interface facilitating decomposition of clustered 3D geometry
into digital twin of contoured method
(Created by Author)

STAGE 3

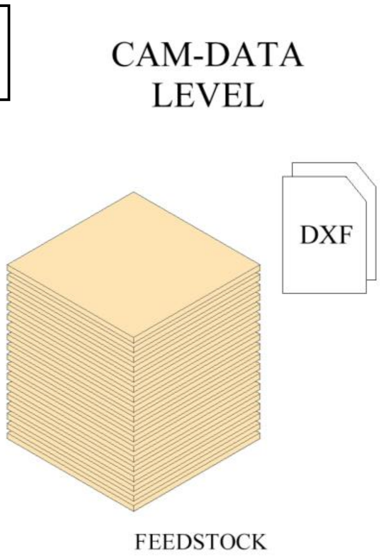
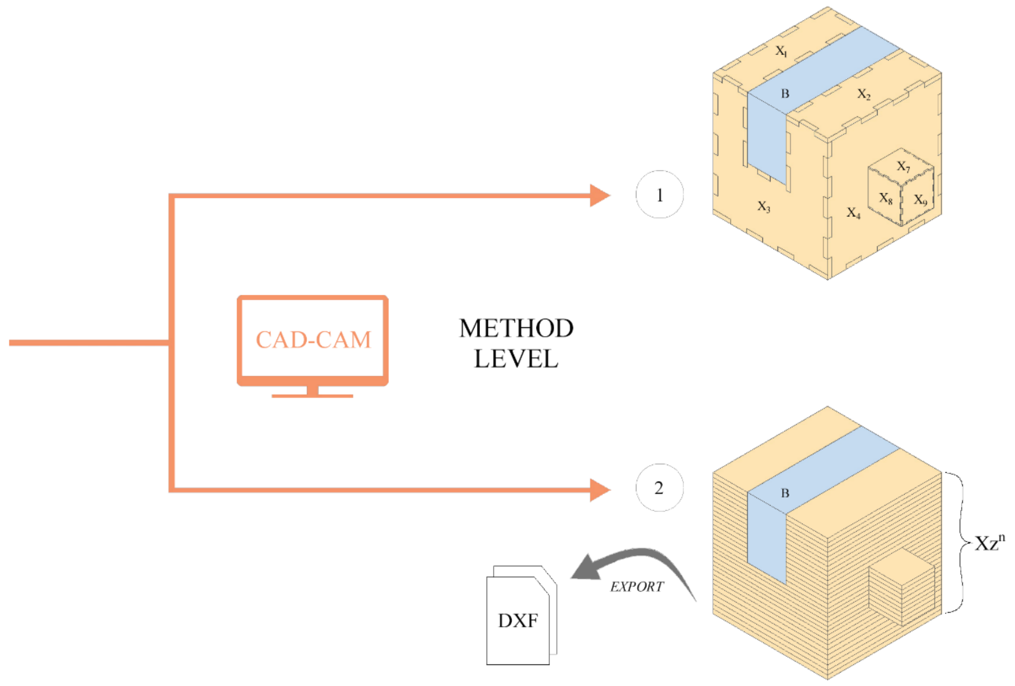


Fig.39. STAGE 3: Cut parts through subtractive manufacturing machine (like laser cutter) directly from CAD-CAM data. (Created by Author)



Plate

DfADR Pros:

- *Less fasteners*

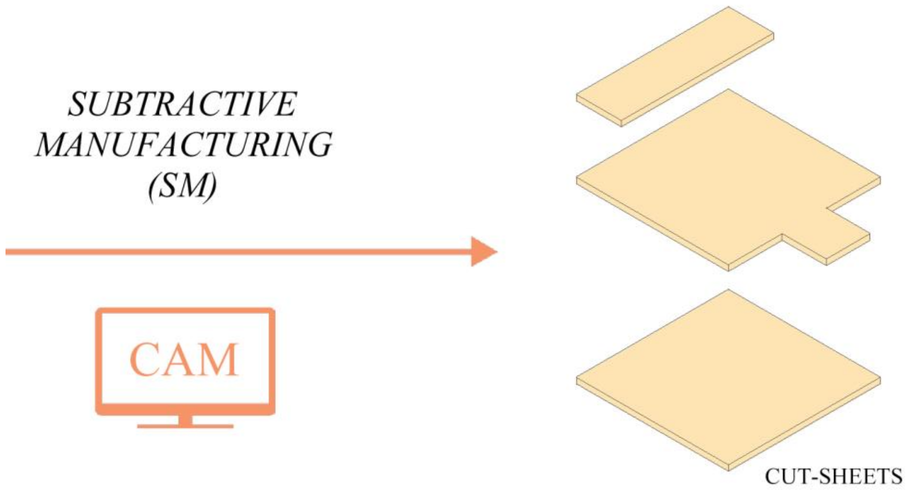
DfADR Cons:

- *Multiaxial*
- *Orthogonal connection*

Contour

DfADR Pros:

- *Negligible fasteners*
- *Single-axis (z)*
- *Face-Face connection*



SM Pros:

- *No. of unique types: 03*
- *High accuracy*
- *Scalability*
- *No support structure*

SM Cons:

- *Wastes from cut-sheets*

STAGE 4

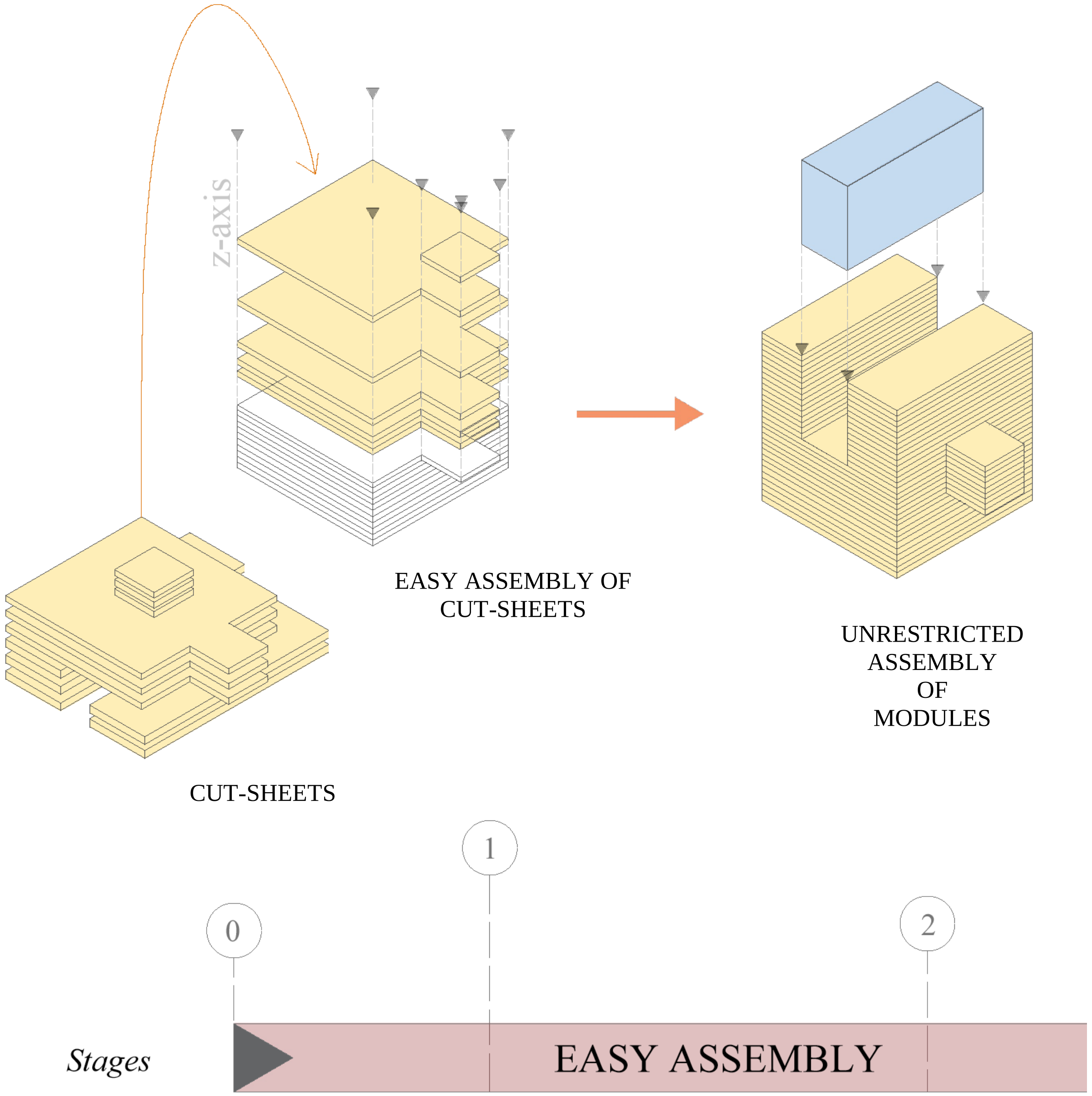
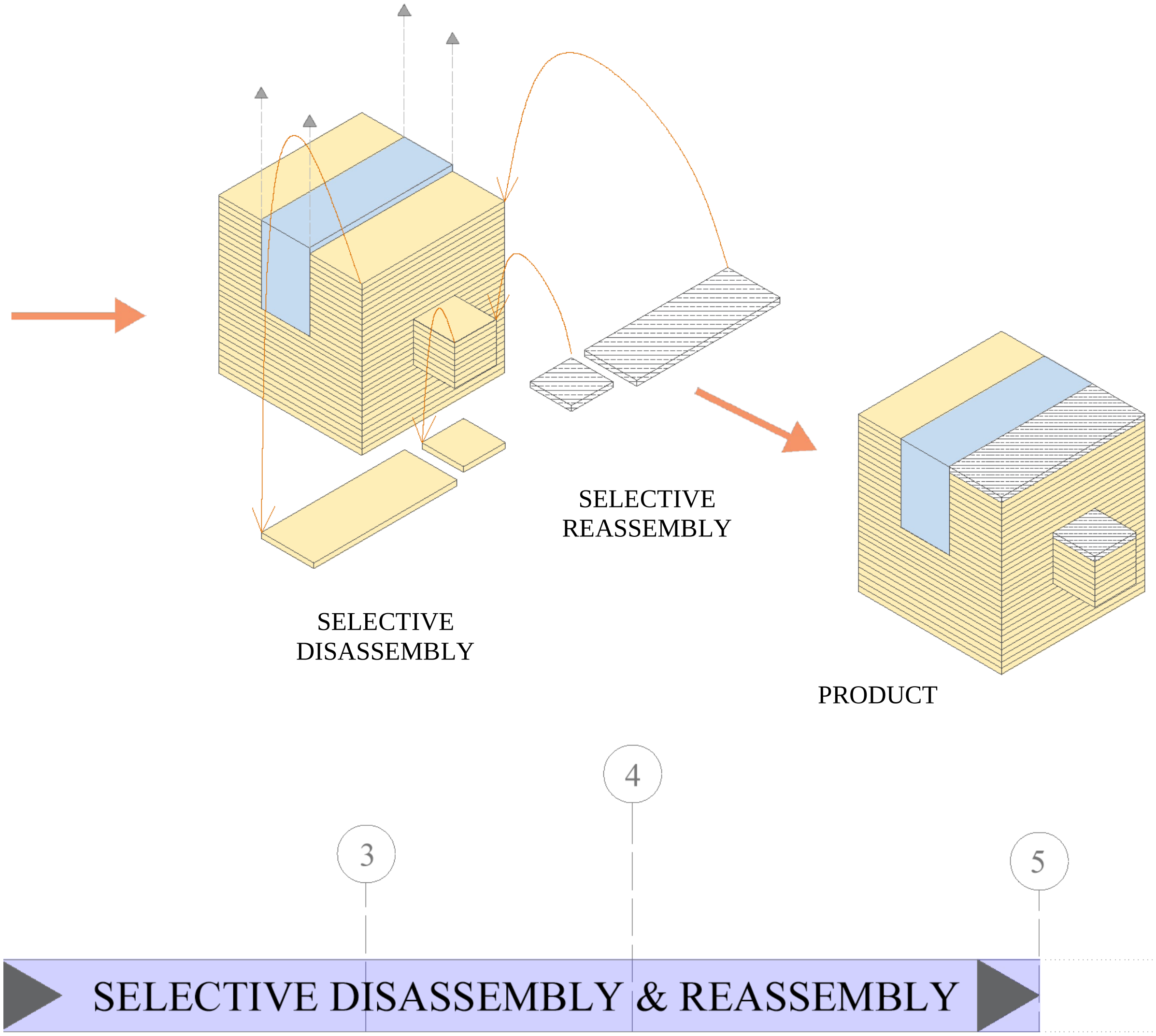


Fig.40. STAGE 4: Prototyping process – Assembly, Disassembly & Reassembly. (Created by Author)


SELECTIVE
REASSEMBLY
SELECTIVE
DISASSEMBLY
PRODUCT
4
3
5
SELECTIVE DISASSEMBLY & REASSEMBLY

Chapter 5.3. Rapid Prototyping

The methodology of rapid prototyping (RP) provides a design space for possible design alternatives artefacts: what are the other possible alternatives, how are these alternatives related, what are the tradeoffs among them? Through design iteration and rapid prototyping, I aim to develop a set of scale models of novel passive solar wall panels. The system boundary of research laboratory environment mainly involves materials at disposal, RP fabrication machines employed, CAD software used and the CAD-CAM interface that guides successful simulation. Within the scope of my thesis, the passive solar wall panels are prototyped as single-material assemblies. The salient features of interior components in the system boundary of research laboratory environment are as follows:

- HDF / Masonite (thickness of 0.120mm)
- Laser-cutting machines (subtractive manufacturing)
- FDM 3D printers (additive manufacturing)
- Adhesive
- CAD-CAM interface software (LuBan)
- CAD tools (Rhinoceros 3D, AutoCAD)

The relevance of RP is supported by highly-cited paper ‘Materializing design: the implications of rapid prototyping in digital design’ that introduces the concept of ‘Digital Design Fabrication (DDF)’ as a method of rapid prototyping (RP) integrated design rationale. According to the paper, “the DDF method is a two-stage process of working that integrates generative computing and RP into one process.” One of the major takeaways from the paper is the focus on “advantages of a continuous processes of design conceptualization, materialization, and fabrication”. (Sass & Oxman, 2006). The goal of this methodology is to perform tasks and make decisions that claim to easily assemble, selectively disassemble and reassemble scaled model of passive solar wall panels. A few snapshots of RP in laboratory environment is shown in Fig. 24 and Fig. 25. Materialization as a way of designing fulfills Lesgold’s presentation of learning by doing in ‘Tools to assist learning by doing: Achieving and assessing efficient technology for learning’ which he defines as “an opportunity to manage the full domain or real-life experiences through activity-based learning.” He argues that it is necessary to combine rules with conceptually based activity to prepare people for real-world experiences. (Lesgold & Nahemow, 2001). Advantages of performing RP is supported by the paper’s remarks that “the impact of digital fabrication processes was negligible compared to the materials manufacturing process. This means that any digital fabrication project that can save materials compared to conventional construction will allow for reduction of environmental impacts. Furthermore, the study highlighted the opportunities for integrating additional functions in digitally fabricated structures to reduce the overall environmental impact of these multi-functional elements. However, the integration of multiple functions allowed great savings only when these functions had a large environmental impact.” (Agustí-Juan & Habert, 2017, p. 2790). RP is facilitated by CAD-CAM interface. The CAD-CAM interface provides with a range of different techniques and controls on material-geometries, and types of assembly processes.

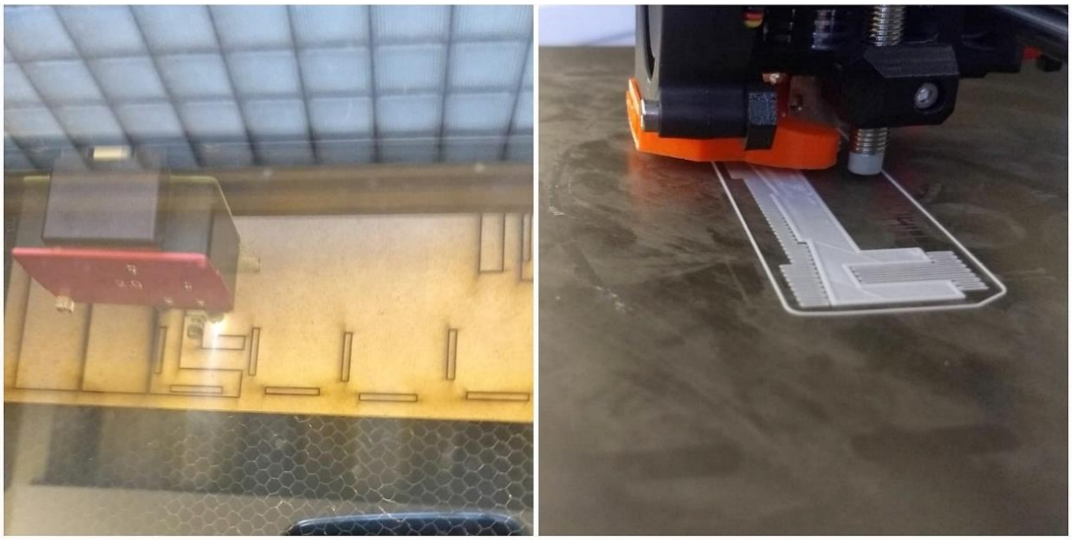


Fig. 41. Digital Fabrication Tools at RP disposal (Photographed by Author)

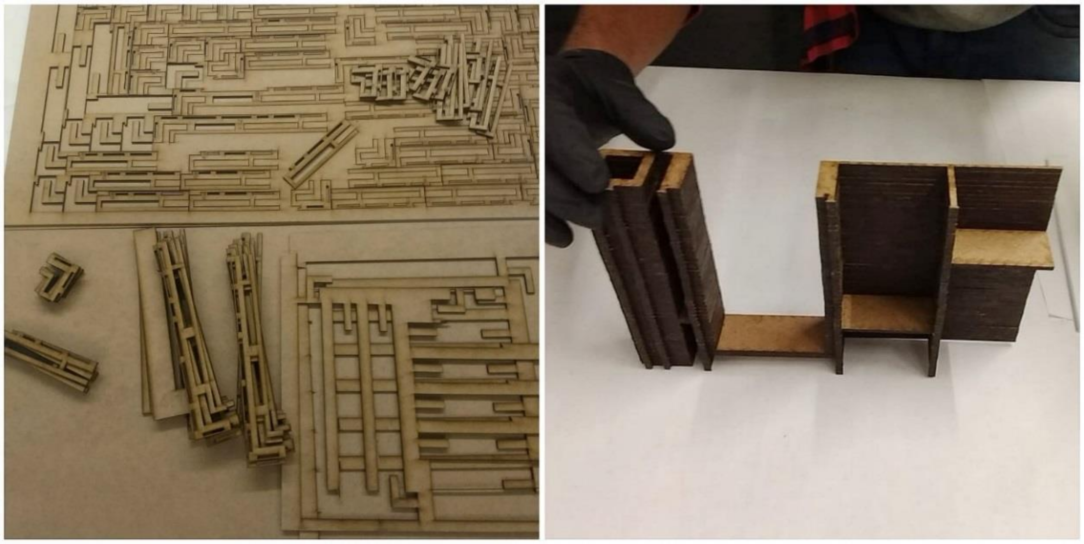


Fig. 42. RP process involving sorting, assembly and iteration (Photographed by Author)

Part VI: Study Scale

This part of my thesis attempts to address the first research question of **"How can we digitally design-produce a passive solar wall to easily recover its panels and components?".** There are three chapters under this part. Chapter 6.1. and Chapter 6.2. expand on the design for assembly, disassembly and reassembly (DfADR) framework within the digital design and digital production system respectively. Chapter 6.3. presents documentation of wall prototypes through rapid prototyping (RP). A wide range of materialized wall prototypes (scale 1:12) are presented that assisted in trials and iteration throughout performing the DfADR framework.

Chapter 6.1. Digital Design System

The Digital Design System is part of the design end of the system. The Digital Design System is ideated and to be developed for direct use of digital designers. Thereby, for building designers the interface of this system must be familiar. In the laboratory environment for my thesis, I posed as the digital designer and immersed myself in the system. The steps were laid out clearly in the previous section and will be followed as per. Both AutoCAD and Rhinoceros 3D were at my disposal during this leg of the process.

Section 6.1.1. Stage 1: CAD environment

The digital designer usually begins with conventional tools to create design of a standard wall with material representation and scaled dimensions. However, to expand the scope of my thesis, I have considered two scenarios:

1. Designer provides with 3D CAD model of standard wall panels where high amount of external inputs is necessary mainly regarding the context to take informed decisions on the material composition that will suit the site best (Fig. 43).
2. Designer provides 3D CAD model of typical passive solar wall panels. In both cases, CAD environment facilitates clustering based on three parameters of component typologies, material compatibilities and connection qualities. The input wall panel provides with height and span which remains same throughout the process, but thickness varies. The output of clustering in CAD environment is a supercomponent, as shown in Fig. 43. For my case, it is the thermal mass, whose materiality for RP is HDF/Masonite. Due to clustering, the connection diagram is very simple.

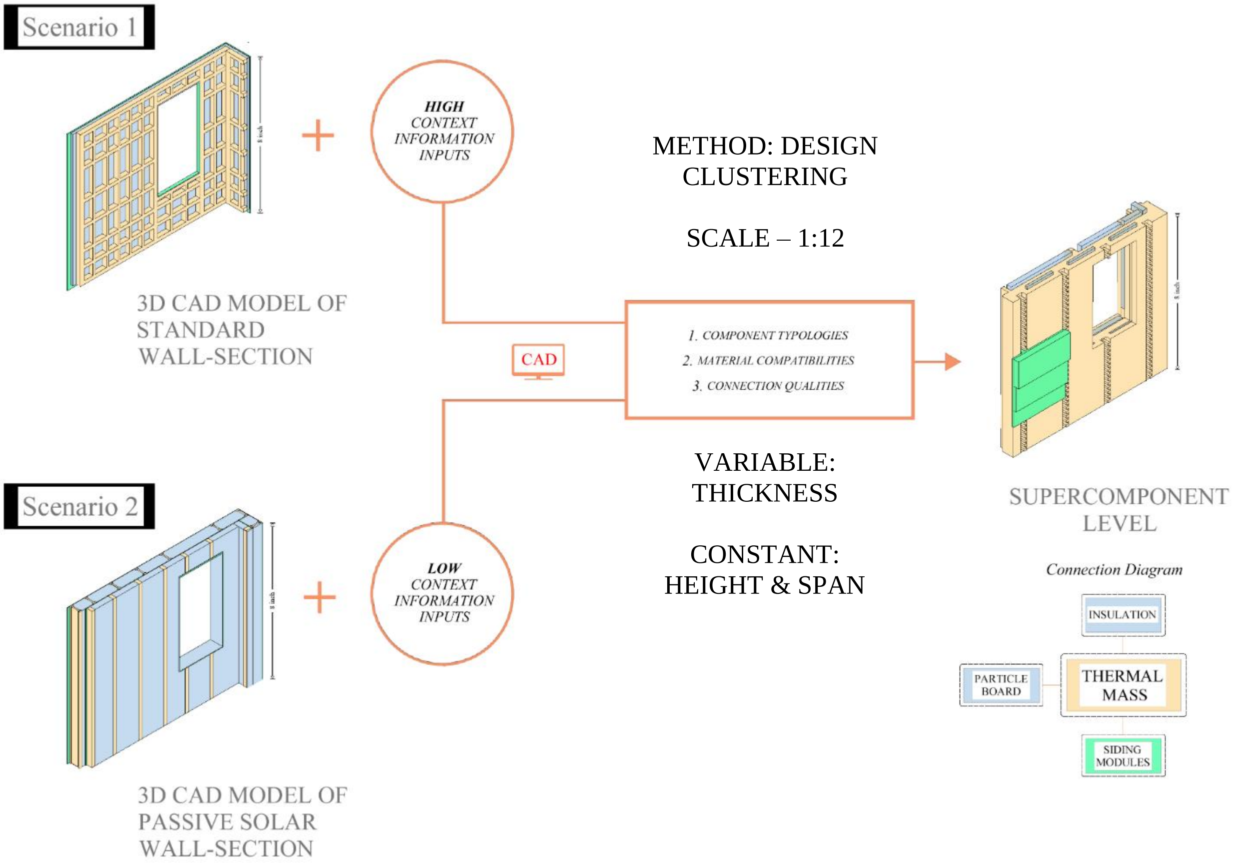


Fig.43. STAGE 1: Two scenarios in CAD environment: i) Designer provides with 3D design of / with standard wall panel ii) Designer provides with 3D design of/with passive solar wall panel (Created by Author)

Section 6.1.2. Stage 2: CAD-CAM interface

As shown in Fig. 44, the thermal mass represented by HDF/ Masonite at 1:12 scale acts as the super component undergoing transformation. The contour sections here have offsets in z-axis at every 0.120 inch, to align with the material thickness. Insulation and siding are modules that cannot be disassembled further into parts. The output of this stage is CAM-ready data exported into readable files. The Method Level that the super component gets decomposed into is based on advantages of ‘contour’ method for DfADR.

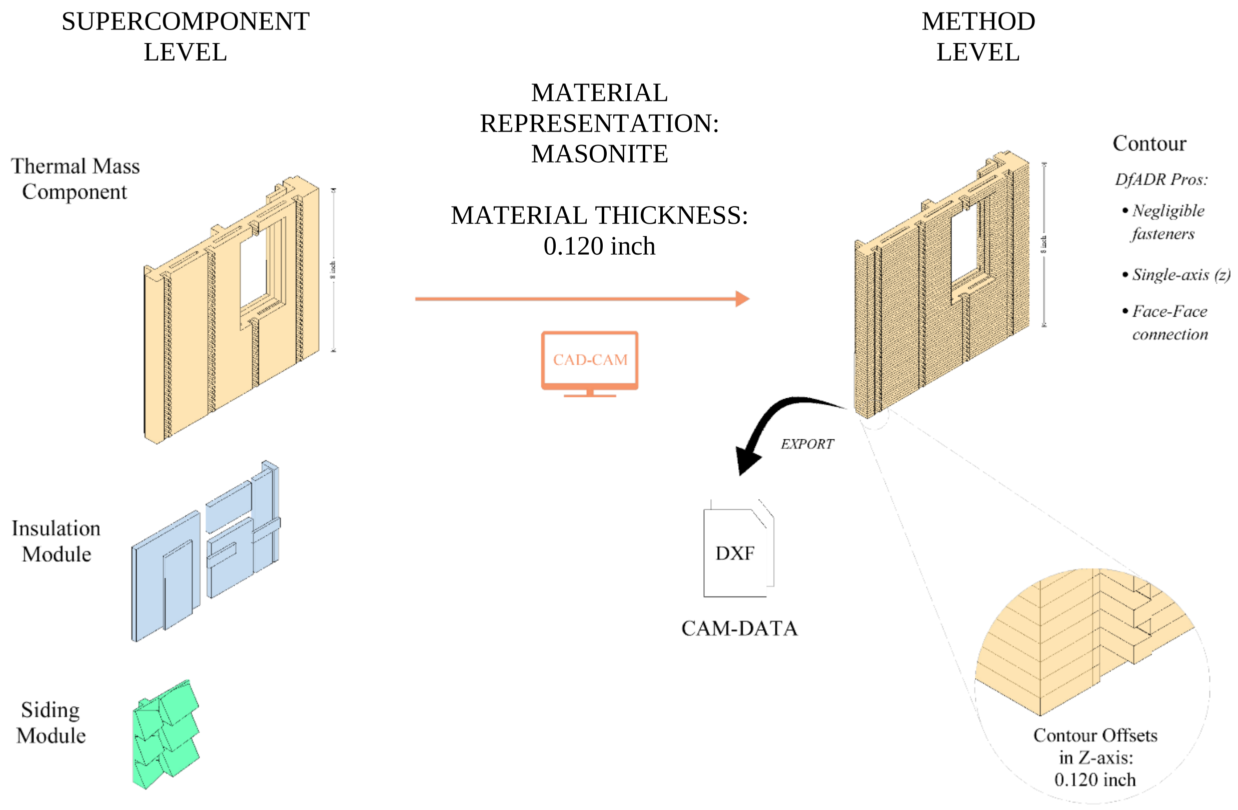


Fig.44. STAGE 2: Thermal Mass component undergoing CAD-CAM decomposition into contoured method, Modules of insulation and siding do not undergo contouring
(Created by Author)

6.2. Digital Production System

The Digital Production System is part of the making or the production end of the system. It is ideated and to be developed for direct use of digital designers who want to materialize or build their artefacts. In the laboratory environment for my thesis, I posed as the digital fabricator and immersed myself in the system, after the digital design step. The steps were laid out clearly in the previous section and will be followed as per. Both laser cutter and 3D printers were at my disposal during these latter stages of the process.

Section 6.2.1. Stage 3 : CAM environment

At this stage of the framework, subtractive manufacturing is employed to cut the parts from the file exported in previous step (Fig. 45). At the input side, Material: Masonite / HDF, Dimension of one sheet: 9 in x 1.6 in x 0.120 in and Total Material Embodied Energy of feedstock: 22.44 MJ (or) 1/250 BOE. At the output side, Total Material Embodied Energy in super component prototype: 10.28 MJ (or) approx. 1/500 BOE. Using subtractive manufacturing has the following advantages (for no. of cut-parts: 66)

- High accuracy and Scalability
- No support Structure (unlike in additive manufacturing)

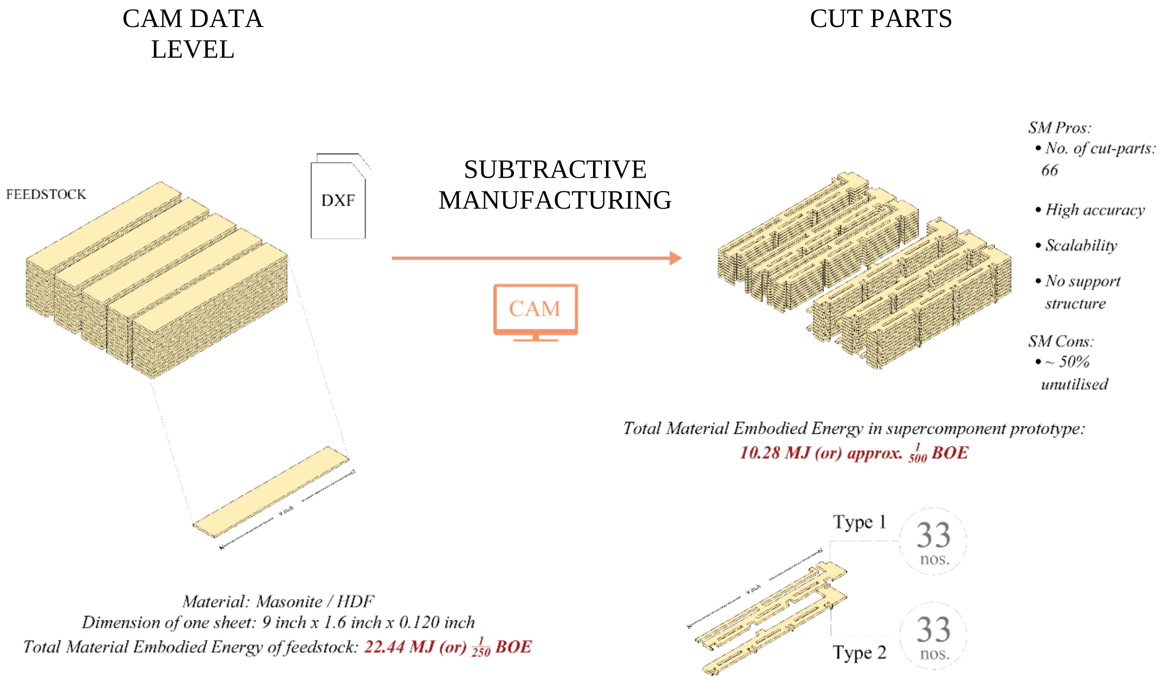


Fig.45. STAGE 3: Cut parts of HDF/Masonite material through subtractive manufacturing machine (like laser cutter) directly from CAD-CAM data, 0.120-inch-thick HDF becomes the associative material for lab scale representing timber of real scale
(Created by Author)

Section 6.2.2. Stage 4 : Easy Assembly, Selective Disassembly & Reassembly

At this stage of the framework following the process established in earlier section, 100% material embodied energy can be recovered from digital passive solar wall panels (Fig. 46). The processes under this stage is explained as follows:

i. Easy Assembly: The cut parts are stacked and stored on top of each other. These parts are then selectively assembled by layering on top of each other, held together by glue. The assembly process is easy because it only works and effectively performs in z-axis. The assembly of modules is also easy since they can be attached without destruction of the rest of the product and without the rest of the product obstructing its assembly path.

ii. Selective Disassembly: After the product is assembled completely, there could be a need to selectively disassemble a module. This could be done without obstruction.

iii. Selective Reassembly: The selectively disassembled module could be replaced with another module with same dimensions and connection quality to produce the final artefact.

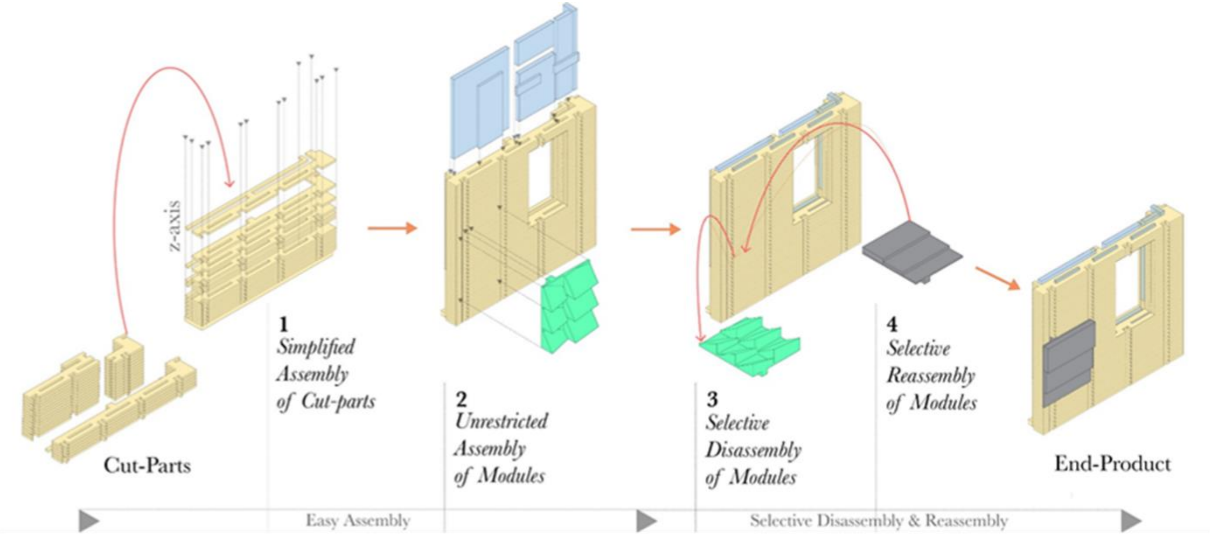


Fig.46. STAGE 4: Prototyping of study scale wall panels by assembly, disassembly & reassembly (Created by Author)

From the previous chapter, I have graphically represented how the wall panel prototype will be materialized. This prototype, for my thesis, is to be regarded as a digital passive solar wall (Fig. 47).

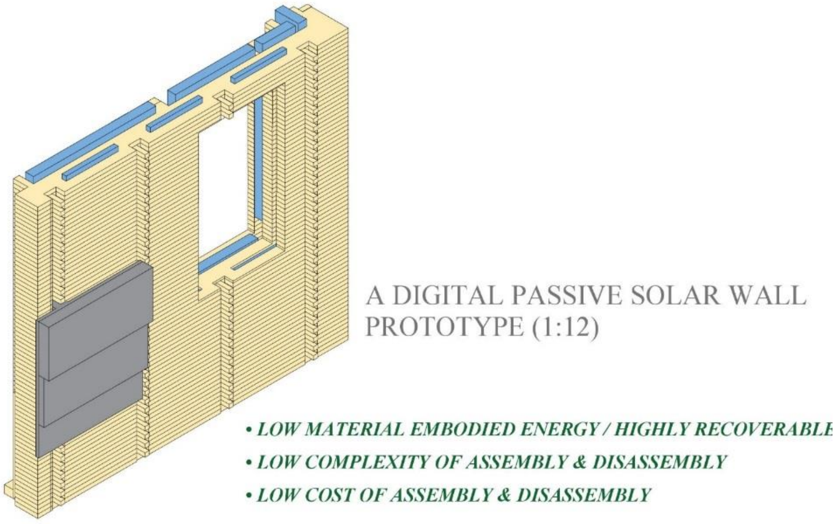
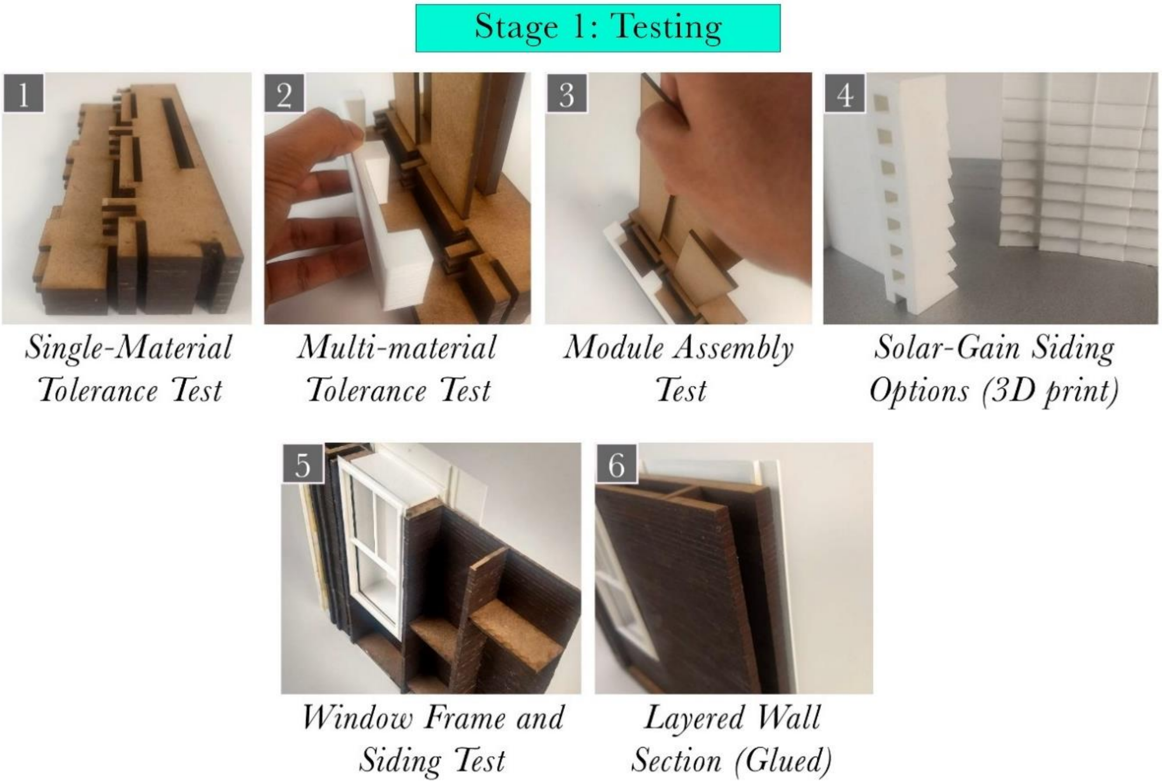


Fig. 47. Isometric representation of final prototype (Created by Author)

Chapter 6.3. Documentation of wall prototypes

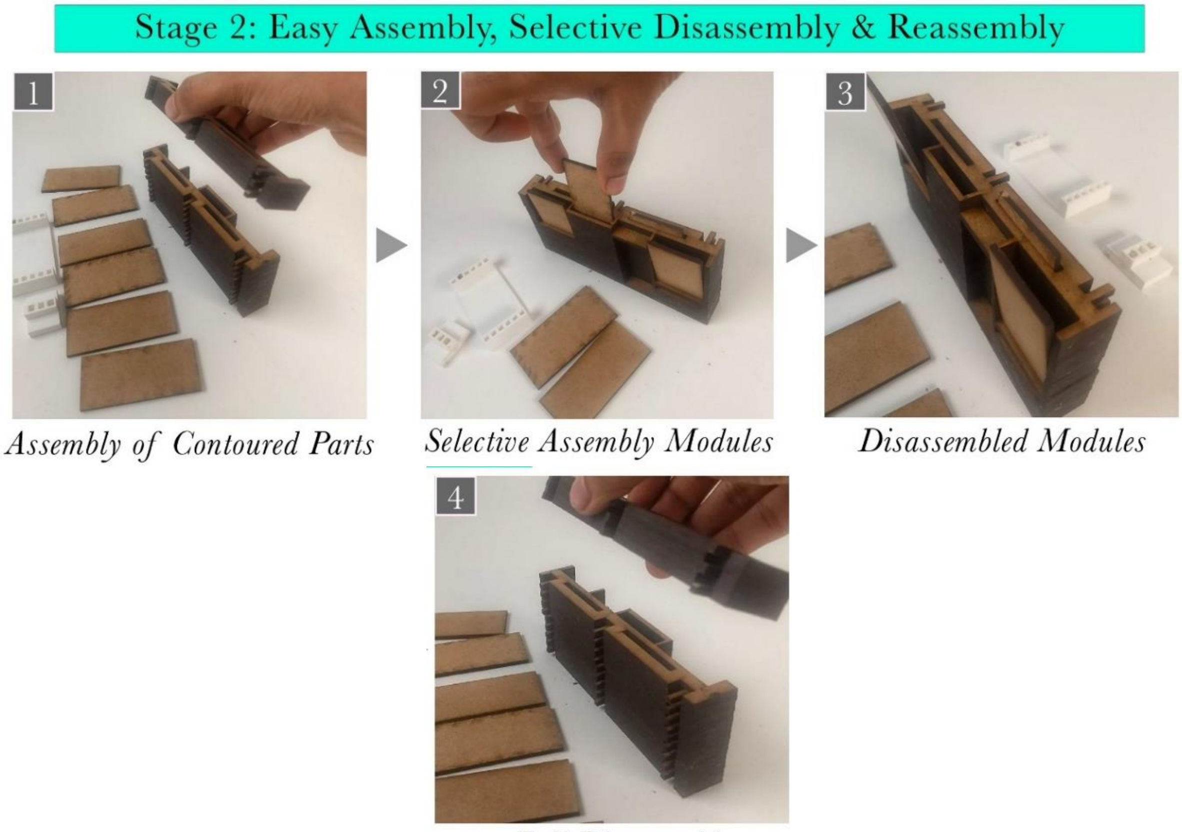
This chapter of my thesis presents a brief documentation of the iterative process and final prototypes as a result of it. Materializing the prototype marks the end of addressing the first research question in the study scale (1:12). For my thesis, a range of scaled prototypes are materialized in laboratory environment that have been documented through photography. Rapid prototyping follows two stages towards addressing my first research question. The two stages, documented under figures 48 (a) and (b), are as follows:

i. Stage 1: Testing. In this stage, I perform prototyping at a component-level. Tests include tolerance test, assembly test, siding options and layering test.
ii. Stage 2: Easy assembly, disassembly & reassembly. This stage is a 1:12 scale demonstration of the design for assembly, disassembly & reassembly framework.


Stage 1: Testing

1 Single-Material Tolerance Test
2 Multi-material Tolerance Test
3 Module Assembly Test
4 Solar-Gain Siding Options (3D print)
5 Window Frame and Siding Test
6 Layered Wall Section (Glued)

Fig.48 (a). Documentation of Prototyping: Stage 1: Testing and Stage (Created by Author)



Assembly of Contoured Parts

Selective Assembly Modules

Disassembled Modules

Full Disassembly

Fig.48 (b). Documentation of Prototyping: Stage 2: Demonstration of easy assembly, disassembly & reassembly
(Created by Author)

Part VII: Island scale

This part of my thesis attempts to address the second research question of “**What are the urban implications when Vinalhaven homes have recoverable wall components?**”. There are three sections to this part. There are three chapters under this part. Chapter 7.1. expands on the full-scale digital passive solar wall panel. Apart from highlight the materiality and advantages of full-scale panel, I attempt to speculate the supervised environment in which it would be produced on-site. Supervision is provided by both human and robotic presence. Chapter 7.2. is a series of graphical representations that narrate the island scale scenario, demonstrating speculative implications of my system in the scale of one island home, two island homes and five island homes. The contributions from this part of my thesis follows a linear multi-scalar urban narrative (Fig. 49) presented through graphical representations.

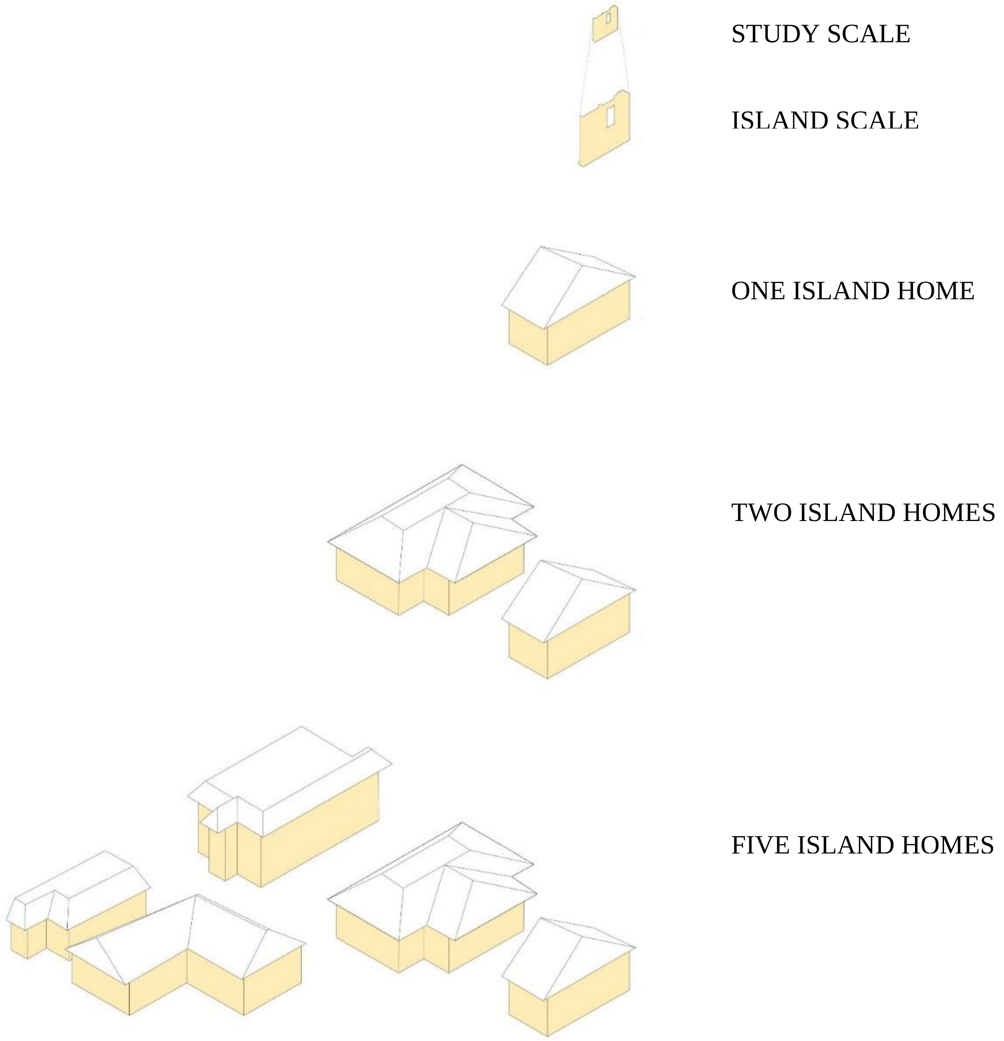
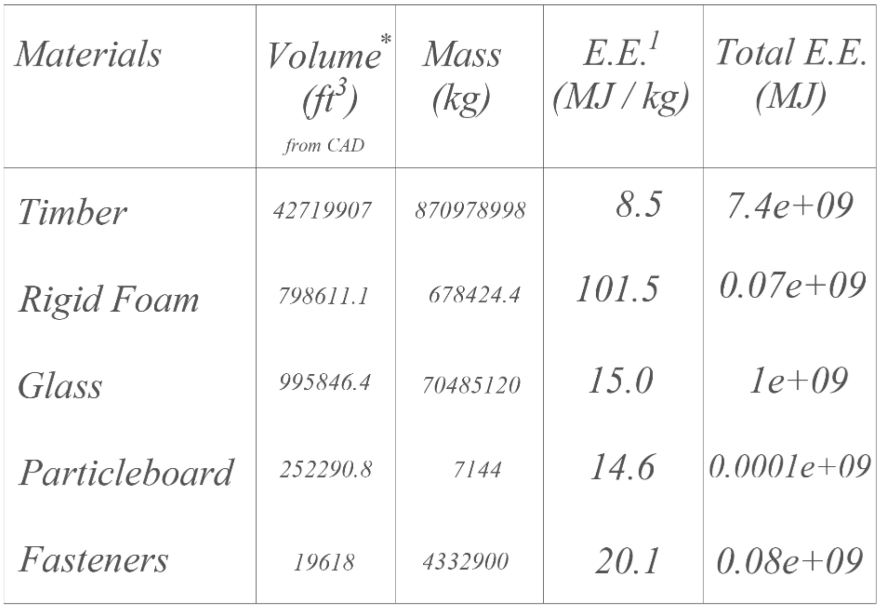


Fig. 49. Multi-scalar speculation of urban implications (Created by Author)

Chapter 7.1. A Digital Passive Solar Wall panel

This chapter presents the output artefact of DfADR framework within the scope of my thesis – a novel passive solar wall panel materialized using digital design-production system. The first step is to scale up the 1:12 prototype. Using the 3D CAD model, I calculated the MEE of one digital passive solar wall panel that led to the following quantifications and conclusions:

1. MEE of one digital passive wall panel is equivalent to 1.4 million barrels of oil, which is significantly lower than that of one typical passive solar wall panel, of same height and span (Fig. 50).
2. MEE shows that DfADR has led to dematerialization/ reduction as well as ensured its 100% recovery. Fasteners are not 100% removed but has been greatly reduced.
3. Foam insulation has been used less and more focus is given to thermal mass so as to increase thermal gain (Fig. 51) The complexity of construction greatly decreases. Such a wall panel is easy to assembly and can be easily renovated by the unskilled dweller as selective disassembly is easy and simple.
4. Cost of construction and renovation significantly decreases due to reduced need for skilled labour, less material use, less material waste and a possibility to recover all MEE in future for creative repurposing.



Materials	*Volume* (ft^3)* *from CAD*	*Mass (kg)*	*E.E.[1] (MJ / kg)*	*Total E.E. (MJ)*
Timber	*42719907*	*870978998*	*8.5*	*7.4e+09*
Rigid Foam	*798611.1*	*678424.4*	*101.5*	*0.07e+09*
Glass	*995846.4*	*70485120*	*15.0*	*1e+09*
Particleboard	*252290.8*	*7144*	*14.6*	*0.0001e+09*
Fasteners	*19618*	*4332900*	*20.1*	*0.08e+09*

Fig. 50. Material Embodied Energy of a digital passive solar wall panel – 1.4 million barrels of oil equivalent. (Based on datasets from ICE, UK)

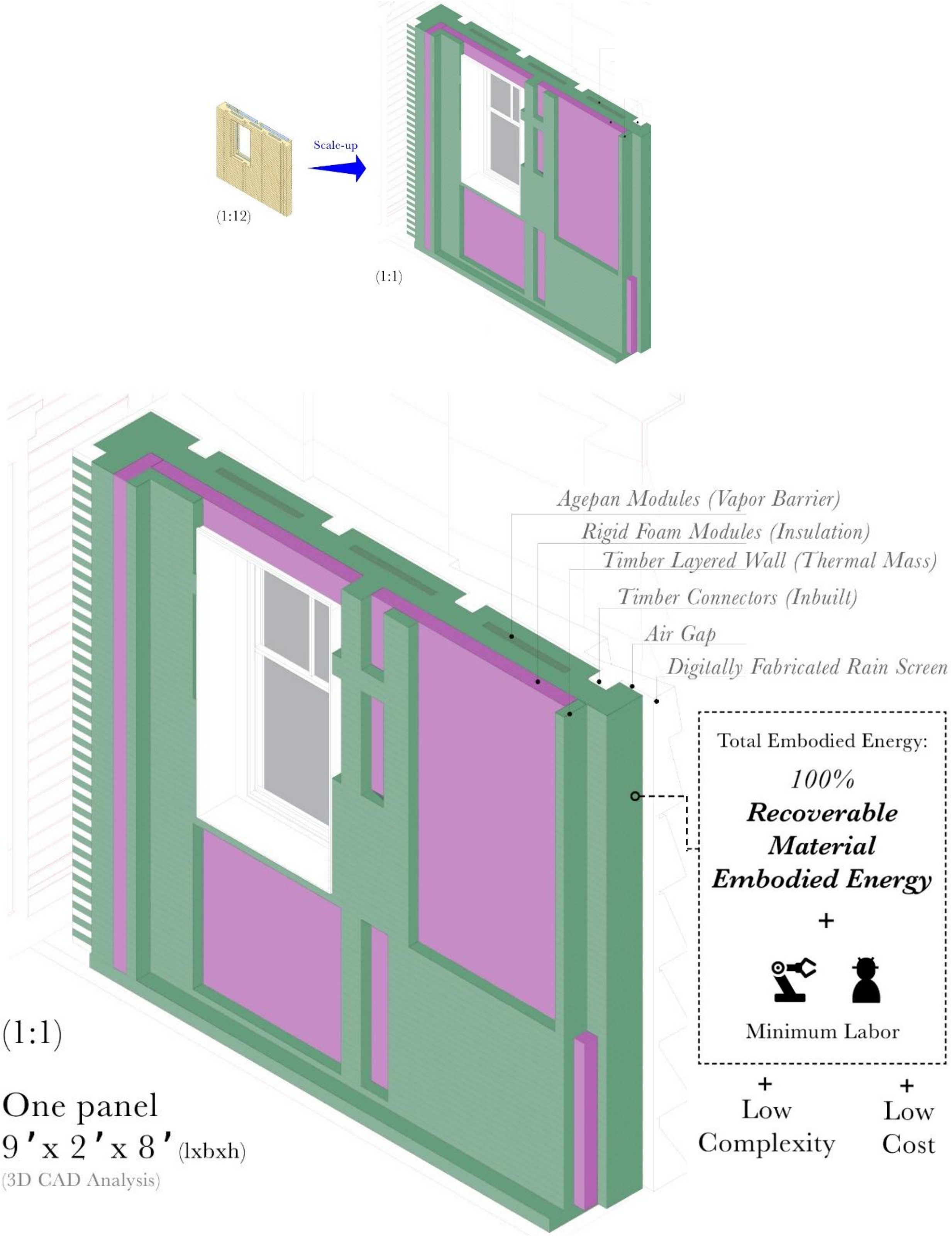


Fig.51. Full Scale Digital Passive Solar Wall panel materialized to support my claim for a wall with 100% recoverable material embodied energy.
(Created by Author)

Chapter 7.2. Multi-scalar urban speculation

My thesis considers assembly, disassembly and reassembly to a great extent in 'Digital Design-Production System’ and speculates the use of robotic technology to perform the tasks in an efficient and low-carbon operating process. The speculative images in this chapter presents automated assembly in island scale. This is supported and further explored by the paper ‘Multi-objective co-operative co-evolutionary algorithm for minimizing carbon footprint and maximizing line efficiency in robotic assembly line systems’ that primarily focuses on developing a mathematical model to simultaneously minimize the total carbon footprint and maximize the efficiency of robotic assembly line systems. According to the paper, robots can operate 24 hour a day without worries of fatigue and can perform different tasks by re-programming. The effective utilization of robot assembly lines evolves into the need to solve the Robotic Assembly Line Balancing (RALB) problem, in which two sub-problems; task assignment and robot allocation, are addressed simultaneously. This paper focuses on the carbon footprint caused by energy consumption. In this study, two types of energy consumption are considered. The first type of energy consumption is the energy consumed while performing the operation and the second type of energy consumption is the energy consumed while the robots are kept idle between operations. (Nilakantan et al., 2017). The following sections uses tools of graphical representation to speculate scenarios in urban scales from one wall panel to five island homes.

Based on the abovementioned study and my conceptual framework that involves the use of digital design-fabrication tools, I attempt to stage easy assembly, selective disassembly and complete disassembly at island scale. Though automated robotic assembly has been promoted within the scope of my thesis, tasks during the DfADR methodology is to be delegated between digital supervision and human supervision. Broadly, the following steps occur in island scale:

- STAGE 1: Full Assembly – Automated (as demonstrated in Fig. 52 and Fig. 53.a)
- STAGE 2: Selective Assembly – Manual (as demonstrated in Fig. 53.b)
- STAGE 3: Selective Disassembly – Manual (as demonstrated in Fig. 53.c)
- STAGE 4: Full Disassembly – Automated (as demonstrated in Fig. 53.d)

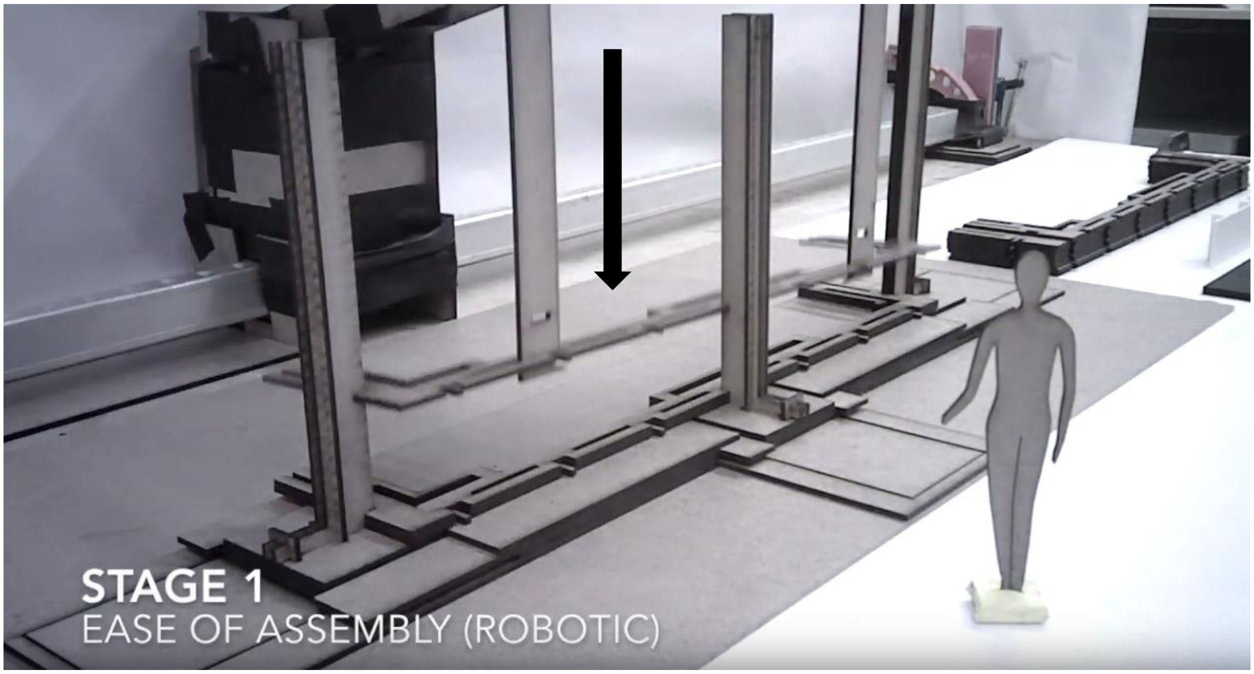


Fig. 52. Stage 1: Ease of Assembly - Automated (Source: Demonstration photo). The photo shows automated assembly of cut parts on-site by z-axis stacking.

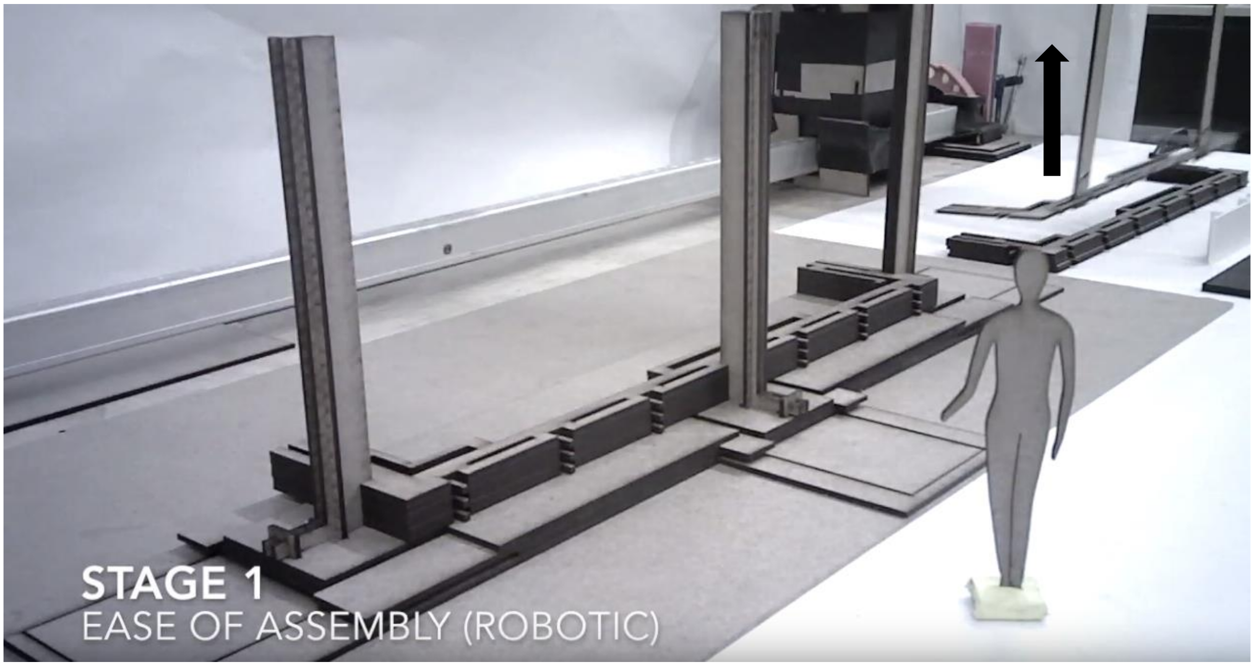


Fig. 53 (a). Stage 1: Ease of Assembly - Automated (Source: Demonstration photo). The photo shows automated retrieval of cut parts on-site.

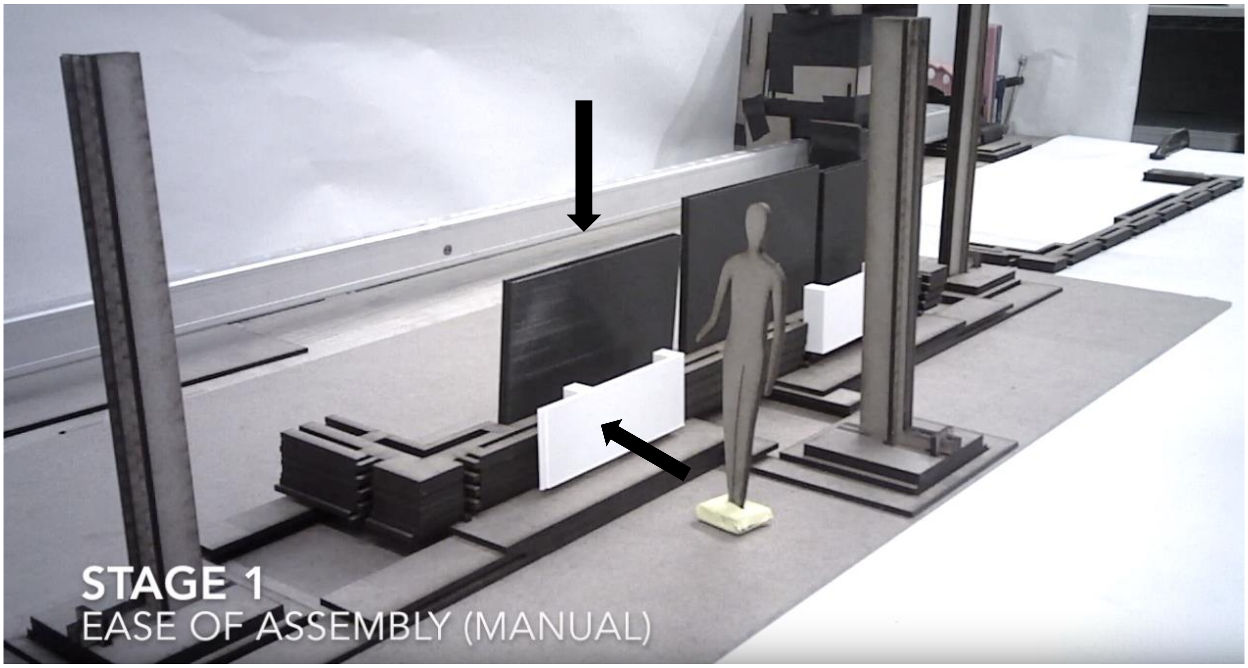


Fig. 53 (b). Stage 1: Ease of Assembly - Manual (Source: Demonstration photo). The photo shows manually performed assembly of wall-components, especially modules.

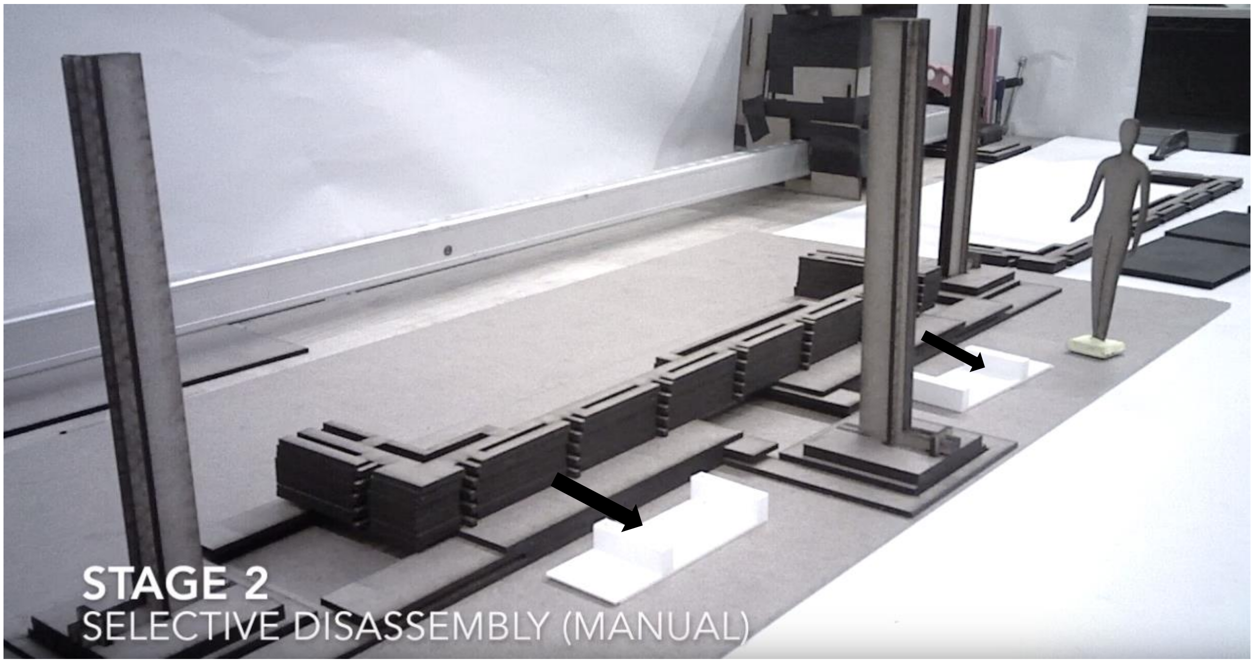


Fig. 53 (c). Stage 2: Selective disassembly - Manual (Source: Demonstration photo). The photo shows manually performed selective non-destructive disassembly of wall-components, especially modules. This is a recurring event, throughout the mid-life stage of the walls.

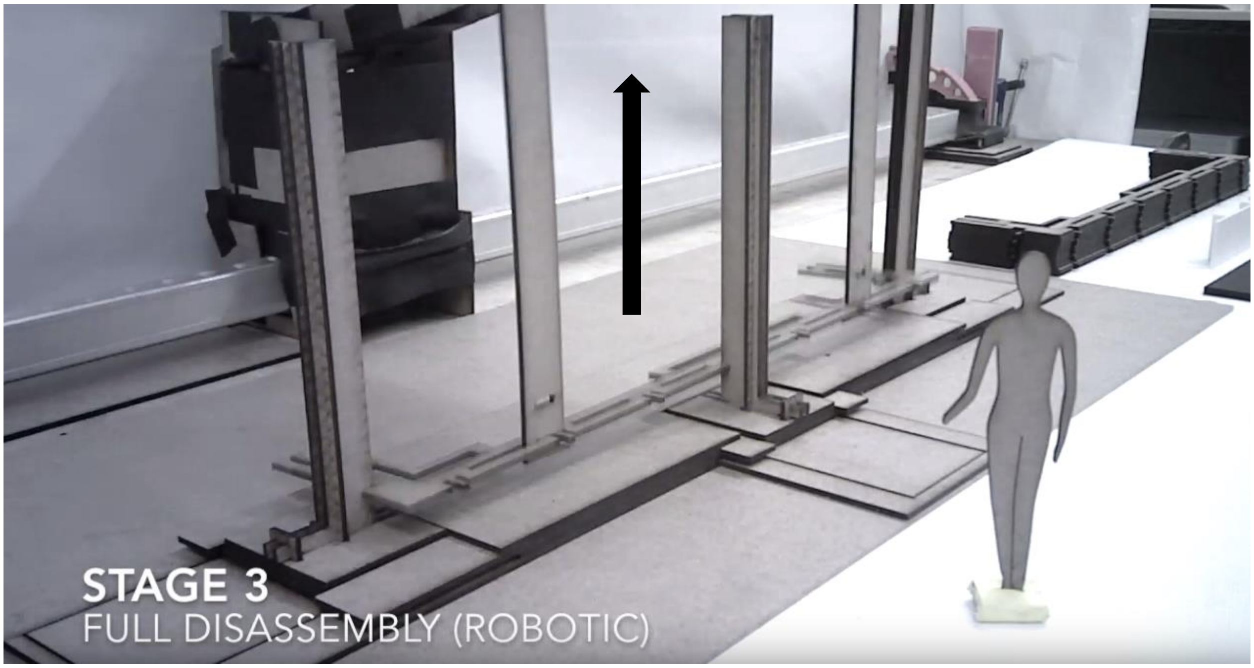


Fig. 53 (d). Stage 3: Full disassembly - Automated (Source: Demonstration photo).
The photo shows non-destructive disassembly at end-of-life of thermal mass materials by automated z-axis retrieval.

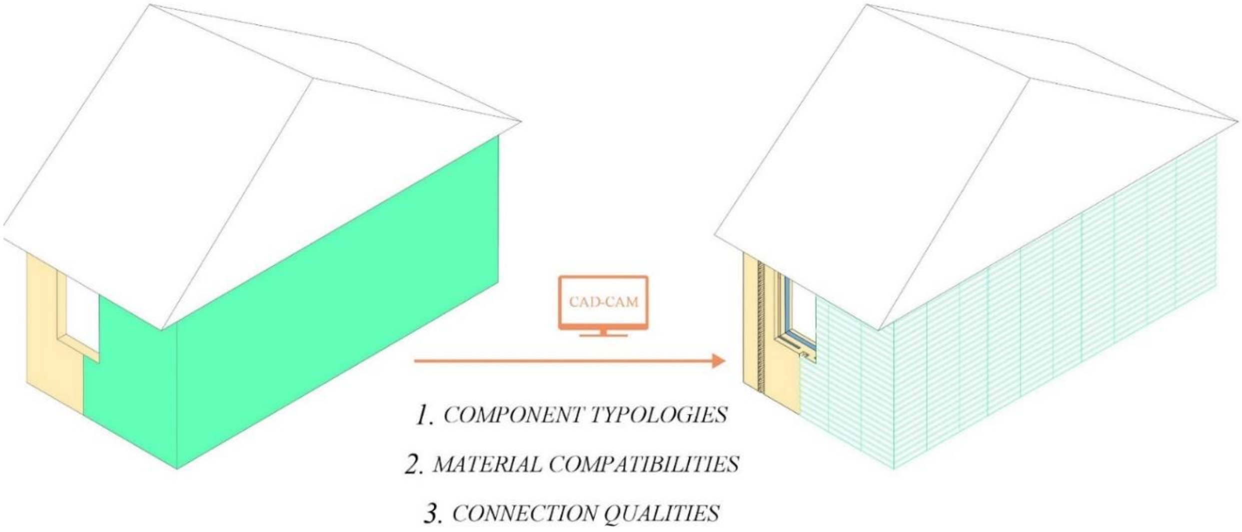


Fig. 54. One Island Home scale: CAD-CAM interface (Created by Author)

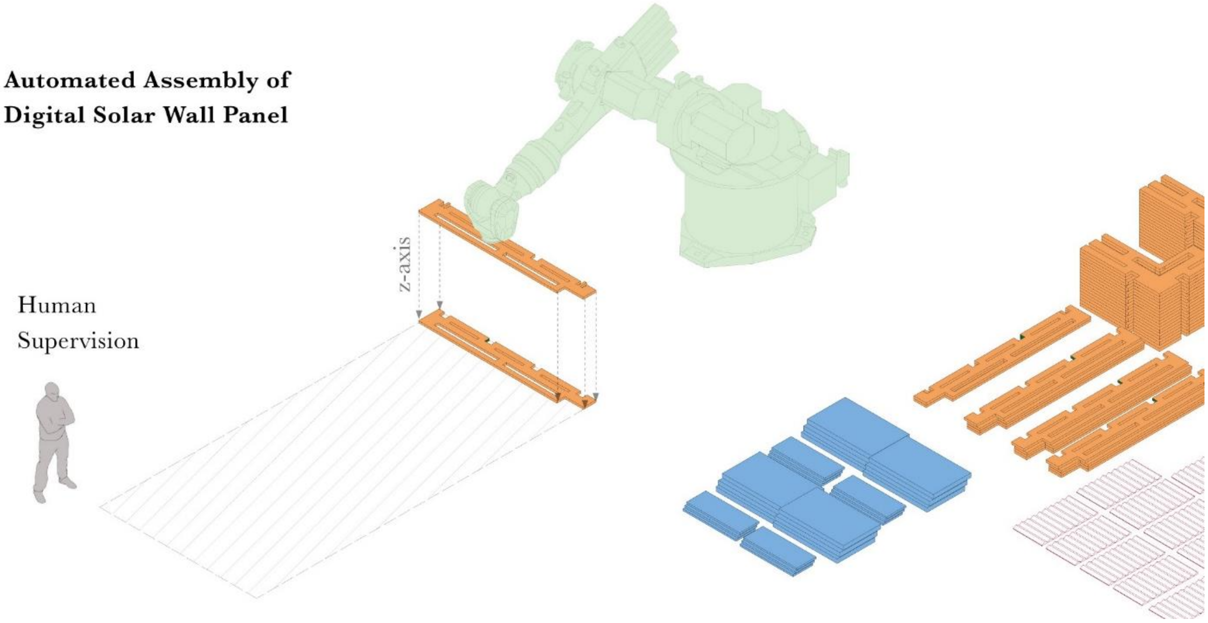


Fig.55. One Island Home: Robotic arm accurately stacking cut parts to on top of each other as per CAD-CAM data to build one panel.
(Created by Author)

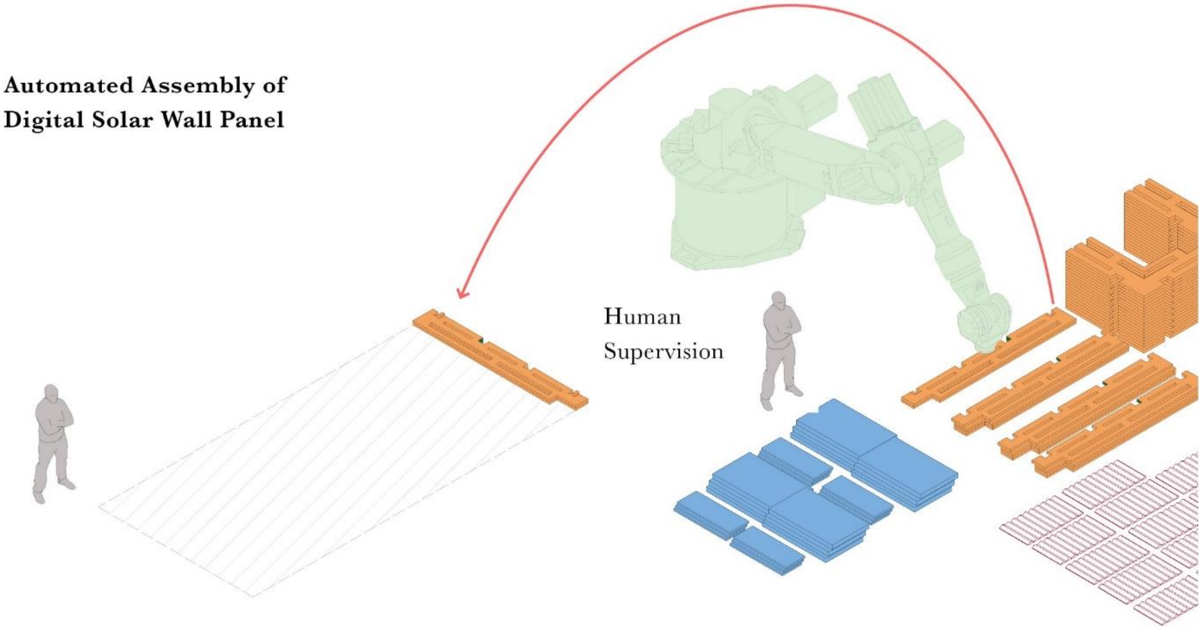


Fig.56. One Island Home: Robotic assembler performing repetitive task of assembly, under human supervision.
(Created by Author)

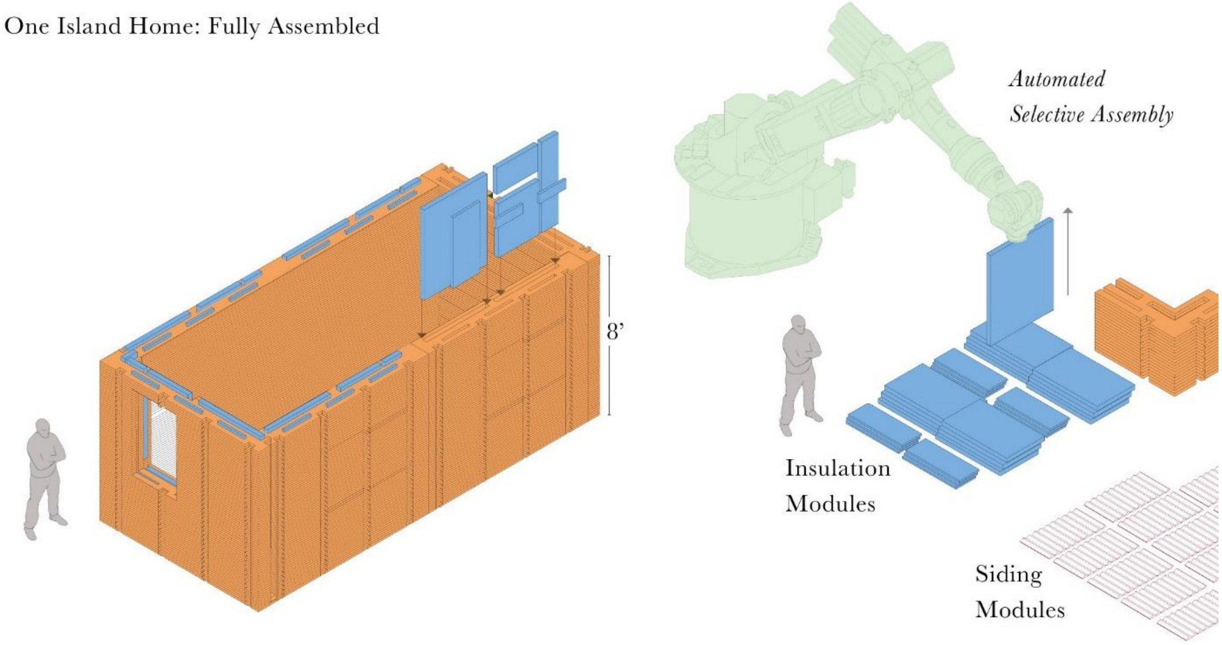


Fig.57. One Island Home: Full assembly of multiple wall panels. The process involves selective assembly of large modules by robotic assembler.
(Created by Author)

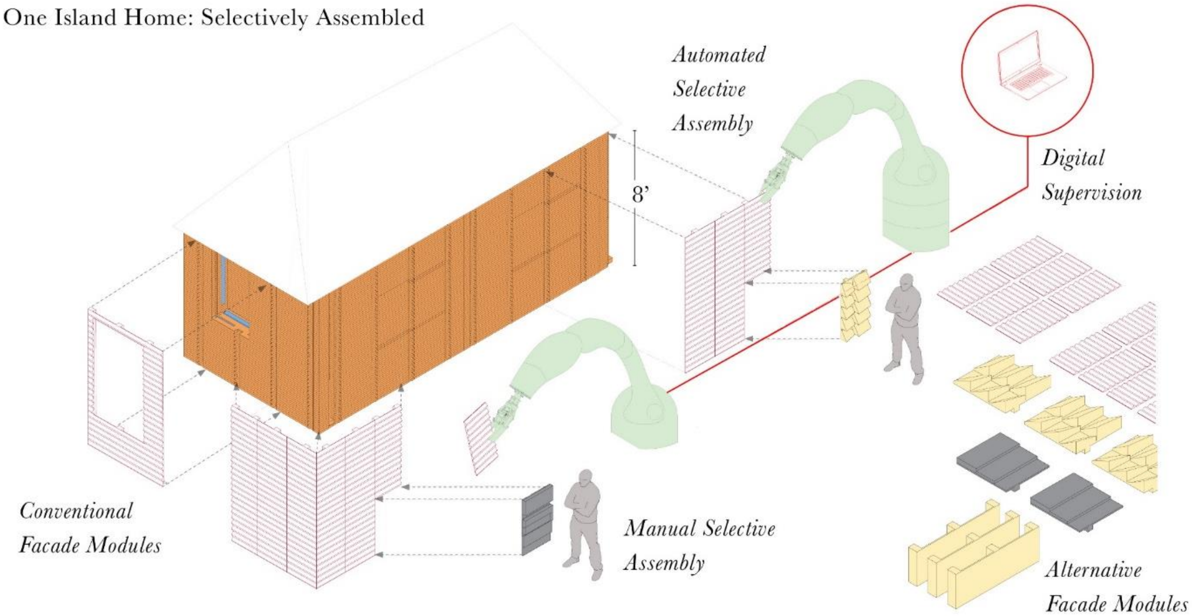


Fig.58. One Island Home: Selective Assembly of modules, large modules by automation and smaller modules by humans.
(Created by Author)

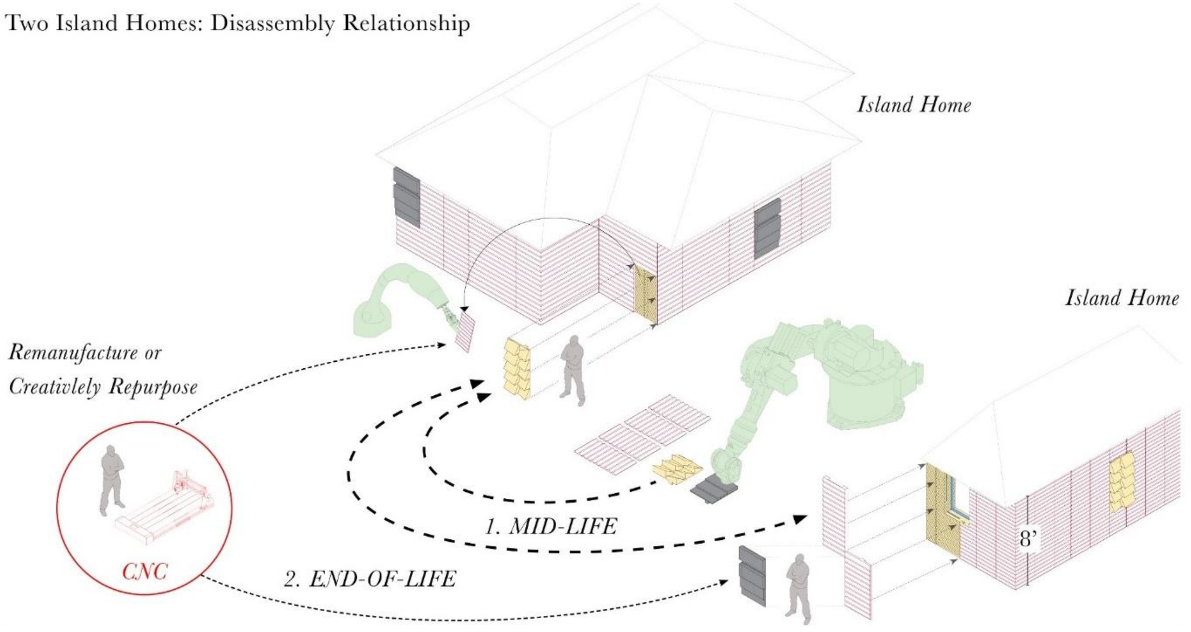


Fig.59. Two Island Homes: (1) Selective disassembly and reassembly of modules at mid-life stage due to homeowner's desires (2) Selective disassembly and reassembly of modules at end-of-life stage due to need for replacement or damage. At this stage, the modules and components could be creatively repurposed into other products of higher entropy.
(Created by Author)

As graphically represented in Figure 59, in two island homes of Vinalhaven's downtown, situations arise where there is 'a need to disassemble' and reassemble. Such scenario speculations guide in comprehending what could be the urban implications at island scale from my system. At the mid-life of a particular module or component, selective disassembly could be performed. There might be the following mid-life situations necessitating my system:

i. Scenario 1: When the year-round population is low, or when a homeowner is not indoors, he or she could selective disassemble and lend the component to someone else who wants it for more solar gain on south side or insulative properties. In this case, there is a direct exchange. Under the same scenario, another reason of direct exchange could arise when a homeowner wants to adopt a new aesthetic style.

ii. Scenario 2: When a homeowner has to get new component or module because of sudden issue at mid-life of current module or component. As and when he or she disassembles this component, the artefact could be utilised again depending upon its reuse capability.

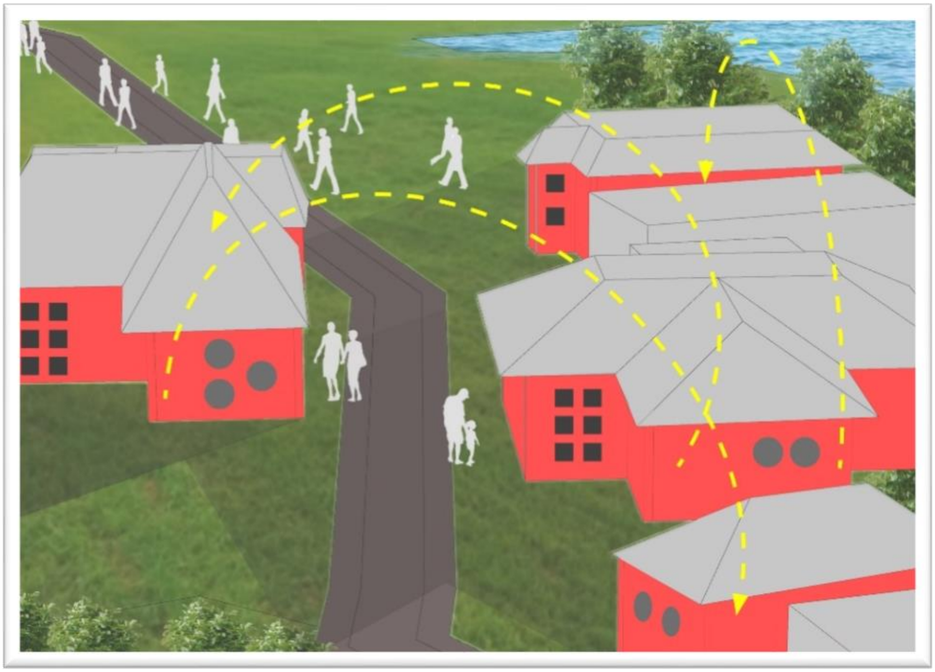


Fig. 60. Five Island Homes: A reassembled neighborhood defining an eclectic urban aesthetic revealing an underlying embodied energetics. (Created by Author)

My thesis develops a scaling-up method that attempts to imagine a neighbourhood of five island homes in Vinalhaven’s downtown. The following is a discussion around the urban implications from disassembly and reassembly processes between the five island homes. Through speculation, I postulate a closed-loop circular system of material embodied energy. With disassemble-able components in place, it is possible to envision a neighbourhood with an architectural expression that is eclectic in its aesthetic, but speaks of an underlying energetics. Such a neighbourhood could be imagined as analgous to a microgrid system. In a typical microgrid, operating energy is shared across the neighbouring homes. In my thesis, the paradigm of material embodied energy speculates an urban environment where sharing disassembled components with neighbours would lead to a circular system. Ownership of the building components could be an avenue to be explored further. I haven’t been able to address the five island home scale directly through my thesis. My next step pushing the envelope of this research work is to do quantitative and qualitative analysis of how design for assembly, disassembly and reassembly enriches the urban realm within the system boundary of five island homes.

Part VIII: Beyond Maine's islands

This part concludes the research work for my thesis. The main contribution of my thesis is **a methodology for design-production of affordable houses in order to:**

1. **Recover its material embodied energy**
2. **Easily assemble and disassemble its walls**
3. **Decrease energy burden in these island homes**

My thesis is developed around a foundational principle of Design for Assembly, Disassembly & Reassembly using CAD-CAM and digital fabrication tools. In study scale, my way of working is learning by doing through rapid prototyping. In island scale, I speculate the urban implications for up to five island homes.

As a part of an ongoing discourse on design and embodied energy, the sections in this part highlights the relevance of my approach and need of similar systemic strategies beyond Maine's islands. The burdens of Maine's islands are not unique if one starts exploring other low-income marginalized communities across the world, especially in colder regions. The aim of the following two sections is to stifle environmentally benign thinking in the readers. Throughout the sections, my intent of expanding the scope of my research is supported by previous studies and datasets.

Chapter 8.1. Energy Burden around the world

Conditions prevalent in Maine's islands can be found in other islands across the world too. 'A review of renewable energy utilization in islands' points to the less amount of traditional energy resources in islands due to their isolation, limited area and remoteness. Imported fuel is still the main energy source in most islands around the world. According to the paper, limited fuel supply and environmental pollution issues lead to use and exploitation of local alternative renewables for sustainable electricity supply, and most islands have renewable energy resources in abundance. (Kuang et al., 2016, p. 511).

My motivation in equitable energy transition originates from socio-economic realities of energy burden. The term has been defined and studied extensively in past two decades. According to the 2010 paper 'Energy burden and the need for integrated low-income housing and energy policy', Energy Burden reflects the disparate allotment of financial resources among low-income households on energy expenditures. Compared to middle- and upper-income households that spend 5 percent or less of their total household income on energy purchases, low-income households' energy purchase expenditure is 10 percent or more of their income. The burden is increases further among the very poor, who are likely to spend over 20 percent on energy purchases. Low-income households find it more difficult to adapt to greater variability in energy pricing, as experienced with oil, gas, and electricity rates in recent years. These homes are disproportionately less energy efficient compared to non-poor households, especially in urban areas with older housing stock. The paper concludes by emphasizing greater public awareness of this issue coupled with clear understanding of the relations between policies to promote higher and better funding allocations for policy initiatives that target this issue and improve the energy burden faced by low-income families in the United States. (Hernández & Bird, 2010). The paper highlights the importance of Low-Income Home Energy Assistance Program (LIHEAP), a program under the U.S. Department of Health & Human Services, that provide federally funded assistance in managing costs related to home energy bills, energy crises and weatherization.

Fig. 61. Low Income Home Energy Assistance Program logo, by LIHEAP
(Retrieved from https://www.acf.hhs.gov/ocs/programs/liheap)

My thesis's focus of energy burden within low-income households (or the 'heat or eat dilemma') is further supported by the paper 'Energy Burden and the Need for Integrated Low-Income Housing and Energy Policy' that calls fuel poverty an acknowledged problem, but reveals that additional policy interactions and dynamics make the energy burden of the poor, low-income renters specifically, far worse than policymakers realize. The paper has three main objectives wherein the first identifies unique dimensions of energy burdens to the poor by using qualitative interview data to reveal health risks, financial problems, and instability associated with energy burden that include, but are not limited to, utilities hardship and fuel poverty. It records individual-level strategies employed by poor householders to deal with utilities hardship. These are mainly temporary fixes to persistent problems aggravated by limited policy coordination between housing and energy assistance. (Hernández & Bird, 2010).

Chapter 8.2. Towards an equitable energy transition

My thesis highlights the importance of the critical concept of ‘energy transition’. Extensive literature exists, especially from policy fields, on the need for energy transition, especially in developing communities. According to Gerald Leach’s paper ‘The energy transition’, “in many developing countries, anecdotal evidence and household energy surveys in many developing nations point to the slow transition, if at all, in rural areas in contrast with the progress in urban areas. The section titled “Access to fuels and urban size” notes challenges in obtaining modern fuels to be the second major constraint on energy transitions. The effects can be best observed in household energy use patterns as per settlement size and remoteness from major trading centers and roads. (Leach, 1992, p. 119).

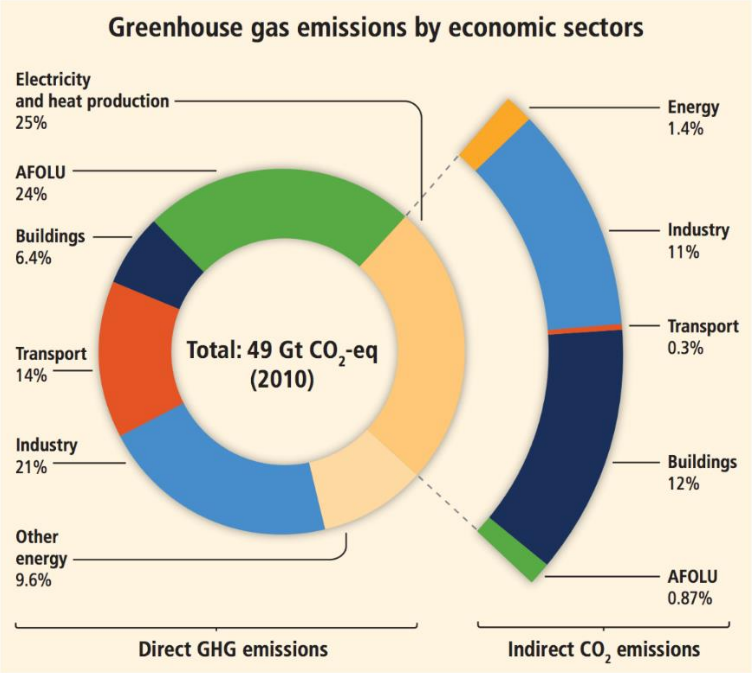


Fig. 62. Total anthropogenic greenhouse gas (GHG) emissions, by IPCC (Pachauri et al., 2014, p. 47)

Due to formulation of the Fifth Assessment Report report, sectoral policy instruments under ‘Human settlements and Infrastructure’ have incorporated Housing Availability and Affordability mandates, building codes, design codes and standards for its regulatory approaches (Pachauri et al., 2014, p. 108). In this report, Intergovernmental Panel on Climate Change (IPCC) foregrounds the building industry’s role as a major economic sector that adds direct and indirect carbon dioxide (CO2) emissions (Pachauri et al., 2014, p. 28) and has increased Global Warming Potential (GWP) (Pachauri et al., 2014, p. 88), but can also tackle Climate Change through measures. The measures in the report focus on energy transition strategies, a shift from fossil fuels to Renewable Energy Sources (RES) like solar. As enlisted in Table 4.4. on Page 101 of this report, recommended sectoral mitigation measures for buildings include key low-carbon energy options like building integrated RES, key energy saving options like systemic efficiency (integrated design, low/zero energy buildings, district heating/cooling) and other options like improving building lifetime, durability of building components and use of low energy/ greenhouse gases (GHG) intensive construction and materials.

Fig. 63. Inequitable energy transition, by Passive House Institute US
(Retrieved from http://www.phius.org/home-page)

More precisely, my motivation is to accelerate residential energy transition from fossil fuels to RES to meet energy demands of houses. A major takeaway from this section is that according to the International Energy Agency (IEA) document titled ‘Transition to sustainable buildings: Strategies and opportunities to 2050’, “residential buildings accounted for 75 % of total energy consumption” by the building industry in 2010, and the tertiary (commercial and industrial buildings) segment the rest (OECD/IEA, 2013). This holds true for the United States of America (U.S.), as according to U.S. Energy Information Administration (EIA)’s ‘2015

Residential Energy Consumption Survey (RECS)’ reports from 1950 to 2009 suggest that both the amount of CO2 emissions associated with residential use and the total amount of energy associated with households more than tripled (RECS/EIA, 2016).

My thesis states that the socio-economic dimension of ongoing technology-centric energy transition approach cannot be ignored. The statement is supported by a recent paper titled ‘Of embodied emissions and inequality: rethinking energy consumption’. This paper notes that “half of the world’s population, approximately 3.5 billion people, of which the majority in regions most vulnerable to Climate Change, emit only about 10% of total global emissions attributed to individual consumption. In contrast, approximately 50% of the world’s greenhouse gas emissions (GHG) can be attributed to consumption by the world’s richest 10 percent, with the average carbon footprint of the richest one per cent being 175 times higher than that of the poorest 10 percent” (Baker, 2018). The paper derives its introductory statement from a 2015 published report by Oxfam Media titled ‘Extreme Carbon Inequality’. The report states that “Climate change is inextricably linked to economic inequality: it is a crisis that is driven by the greenhouse gas emissions of the ‘haves’ that hits the ‘have-nots’ the hardest” (Oxfam, 2015).

Part IX: References

Chapter 9.1. Bibliography

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- Fig.58. One Island Home: Selective Assembly of modules, large modules by automation and smaller modules by humans. (Created by Author)
- Fig.59. Two Island Homes: (1) Selective disassembly and reassembly of modules at mid-life stage due to homeowner’s desires (2) Selective disassembly and reassembly of modules at end-of-life stage due to need for replacement or damage. At this stage, the modules and components could be creatively repurposed into other products of higher entropy. (Created by Author)
- Fig. 60. Five Island Homes: A reassembled neighborhood defining an eclectic urban aesthetic revealing an underlying embodied energetics. (Created by Author)
- Fig. 61. Low Income Home Energy Assistance Program logo, by LIHEAP (Retrieved from https://www.acf.hhs.gov/ocs/programs/liheap)
- Fig. 62. Total anthropogenic greenhouse gas (GHG) emissions, by IPCC (Pachauri et al., 2014, p. 47)
- Fig. 63. Inequitable energy transition, by Passive House Institute US (Retrieved from http://www.phius.org/home-page)
- Table 1: Year-round population and operating energy/electricity rates in six northern unbridged islands of Maine (Data Source: The Island Institute annual reports)
- Table 2. Review of previous study on ‘disassembly’ from the perspective of products, engineering, architecture and construction.