Rethinking Residential Construction

Utilizing 3D Printing as a Viable Residential Construction Method in Southeast Michigan

Caris Wenona Heminger

Master Thesis Studio | 5100-5200
Studio Advisor | Virginia Stanard
External Advisor | James Leach
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Content

Abstract

Three-dimensional construction printing is a form of additive construction that uses 3D printing technologies as a core method to fabricate buildings, construction components, and civil infrastructure. This new process allows for less waste, faster building times, higher productivity, lower need for labor, reduced costs, and newer shapes and designs than the traditional concrete framework. Furthermore, utilizing 3D printing technology can result in a reduction of carbon emissions by saving on transportation and construction equipment. While there are many advantages to using this type of building construction, it is a relatively new process that has some challenges to overcome. 3D concrete printing has a high initial investment cost, requires technical expertise, faces building code hurdles, has limited printing size, and may encounter difficulty with environmental factors when constructed outside.

The intent of this thesis is to study how implementing 3D printing in residential construction in Southeast Michigan is a viable construction method in comparison to the traditional wood frame construction that is currently being used. The environmental impacts of each building method throughout the building envelope life cycle was analyzed. Affordability of materials and construction of a new build for each type of construction method within the region was compared. Additionally, the performance of the envelopes in the high humidity, large temperature ranges, prevailing winds, and precipitation levels of Southeast Michigan was examined. Investigating the disruptors of this new technology being implemented in the future was analyzed by considering future climate change and shifts in the labor force. A visual comparison was created from this research showing how 3D printing and wood frame construction varied for the participants involved through the home's life cycle.

The findings of this research show that 3D printed construction has the potential to be more environmentally responsible than traditional wood frame construction. Additionally, it has similar affordability and envelope performance in the region of Southeast Michigan. Moving forward, implementing this construction method can mitigate climate change and provide a necessary shift in the labor force.

Introduction

3D printing technology has been utilized in many fields and progressed to better serve humans. It has been used in the medical field to make organs tailor made for patients, create custom prosthetics, and produce on-demand medical samples. This technology has also been used in the Engineering field to build unmanned aircrafts, create general aviation parts, used in various military applications, build cars, and produce high-end electronics (Drew Turney, et al). In the architecture field, however, it has primarily been limited to producing models. While there has been significant growth in its architectural applications over the past decade, 3D printing still faces pushback from critics. With more research, testing, and making, 3D printing can be driven further and become an asset to the construction industry.

Applying 3D printing in building construction could solve issues the industry faces. The building sector is consistently faced with tight budgets and deadlines. In recent years there have been severe labor shortages and major supply chain delays ("3D Concrete Printing – the Ultimate Guide"). With the unexpected setbacks caused by the Covid-19 pandemic, these problems only became more conglomerated. Introducing robotics in construction could help alleviate some of these issues.

Often times homes are built with unnecessary amounts of material waste in a repeatable cookie cutter fashion that is not considerate of the site climate or context. Additionally, these homes are not strategized for a long-term life cycle. They typically consume more energy than necessary, which accumulates avoidable costs and negative impacts on the environment. Furthermore, these houses are typically not constructed with durable finishes which in turn results in entire homes being thrown out and replaced by the same poor construction.

As the potential for 3D printed construction is being uncovered, research on its adaptability to different regions needs and climate is very relevant. The innovative technique of this relatively new technology can help resolve the specific construction issues an area may face. Whether it be for affordable housing, sufficient housing, or quick disaster relief, learning to optimize 3D printing for a specific region will solidify this construction method as a viable option to traditional forms of building.

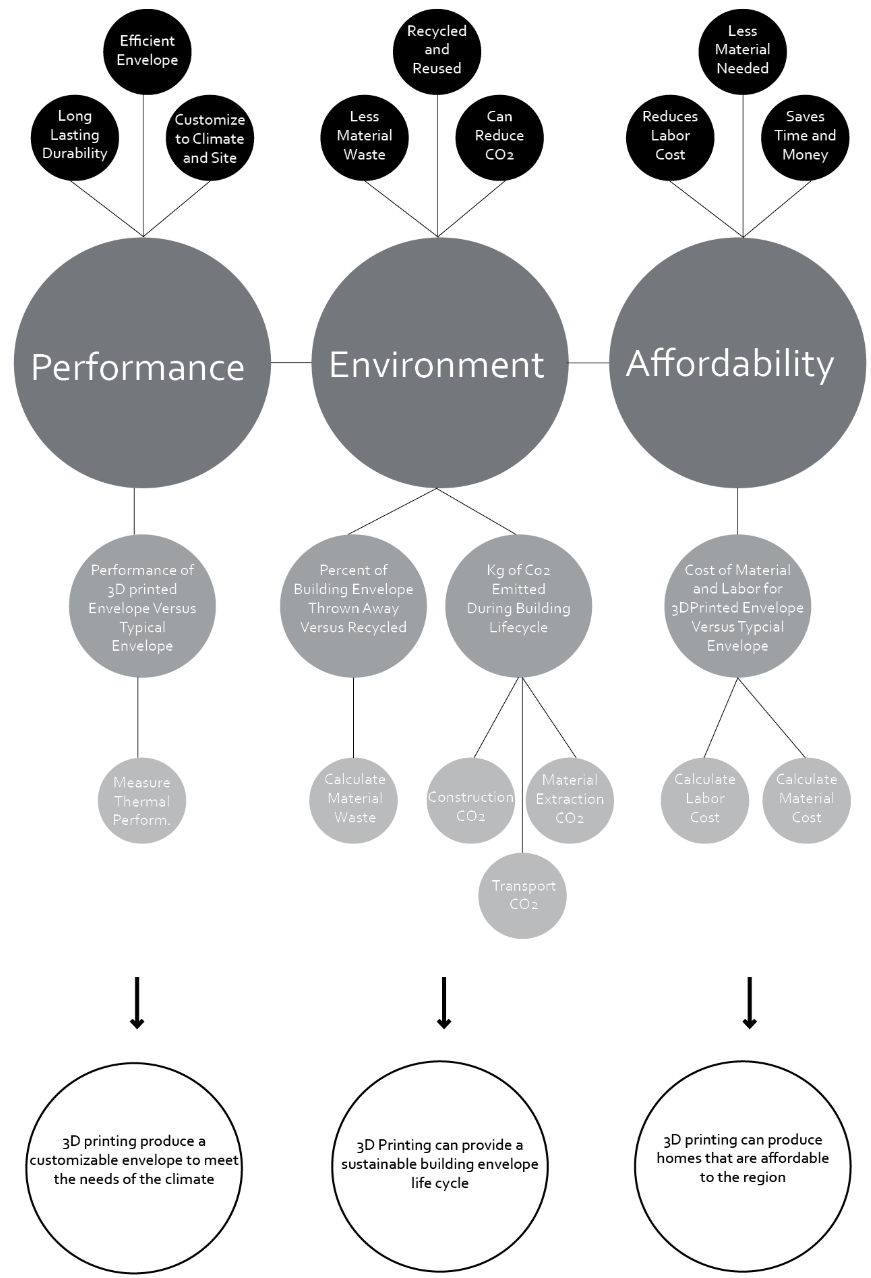


Figure 1.00 Framework diagram

Thesis Statement

3D construction printing is a form of additive construction that uses 3D printing technologies and concrete as a core method to fabricate buildings and construction components. This thesis investigates the viability of implementing 3D printing as a construction method by creating a framework that measures the environmental impact, affordability, and performance of a 3D printed envelope in comparison to the traditional construction used in the region. This framework studies 3D printing as a viable construction method for residential homes in Southeast Michigan by analyzing its CO2 emissions during the building envelope life cycle, its affordability of labor and materials in the area, and the energy performance of its wall envelope in the climate compared to the wood frame construction that is typically used in this region. Additionally, this thesis will investigate the disruptors of the new technology being implemented by considering future climate change and shifts in the labor force. Finally, a narrative of a 3D printed home compared to a traditionally constructed home is followed and highlights the design process, environmental impacts, and users experience of the home's life cycle.

Background

How it Works

3D printing utilizes a large printhead which deposits material in an additive construction process. The printhead can be attached to either a gantry system or robotic arm. A gantry system is a supporting structure consisting of beams and rails that allows the printhead to move in an x, y, and z axis. This type of system can be used for larger commercial building but the support system lacks mobility. A robotic arm is a crane like system than can operate in six different axes. This system has a limited printing size but can create more complex geometric shapes than the gantry system ("How Does a Concrete 3D Printer Work?").

These industrial sized 3D printers are capable of printing many different materials. Metal, plastic, and even clay have been used for 3D printing construction. Most commonly, a special formula of concrete is used. Concrete is the second most used material in the world after water. Concrete is made up of water, cementitious compound, and aggregate. Because typical concrete would clog the printing nozzle many different formulas have been created and even patented for 3D printing. The printing process operates by adding layer by layer, so the formula needs to adhere to itself while also curing quickly enough to support as each of the layers builds up ("How Does a Concrete 3D Printer Work?").

To design and model using 3D printers for construction it starts with a 3D model that is created in a 3D modeling software. From there the model is then sliced and translated into G-code. This code is sent to the printer and guides its path as it deposits the material. This process continues layer by layer until the final product is complete ("How Does a Concrete 3D Printer Work?").

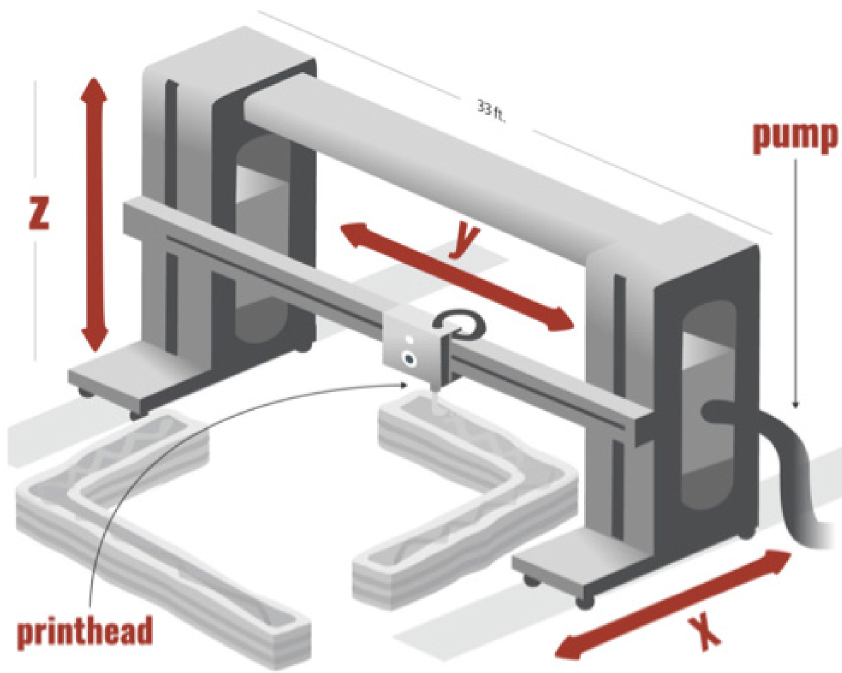


Figure 2.00 Gantry System Diagram

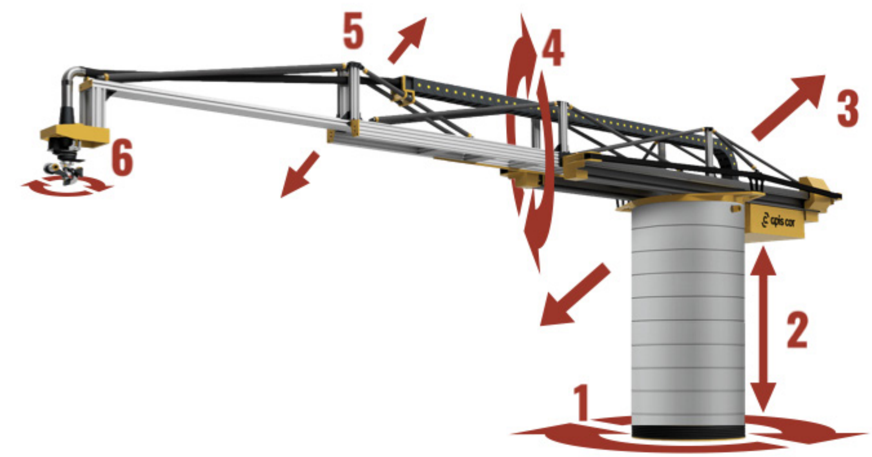


Figure 2.01 Robotic Arm Diagram

History

3D printing is defined as any technology that constructs parts in an additive way. Additive construction is a process in which a product is created by layering materials. This technology dates back to the 1980's when stereolithography (SLA) was created. This technology used a high-powered laser to turn liquid resign into a solid material. Selective laser sintering (SLS), fused deposition modeling (FDM) and direct metal deposition (DMD) are other popular methods of 3D printing that have been invented (Ellis, Grace).

Because 3D printing can accurately create one to one models, it was first used as a tool for creating prototypes. In the architectural field, 3D printing was used to build scale models. As the technology has progressed it has furthered its presence in the construction industry. In 2004, a professor at the University of South Carolina attempted to build the first 3D printed wall. Ten years later a full canal house was built in Amsterdam using 3D printing technology. A major feat was accomplished by the technology in 2016 when it was utilized by the Dubai future foundation to construct its Office of the Future. This office is 2,700 square feet and took just seventeen days to build (Ellis, Grace).

3D printing continues to grow its presence in the construction industry. Many experts in the field are working to fully utilize its capabilities in the building sector. The technology, however, has many opportunities to be fine-tuned to better serve low-income residents. Following are some of the pros, cons, and possibilities when it comes to 3D printed construction.

Pros

Time Efficiency: According to Marco Vonk, Marketing Manager at Saint-Gobain Weber Beamix, "You save about 60% of the time on the jobsite... "

Less Labor: According to Marco Vonk, Marketing Manager at Saint-Gobain Weber Beamix, "You save about... 80% in labor."

Safer Conditions: According to OSHA, more than 5,000 workers are killed on the job each day. Incorporating 3D printing would likely decrease work injuries and fatalities.

Design Freedom: Architects have more creative freedom to build complex designs without greatly incresing the cost or labor.

Affordable: Habitat for Humanity says adding the use of 3D printed concrete saved an estimated 15% per square foot in building costs on their affordable housing project.

Zero Waste: 3D printing is an additive manufacturing process that only uses as much material as is necessary for creating a structure.

Cons

Starting Costs: 3D pritning machines used for construction can cost anywhere from around $180k to over $1M.

Expert Knowledge: New technology requires a level of expertise that is often times niche.

Special Workforce: Finding qualified workers for 3D printing construction when there are already labor shortages could prove to be challenging.

Code Hurdles: There are currently no clear laws and regulations that are defined for 3D printing construction.

Limit Print Size: Due to the limit on the size of the robot, buildings are restricted, usually vertically, on their 3D print size.

Weather Dependent: Weather and other environmental conditions could affect the ability for 3D printing Construction to occur onsite.

Possibilities

Stabilizing: As new technology develops and becomes more common, its cost tends to decrease and become more attainable.

Expert Knowledge: Opportunity to educate. Allows people from ranging backgrounds to contribute new ideas.

Special Workforce: A shift in the workforce could provide workers with safer jobs that are not as physically harmful or exhausting on the body as construction.

Code Hurdles: 3D printed buildings are still being approved to be built. Using these precedents to regulate 3D printed construction will aid this process.

Build Bigger and Smarter: Machines are getting larger and prefabricating wall sections is also a possibility to create larger buildings.

Weather Dependent: Utilizing a portable and reusable tent structure to surround the printing site would create consistent building conditions.

Figure 2.02 Pros, cons, and possibilities comparison

Precedent Study

TECLA Prototype

This is a precedent study that successfully utilized 3D printing and incorporates methods that could be investigated and utilized in Southeast Michigan. The project is located in Massa Lombarta, Italy and serves as a prototype for sustainable homes built utilizing 3D printing technology. Mario Cucinella teamed up with 3D printing company WASP to produce TECLA, a technology with the initiative to created eco-sustainable homes. The goal of this project was to be able to design for different climates and combat homelessness. This study began by implementing bioclimatic design strategies for areas in hot and humid climates ("Tecla").

This prototype is a fifty square meter home that consists of two dome-like structures. This home contains a living area with kitchen and a bedroom with a bathroom. Some of the internal furnishings were also incorporated in the design and 3D printed. This tactic gives the advantage of a completely furnished house withing the construction process but does hinder the flexibility of the layout of the home. This project also only used local material and clay from the ground as the 3D printed material. Additionally, the site was utilized for storm water collection. Another goal of the project was to create autonomy from city girds. This led to the home being efficient of its energy use, waste, and water management ("Tecla").

Figure 3.00 TECLA Prototype Home

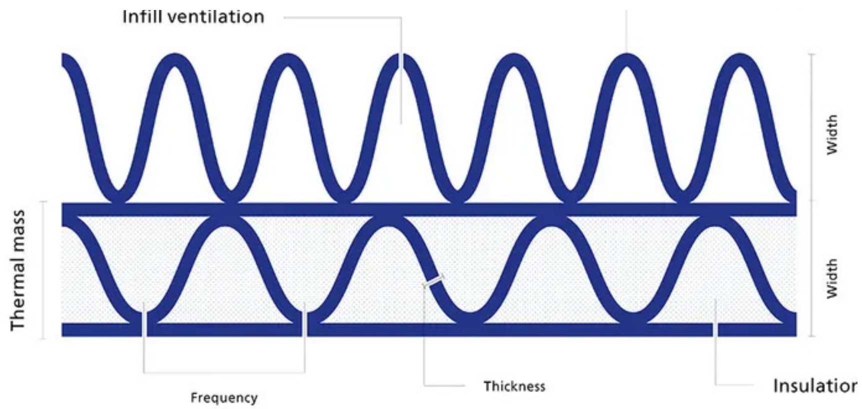


Figure 3.01 Wall infill diagram

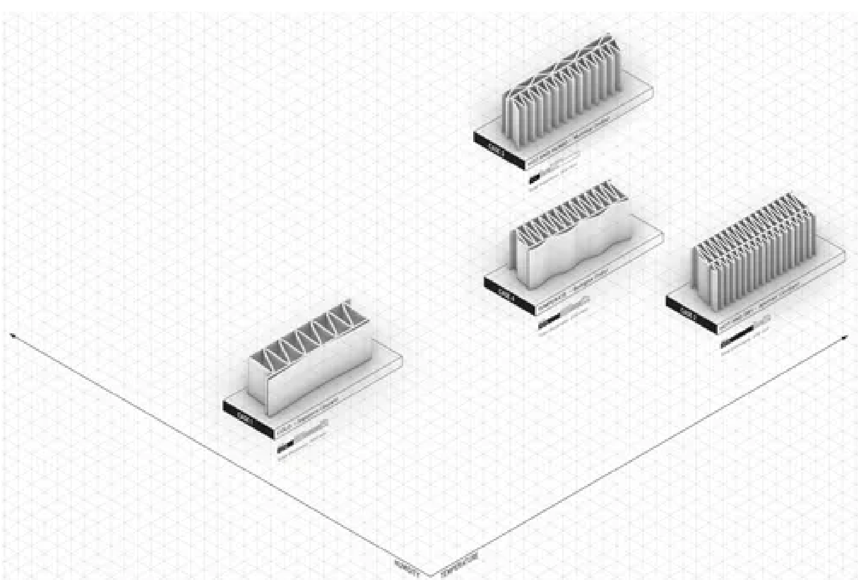


Figure 3.02 Optimization of the wall infill based on the humidity and temperature values of the site

Application

The ability to design for different climates in architecture comes from within the wall envelope. For 3D printed walls this occurrence happens at the wall infill. Because the 3D printer provides flexibility to design it can print any type of wall infill with no extra cost, time, or labor to the project. TECLA specifically looks at three different areas to tackle bioclimatic design which are ventilation, insulation, and thermal mass. Ventilation occurs at the outer layer of the 3D printed wall while insulation happens in the cavities within. Thermal mass comes from the frequency of the infill ("Tecla").

TECLA shows that using innovative technology combined with thoughtful climate sensitive design tactics utilized from the past can feasibly create affordable and eco-friendly homes. Rether than designing cookie cutter homes that are kept comfortable with excessive amounts of material and mechanical systems, envelopes can be thoughtfully designed to a specific climate and site to create a cost effective and environmentally conscious home.

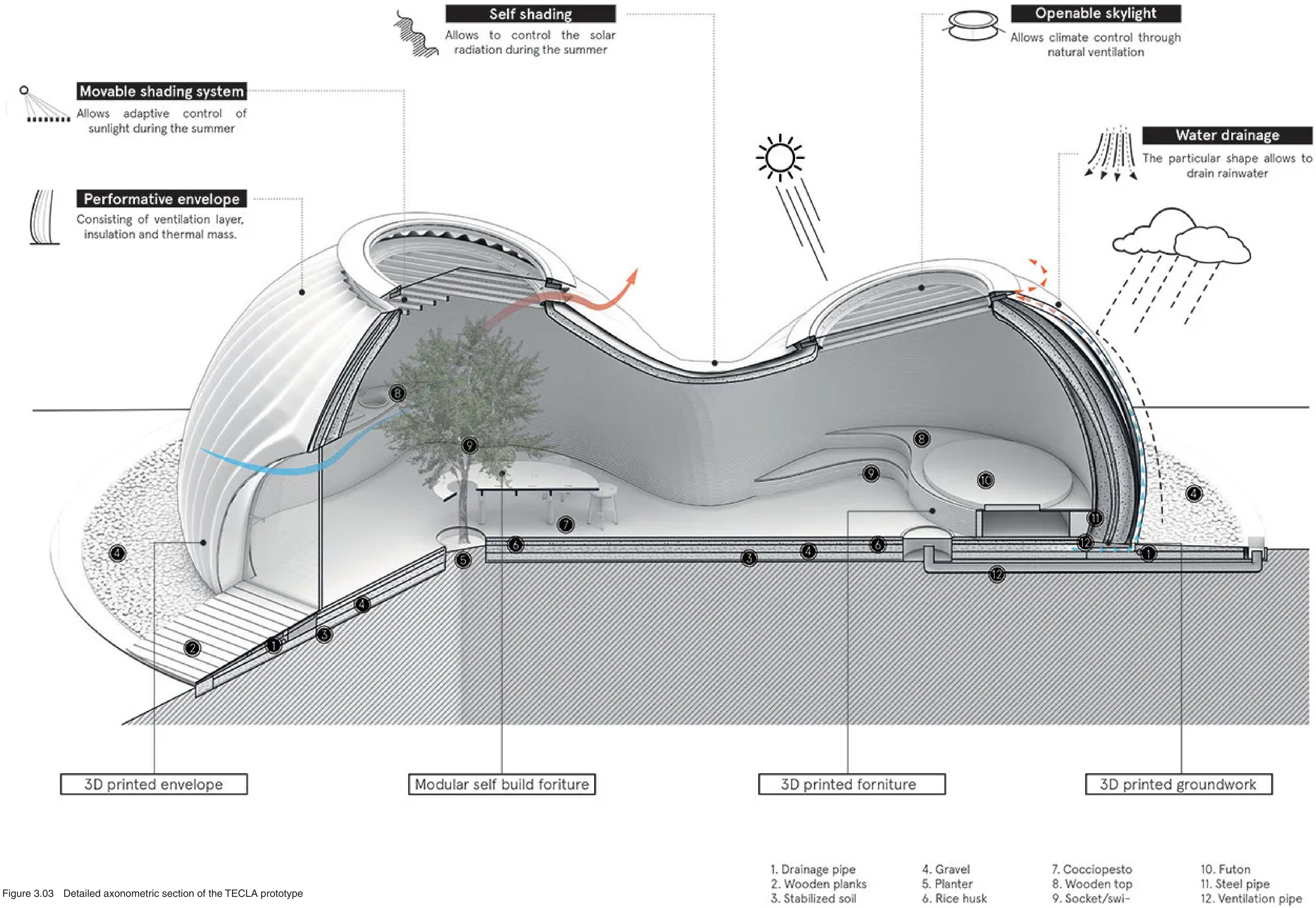


Figure 3.03 Detailed axonometric section of the TECLA prototype

Region Location

Southeast Michigan

The area of Southeast Michigan is made up of seven counties. These counties are Livingston, Macomb, Monroe, Oakland, St. Clair, Washtenaw, and Wayne. In order to analyze the performance of the 3D printed walls in the area, the climate data on the average temperature highs and lows as well as humidity, precipitation levels and wind speed were analyzed. Data was also gathered on the current energy consumption and costs of the counties within the Southeast Michigan region. This data is important as this thesis investigates how 3D printed walls thermally perform to reduce energy consumption as well as costs. Additionally, the current wages necessary to afford a home in the area versus the actual wages being made by those who are renting was researched. This data will help uncover the actual affordability of 3D printed homes in the area.

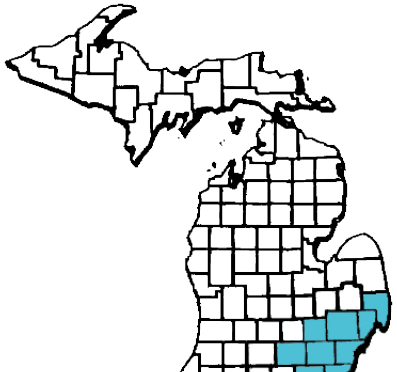


Figure 4.00 Southeast Michigan county map

Climate Data

Figure 4.01 Temperature (F)

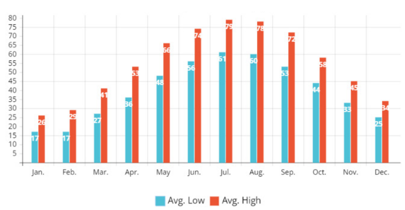


Figure 4.02 Humidity (%)

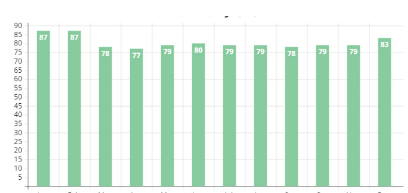


Figure 4.03 Precipitation (in)

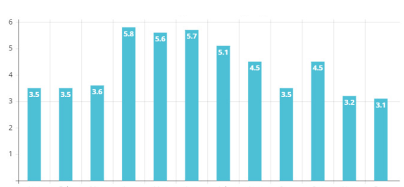
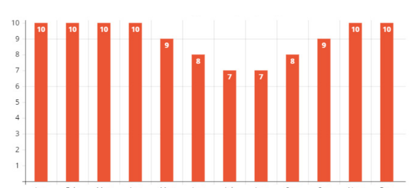


Figure 4.04 Wind Speed (mph)



Affordability

Figure 4.05 Estimated Hourly Renter Wage: 2021

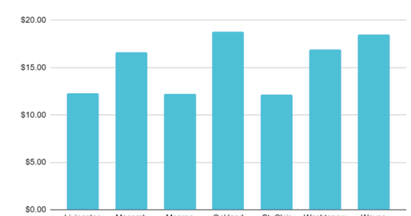
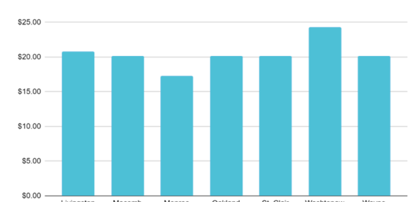


Figure 4.06 Average Wage Necessary to Afford a Two-Bedroom Home: 2021



Energy Consumption and Cost

Figure 4.07 Kilowatt-hour (kWh) of Electricity per Month

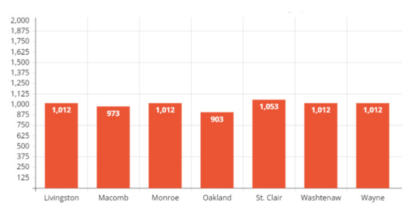


Figure 4.08 Cents/Kilowatt-hour (kWh)

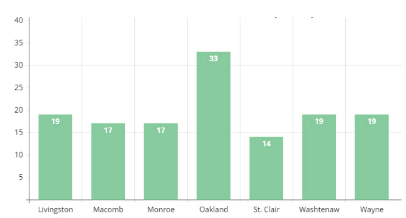
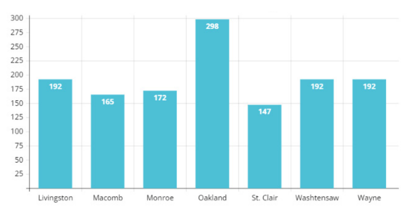


Figure 4.09 Cost in USD of Electric Bill per Month



Environmental Analysis

Material Extraction

To analyze the environmental impacts during material extraction a 4' x 8' wall section for traditional wood frame walls and 3D printed walls was assessed. The CO_2 emissions for the amount of each of the materials within the wall section was calculated using (blah blah blah source). For the 3D printed wall, three different materials for the concrete were analyzed. Laticrete is a traditional concrete brand with harsh impacts to the environment. Lehigh is a concrete that utilizes EcoCemPLC for its aggregate and reduces its CO_2 emissions by 10% in comparison to traditional concrete (Emerson). Blue Planet concrete uses aggregate that absorbs CO_2 when it is created, acting like a carbon sink. This makes the material extraction of Blue Planet concrete carbon negative.

To further the implications of the calculations, the average house size of new builds in Southeast Michigan was calculated. The envelope of these size homes was then also calculated. To find the CO_2 emissions of the average home, the emissions of the wall sections were multiplied to the amount needed for the home size. The result showed wood frame homes emitting 3,126 kg/CO_2, Laticrete 3D printed walls emitting 4,807 kg/CO_2, Lehigh 3D printed walls emitting 4,511 kg/CO_2, and Blue Planet 3D printed walls sequestering 2,551 kg/CO_2. This data is represented by how many trees would need to grow for ten years to combat the CO_2 emissions as well as how many miles would be driven in the average passenger vehicle. For the Blue Planet 3D printed wall this data is represented by how many trees would grow for ten years to match the amount of CO_2 sequestered and how many miles driven in the average passenger vehicle is saved.

Figure 5.00 Wood Frame Wall Section

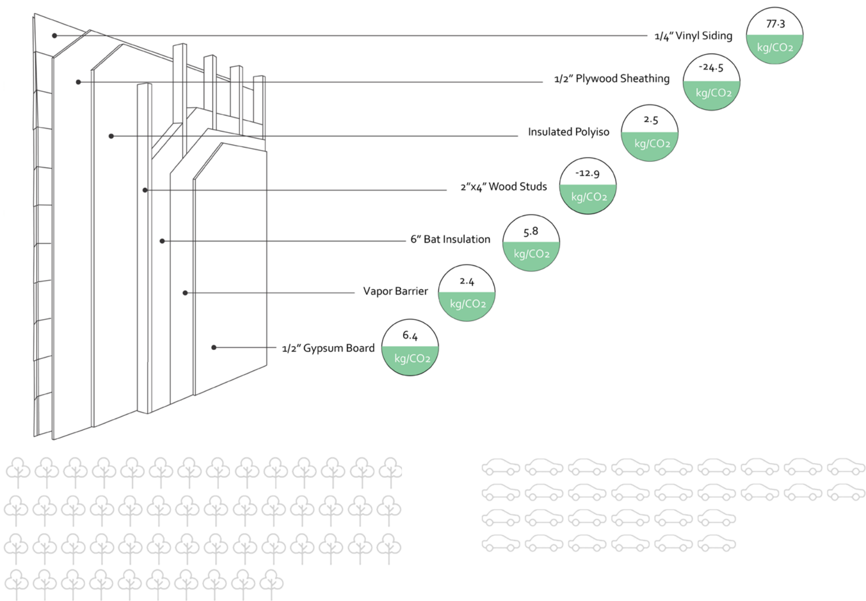


Figure 5.01 Laticrete Wall Section

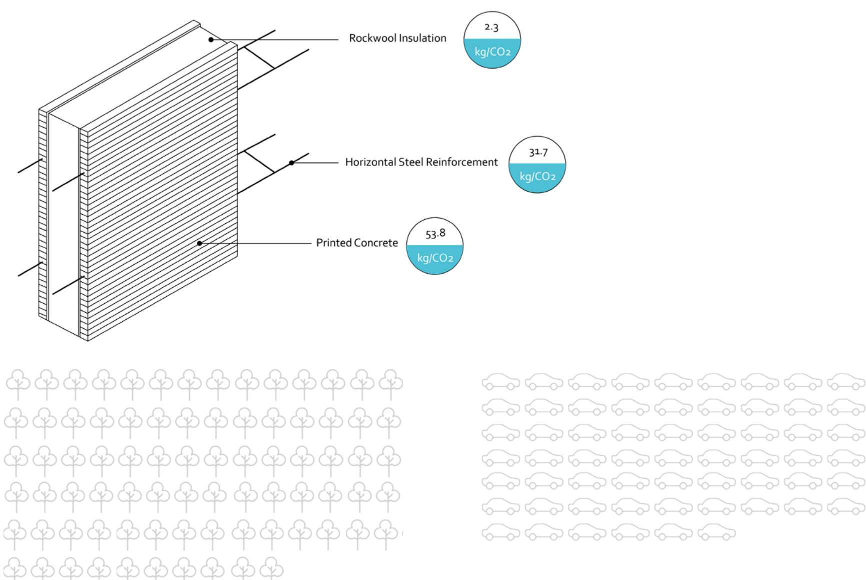


Figure 5.02 Lehigh Wall Section

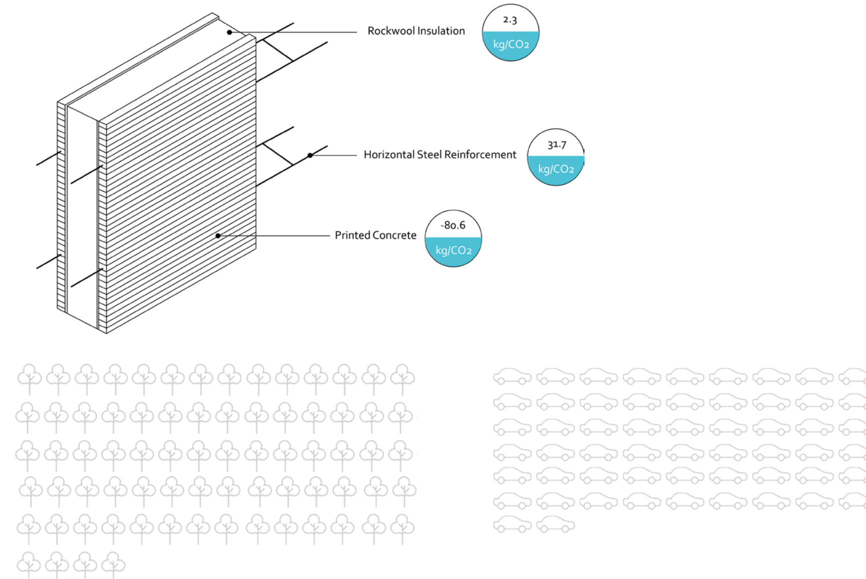
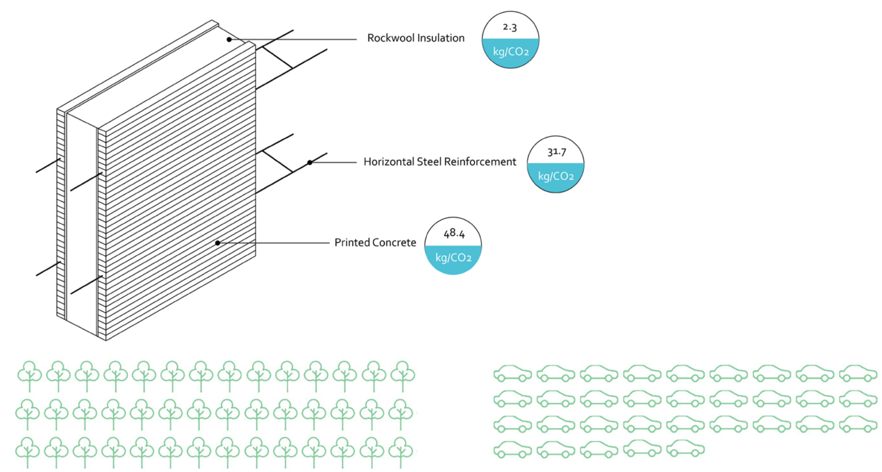


Figure 5.03 Blue Planet Wall Section



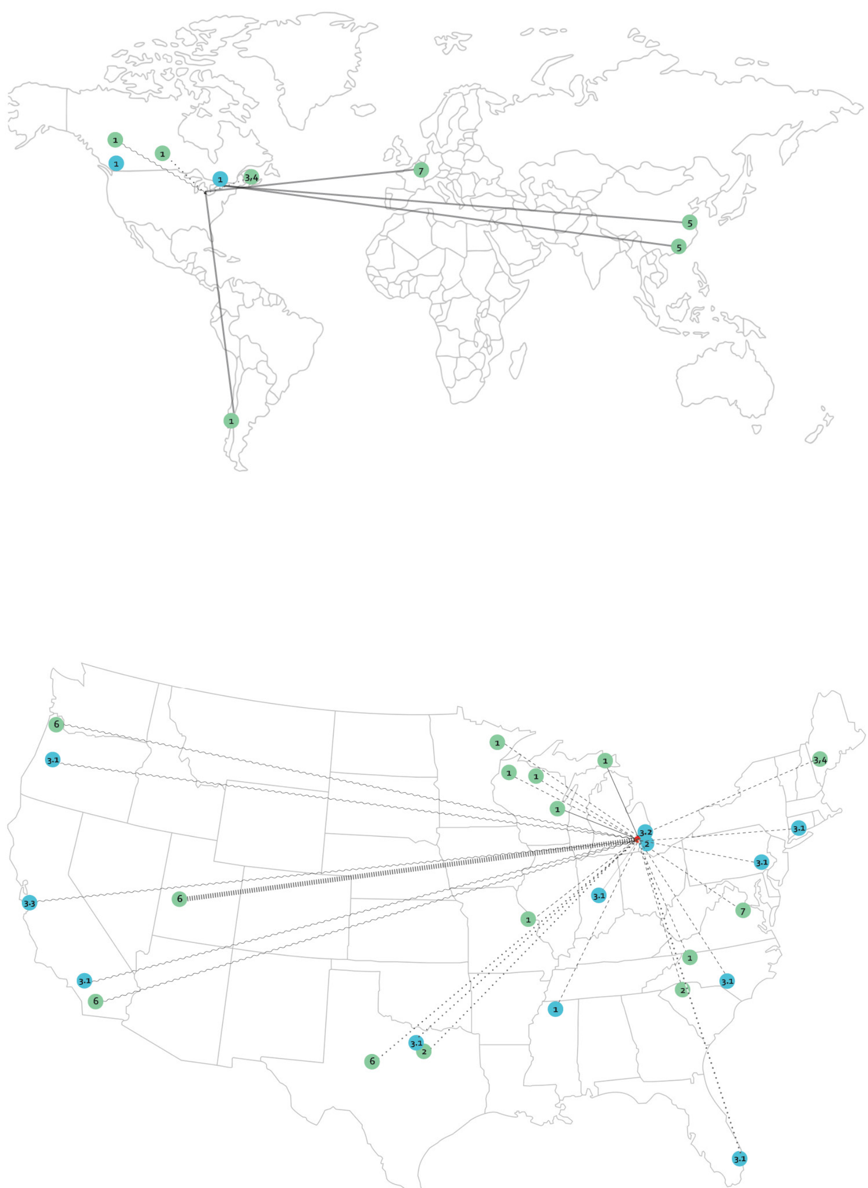


Figure 5.04 Transportation map

Transportation

To calculate the Co2 emission of transportation, the most sold brand of the materials within the building wall section were found at Home Depot. Where they were manufactured and how far they are from Detroit was mapped out and the miles a truck would have travel to get them there was calculated. The closest manufacturers for each material were chosen and the Co2 emissions that would occur when getting the supplies for each wall section was calculated. The results showed that transporting all the materials necessary for wood frames walls emitted 3,607.6 kg/CO2, Laticrete 3D printed walls emitted 281.52 kg/CO2, Lehigh 3D printed walls emitted 151.34 kg/CO2, and Blue Planet 3D printed walls emitted 1,262.82 kg/CO2. This showed that transporting six different materials for a typical building wall section made it more harmful to the environment than the other concrete wall sections. Additionally, while Blue Planet concrete absorbs CO2 in the material extraction process, it performs second worst in transportation.

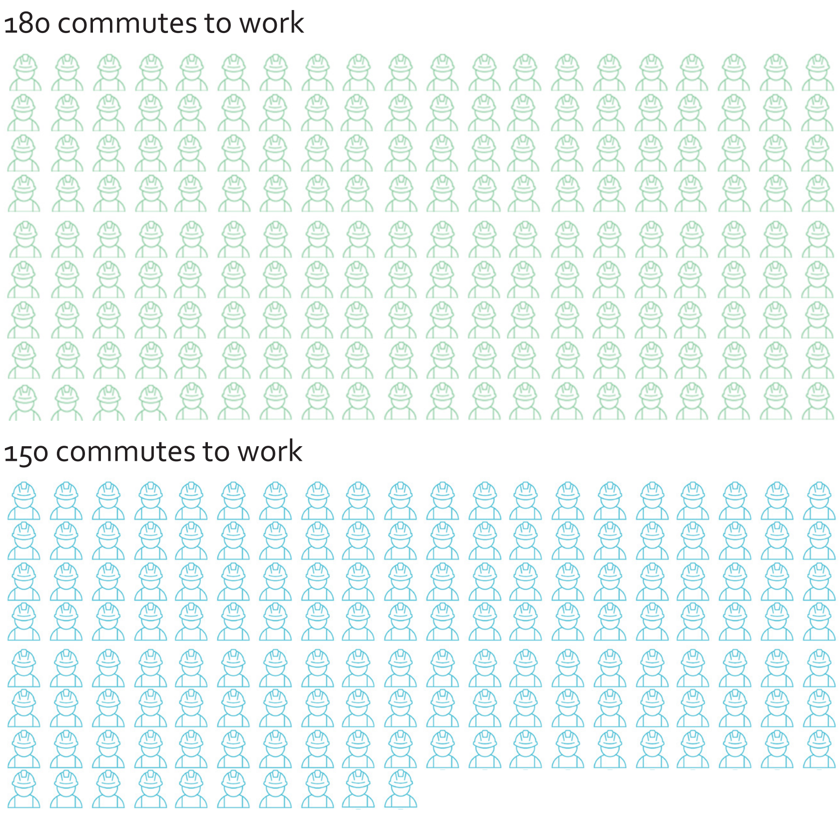


Figure 5.05 Commute Diagram

Construction

To analyze the environmental impacts of construction, the 130-day timeline to build a home created by a company called Chafin communities was assessed (The Chafin Home Building Timeline: What to Expect). The days of construction that varied from 3D printing versus typical wood construction were highlighted. The number of workers that would be needed for those varied tasks and days was noted. The number of times a dumpster would need to be dropped off and picked up from the site was also noted, which is three times more for typical constriction due to all the waste. While there are no direct numbers related to CO_2 emissions, the end results show that 3D printing is 15% faster and saves 30 commutes to the jobsite.

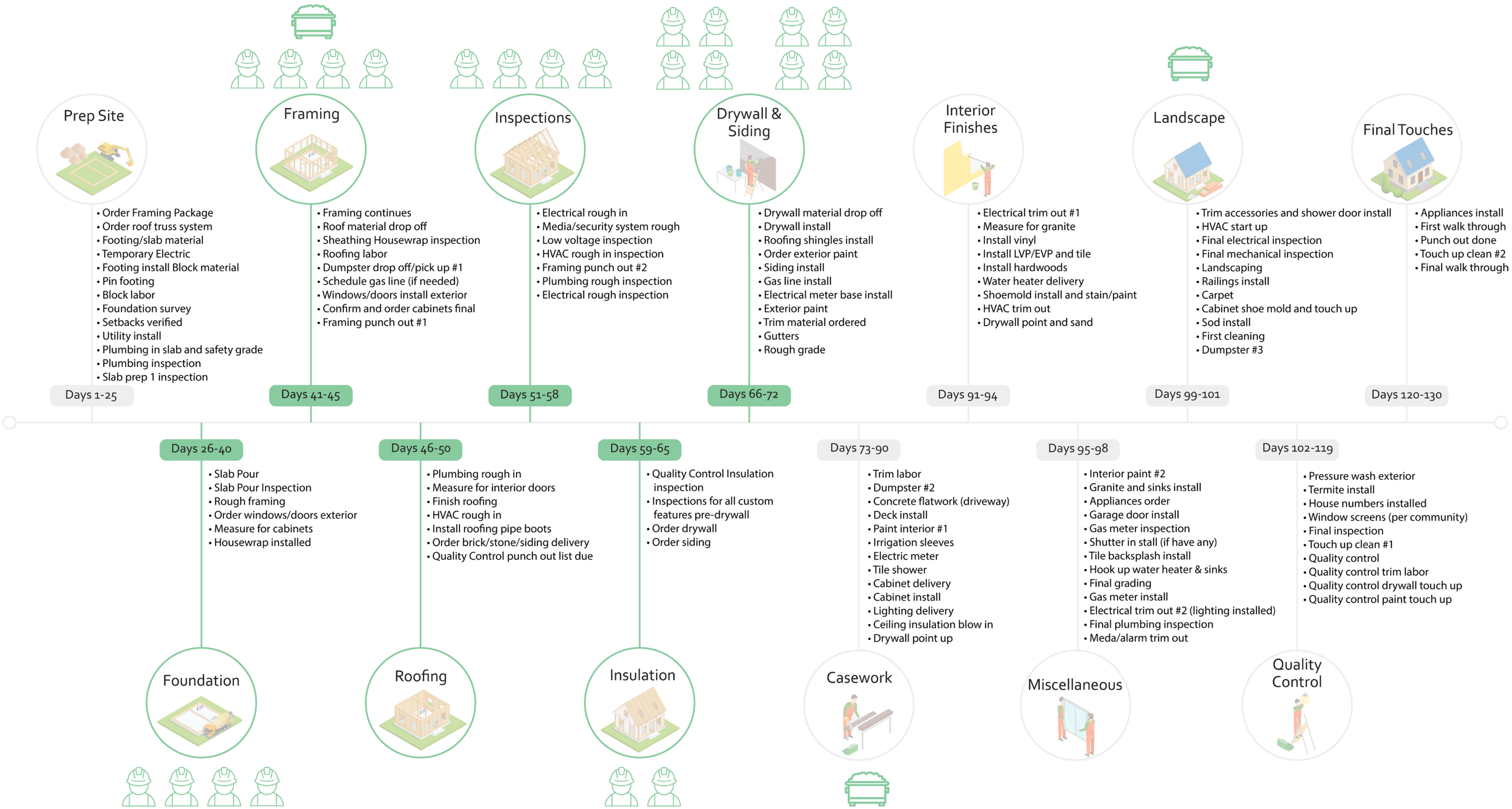


Figure 5.06 Typical Wood Frame Timeline

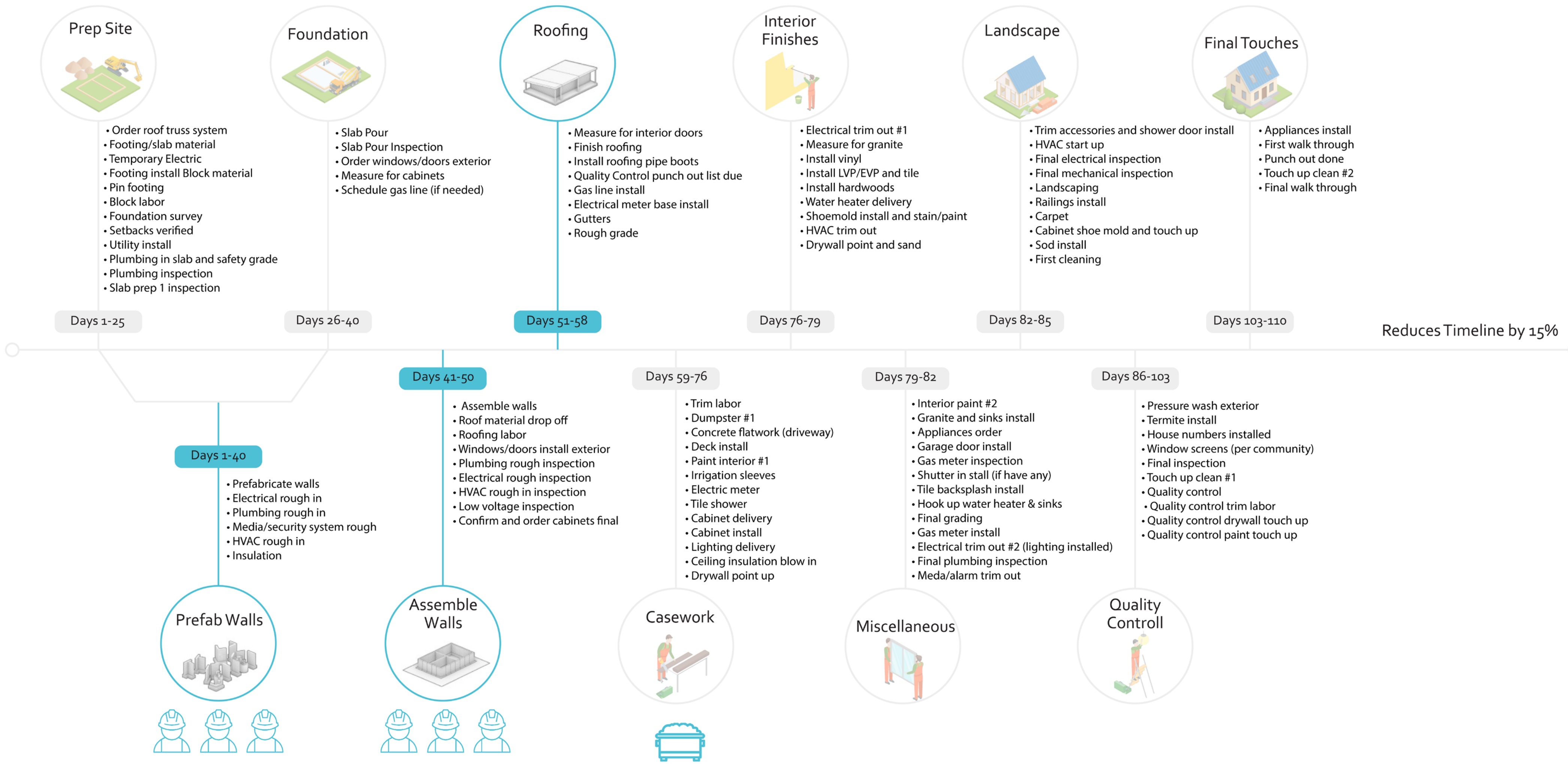


Figure 5.07 3D Print Timeline

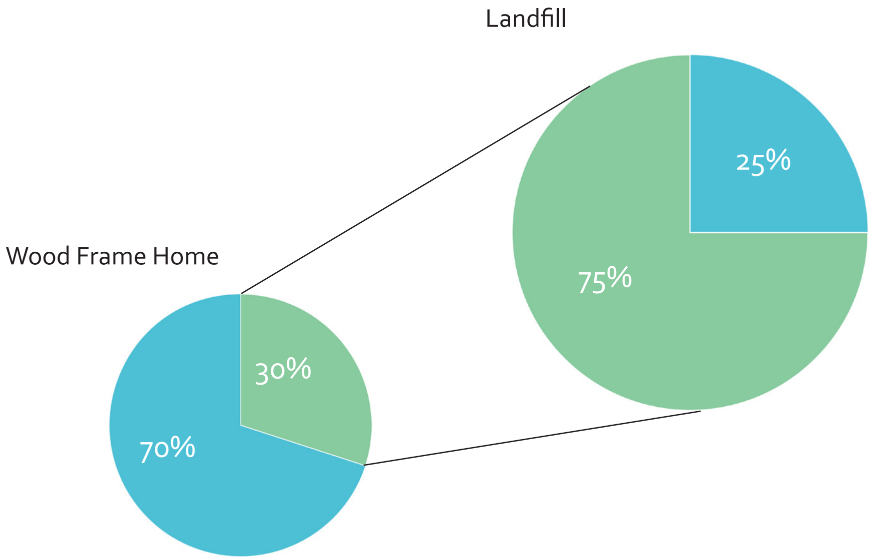


Figure 5.08 Waste Diagram

Wood Frame Materials

- ✓ Vynle Siding
- ✓ Polyiso Insulation
- ○ Plywood
- ○ Dimensional Framing Lumber
- ✓ Fiberglass Insulation
- ✗ Gypsum
- ✗ House Wrap

3D Print Materials

- ✓ Rockwool Insulation
- ✓ Structurl Steel
- ○ Concrete

- ✓ Recyclable
- ✗ Non-Recyclable
- ○ Varies

Figure 5.09 Recyclable Diagram

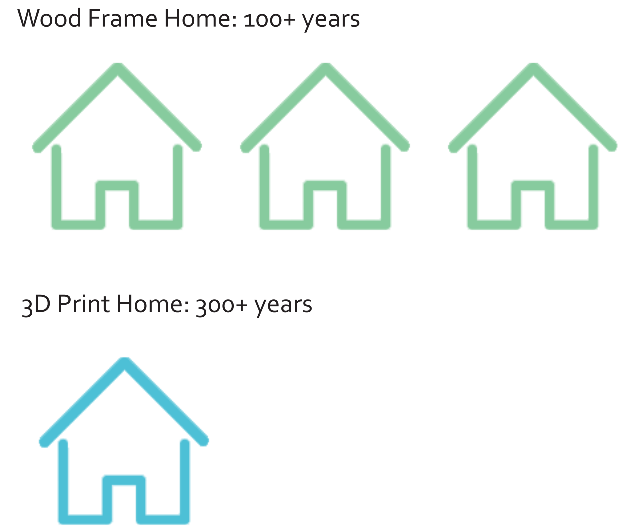


Figure 5.10 Durability Diagram

Waste vs. Recycle

Looking into the waste of typical stick-built homes, 30% of the materials brought to the job site are thrown out and 75% of those end up in landfills (23 Construction Waste Statistics & Tips to Reduce Landfill Debris). 3D printing offers virtually no waste. Looking into durability it was projected that stick built homes could last 100 years when cared for properly (Potter). It is projected that 3D printed homes can last 300 years or more (Geick). The recyclability of the materials in each wall section were assessed as being able to be recycled, non-recyclable, and varied depending on their condition and if they had been treated with chemicals. A typical wood frame wall has many materials that cannot be recycled or are likely not recyclable based on their condition and how they were manufactured. Additionally, it is difficult to disassemble the layers of a wood frame wall. There is no material in a 3D printed wall section that cannot be recycled, although the concrete varies. Additionally, it is much easier to disassemble the 3D printed wall enveloped.

Affordability Analysis

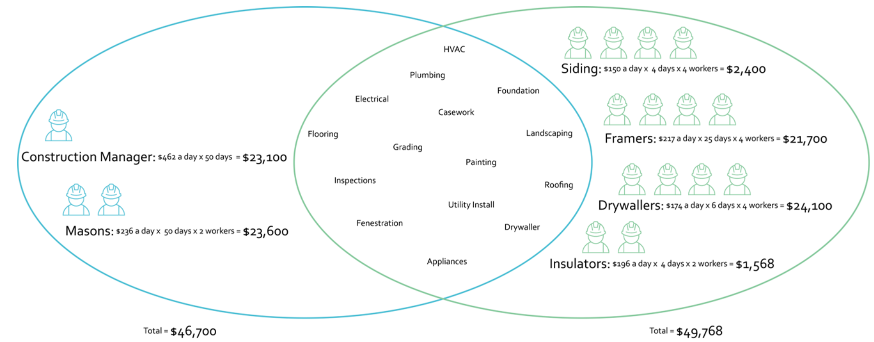


Figure 6.00 Labor Cost Diagram

Cost of Labor

To calculate the cost of labor of just the building envelope, the construction timeline and the average income of jobs in the area were used to calculate the overall cost. The number of people on the job and for how many days and what they charge was used to find the totals. This is a work in progress so some of the 3D print labor charges were guesses. Overall, the labor costs were similar with 3D printing costing $46,700 and typical wood frame wall construction costing $49,768.

Cost of Material

Previous calculations of the building envelope size and material brands were used to calculate the cost for each building envelope's material costs. The amount of material needed for each building envelope and their cost were multiplied. This resulted in similar costs for the different building envelopes with typical wood frame walls costing $30,814.05, Laticrete costing $30,059.81, Lehigh costing $29,832.32, and Blue Planet costing $30,059.81.

THERM Analysis

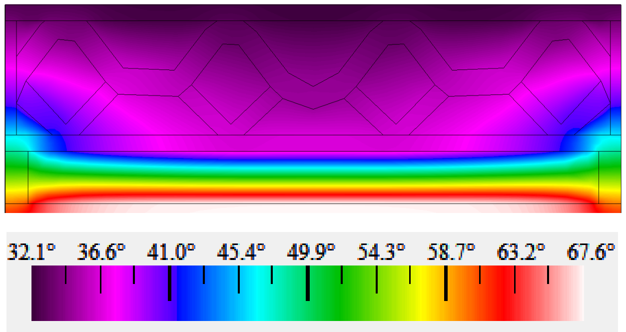
Thermal Performance

For the beginning of this thermal study, six 3D printed wall sections were digitally modeled in AutoCAD and imported into THERM. The interior temperature was set to 68 degrees Fahrenheit and the exterior temperature was set to 32 degrees Fahrenheit. This first input was meant to determine which composition of 3D printed wall infill would perform the best thermally. The wall section with the indoor temperature closest to the initially set 68 degrees was determined to have performed the best thermally. The temperature next to each iteration indicates the final temperature of the finished face on the interior side of the 3D printed wall.

The second part of this study took the best thermally performing 3D printed wall section from the first part of the study and compared it to a typical wood frame wall section in the four seasons of the Southeast Michigan climate. The interior temperature for each season remained at 68 degrees. The exterior temperature was determined by the average low of the three spring months and three winter months and the average high of the three summer and three fall months. The temperature below each iteration indicates the final temperature of the finished face on the interior side of the 3D printed wall.

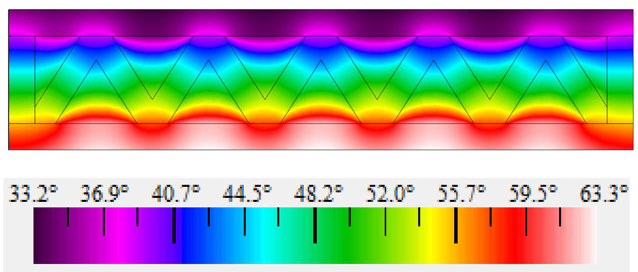
The final part of this study investigates the thermal performance of fenestration details in 3D printed wall sections compared to typical wood frame wall sections in the four seasons of Southeast Michigan. The temperatures were set just as the previous part of the study. The temperature below each iteration indicates the final temperature of the finished face on the interior side of the 3D printed wall.

3D Printed Wall Iterations



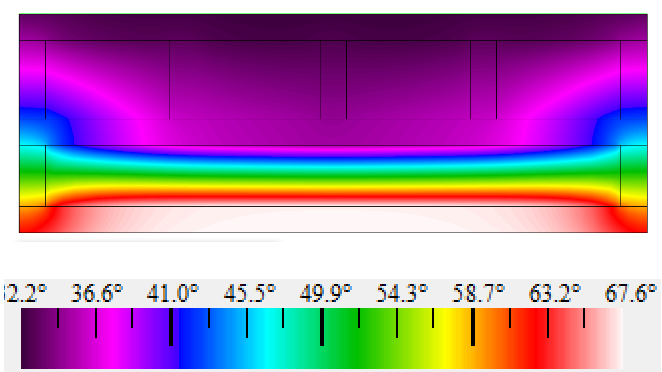
64.8 F

Figure 7.00 3D printed wall iteration



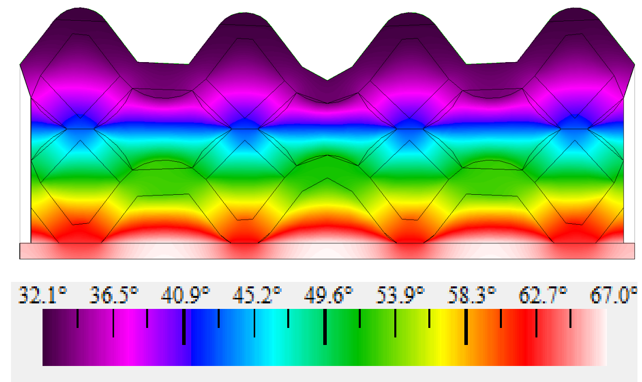
63.0 F

Figure 7.01 3D printed wall iteration



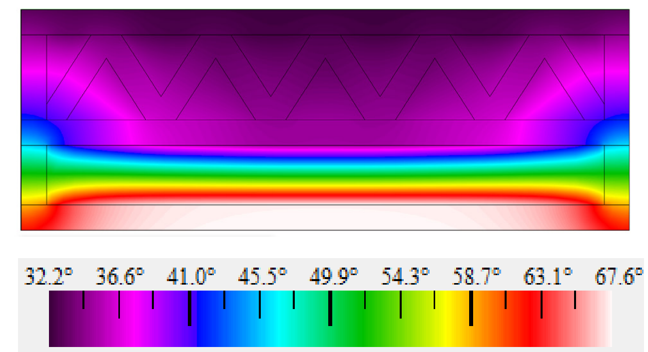
64.7 F

Figure 7.02 3D printed wall iteration



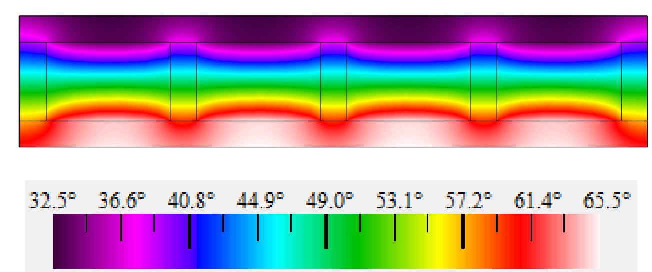
64.2 F

Figure 7.03 3D printed wall iteration



64.7 F

Figure 7.04 3D printed wall iteration



65.1 F

Figure 7.05 3D printed wall iteration

3D Printed Wall

Winter: December, January, & February

Avgerage low temperature (F): 20
Average percipitation levels (in.): 3.4
Average wind speed (mph.): 10

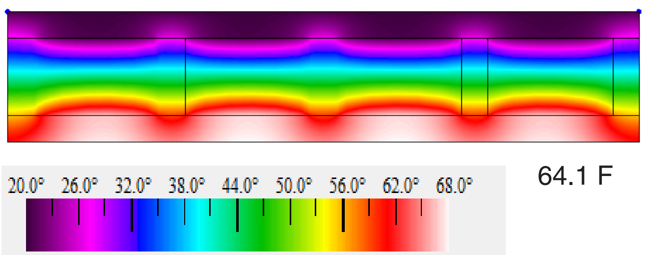


Figure 7.06 3D printed wall winter

Spring: March, April, & May

Avgerage low temperature (F): 37
Average percipitation levels (in.): 5
Average wind speed (mph.): 10

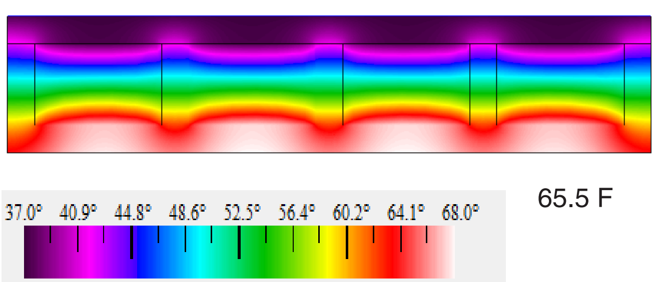


Figure 7.07 3D printed wall spring

Summer: June, July, & August

Avgerage high temperature (F): 77
Average percipitation levels (in.): 5.1
Average wind speed (mph.): 7

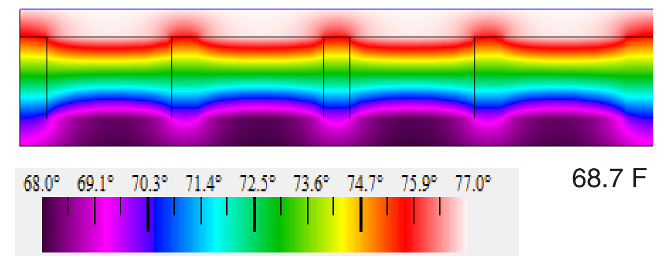


Figure 7.08 3D printed wall summer

Fall: September, October, & November

Avgerage high temperature (F): 69
Average percipitation levels (in.): 3.7
Average wind speed (mph.): 8

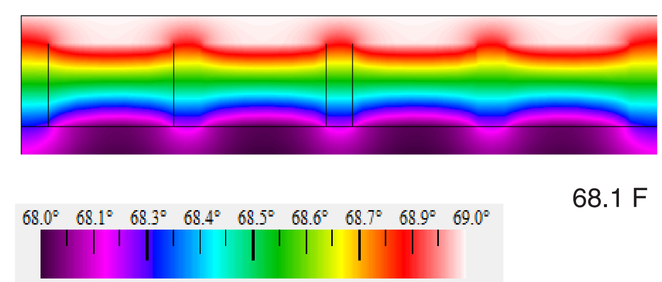
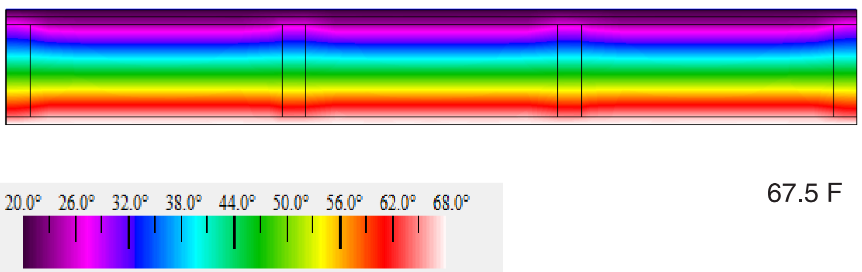


Figure 7.09 3D printed wall fall

Typical Wood Frame Wall

Winter: December, January, & February

Avgerage low temperature (F): 20
Average percipitation levels (in.): 3.4
Average wind speed (mph.): 10

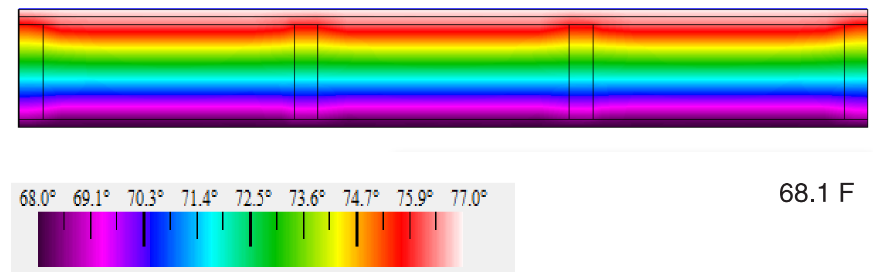


67.5 F

Figure 7.10 Wood frame wall winter

Summer: June, July, & August

Avgerage high temperature (F): 77
Average percipitation levels (in.): 5.1
Average wind speed (mph.): 7

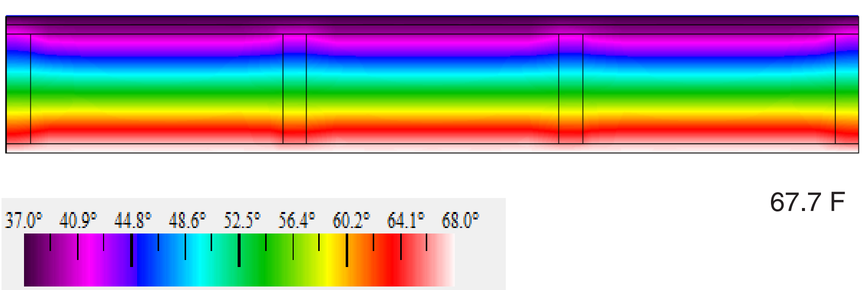


68.1 F

Figure 7.12 Wood frame wall summer

Spring: March, April, & May

Avgerage low temperature (F): 37
Average percipitation levels (in.): 5
Average wind speed (mph.): 10

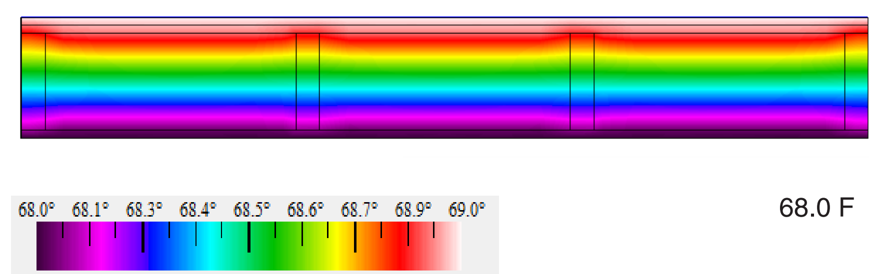


67.7 F

Figure 7.11 Wood frame wall spring

Fall: September, October, & November

Avgerage high temperature (F): 69
Average percipitation levels (in.): 3.7
Average wind speed (mph.): 8



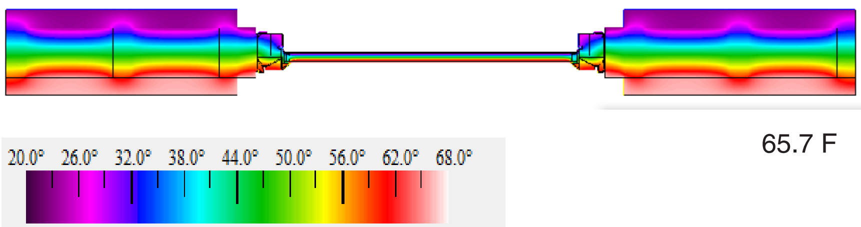
68.0 F

Figure 7.13 Wood frame wall fall

3D Printed Wall Window Detail

Winter: December, January, & February

Avgerage low temperature (F): 20
Average percipitation levels (in.): 3.4
Average wind speed (mph.): 10

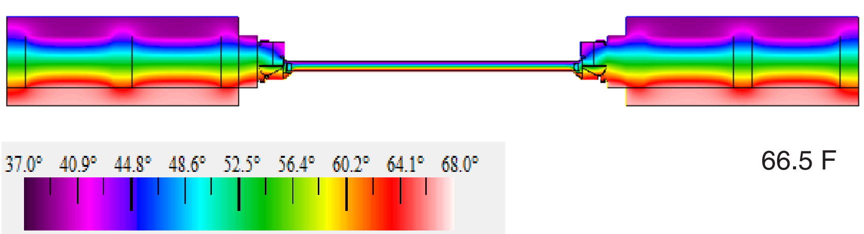


65.7 F

Figure 7.14 3D printed window detaill winter

Spring: March, April, & May

Avgerage low temperature (F): 37
Average percipitation levels (in.): 5
Average wind speed (mph.): 10

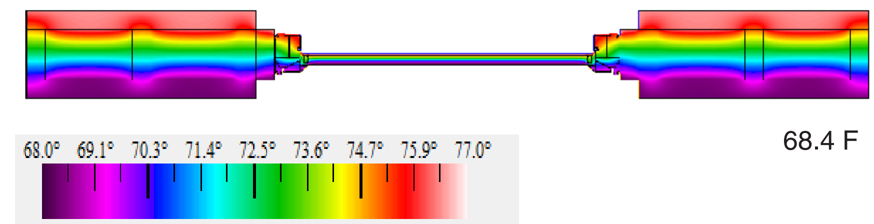


66.5 F

Figure 7.15 3D printed window detail spring

Summer: June, July, & August

Avgerage high temperature (F): 77
Average percipitation levels (in.): 5.1
Average wind speed (mph.): 7

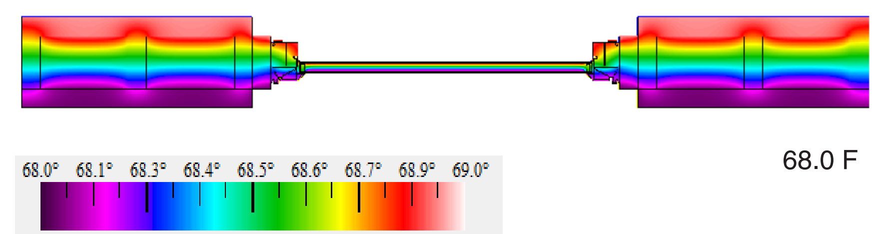


68.4 F

Figure 7.16 3D printed window detail summer

Fall: September, October, & November

Avgerage high temperature (F): 69
Average percipitation levels (in.): 3.7
Average wind speed (mph.): 8



68.0 F

Figure 7.17 3D printed window detail fall

Typical Wood Frame Wall Window Detail

Winter: December, January, & February

Avgerage low temperature (F): 20
Average percipitation levels (in.): 3.4
Average wind speed (mph.): 10

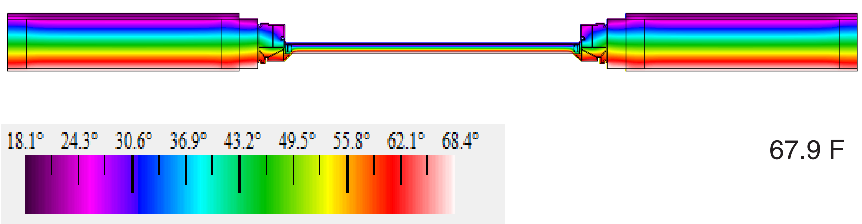


Figure 7.18 Wood frame window detaill winter

Spring: March, April, & May

Avgerage low temperature (F): 37
Average percipitation levels (in.): 5
Average wind speed (mph.): 10

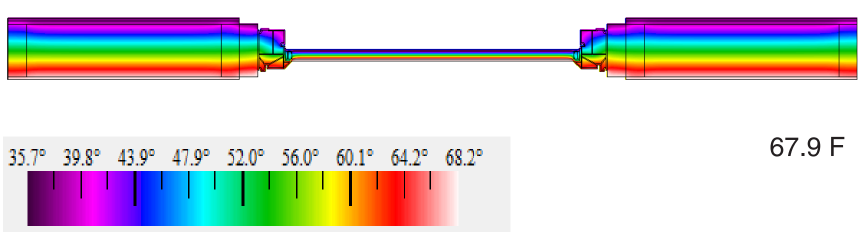


Figure 7.19 Wood frame window detail spring

Summer: June, July, & August

Avgerage high temperature (F): 77
Average percipitation levels (in.): 5.1
Average wind speed (mph.): 7

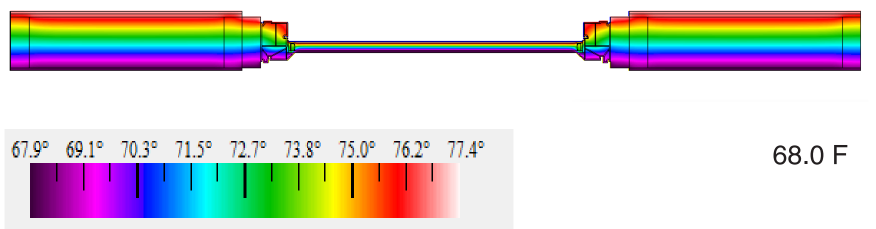


Figure 7.20 Wood frame window detail summer

Fall: September, October, & November

Avgerage high temperature (F): 69
Average percipitation levels (in.): 3.7
Average wind speed (mph.): 8

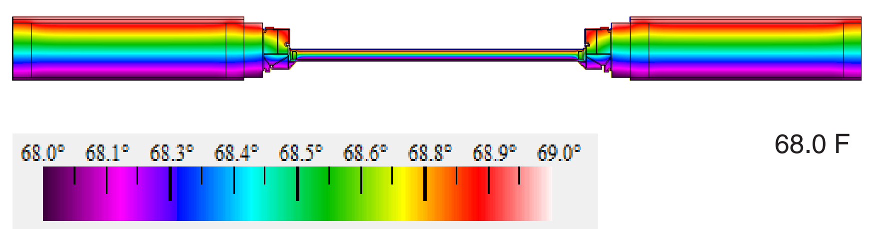


Figure 7.21 Wood frame window detail fall

Results and Discussion

According to this THERM analysis the 3D printed wall has similar results of its thermal performance when compared to the typical wood frame wall and performs worse when it comes to window details. This shows that further investigation on the ideal 3D printed infill for the Southeast Michigan region is needed.

While 3D printed walls may not significantly outperform thermally, there are many other aspects to the performance of the wall envelope that the THERM software cannot detect. Ventilation and precipitation are other factors to consider when discussing the performance of a wall envelope. Additionally, the previously mentioned durability, reduced material use, less labor, and faster build times of 3D printed walls can be measured and factored into its viability as a beneficial building method for the Southeast Michigan region.

Method Comparison

Planning

A visual was created to compare how wood frame and 3D printed homes varied for the participants involved. Starting with wood frame construction, the design and construction are relatively separate processes, and the client is consulted but typically does not have a hand in any of the modeling or drawings. When it comes to 3D printed construction, the design and construction process are relatively close knit because the construction is the literal printing of the model designed. In this case there is potential for the client to have a more hands-on role with design.

Use

What a user may experience while living in a 3D printed versus wood frame home was also compared. The use of the wood frame building over time, a homeowner can expect to replace the siding of the home every 10-20 years (Sociusadmin). The construction method of the home does allow for additions to be made, so it is flexible in its ability to adapt to fit the needs of the user if they were to change. The durability of the 3D printed concrete home over time allows minimal upkeep for a homeowner. This helps reduce the cost and environmental impact of this construction method. While interior walls can be changed and adapted, additions could be difficult with this more permanent building material making it less flexible to adapt to the users' needs as they may change.

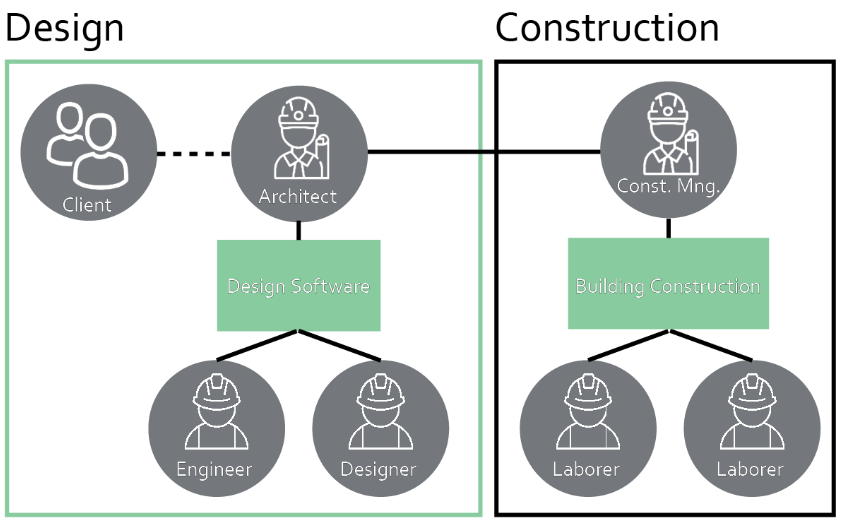


Figure 8.00 Wood frame home planning diagram

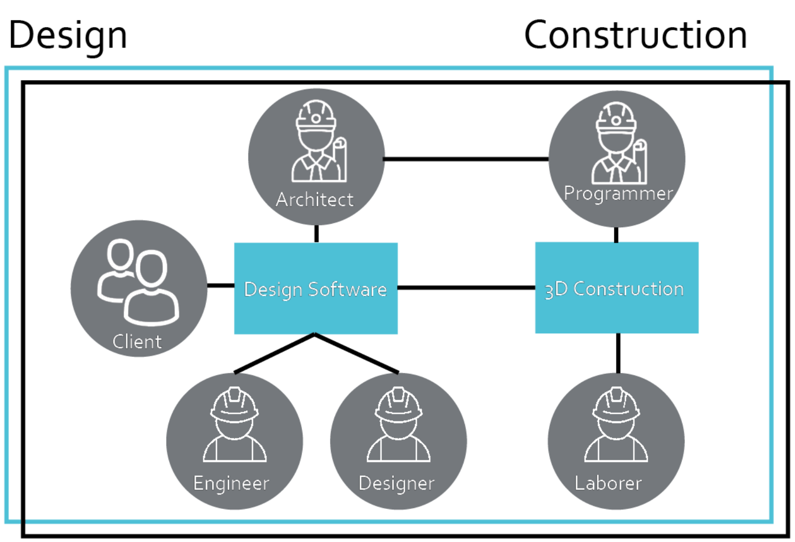


Figure 8.01 3D printed home planning diagram

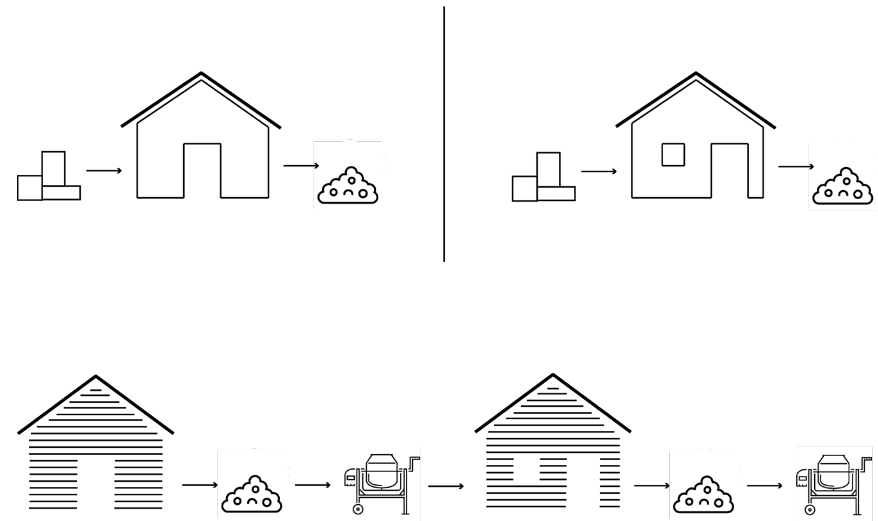


Figure 8.02 End of life cycle diagram

End of Life

While a wood frame house may go through many users, after several years of the home's existence, it is expected to be completely torn down, thrown away, and new building material will be bought to start over on the site. If the building is well taken care of, it could last a hundred years or more. However, throughout this timeframe the exterior finish will have to be replaced several times, as previously discussed. A 3D printed home is expected to last several hundred years due to the curability of concrete. At the end of its life, it is possible that the materials of the home can be broken down, reused, and reprinted to create the next home.

Disruptors

This thesis thus far makes a case for 3D printing being implemented now, but pushing the study of 3D printing walls further, possible future disruptors to the construction industry and how this construction method will adapt was investigated. For this investigation, disruptors are defined as anything that will cause major change to the way in which a market or industry operates. The two disruptors researched were how climate change will affect this region and the labor shifts that will occur.

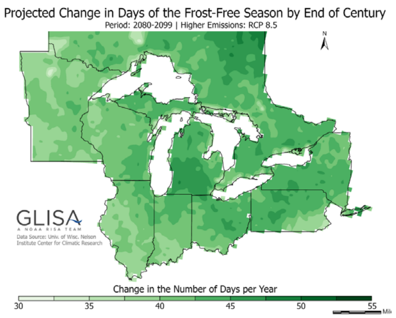


Figure 9.00 Projected frost change

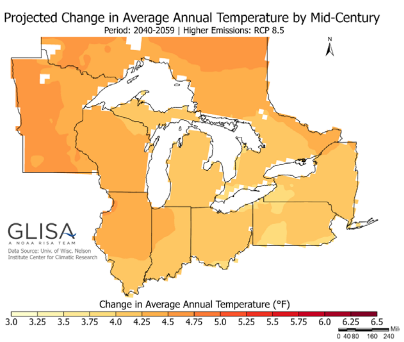


Figure 9.01 Projected temperature change

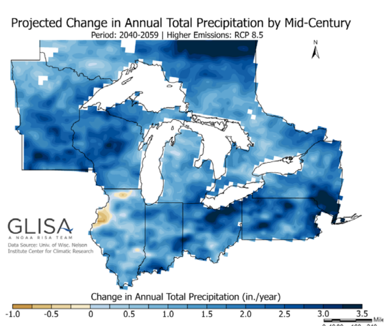


Figure 9.02 Projected pewcipitation change

Climate Change Scenario

For the climate change scenario projections are in comparison to the 1980-1999 period and are taking into consideration the RCP8.5 scenario, which is the highest baseline emissions scenario in which emissions continue to rise throughout the twenty-first century ("Climate Impacts"). The driving forces for the construction industry would be to mitigate the impact on climate change and adapt to the temperature changes. The research conducted shows how wood frame walls and 3D printing walls react to mitigate climate change with their materials choices, optimization, and recyclability and how they adapt to climate change with their construction.

Materiality

Wood is a building material that is considered carbon negative due to the amount of carbon sequestered while trees grow to be harvested. The abundant use of wood has caused deforestation that the industry must look to combat. Wood frame walls also have other areas for improvement on materiality such as the plastic siding, gypsum wall finishes, and foam insulation. Bamboo, Hempcrete, and recycled plastic siding are all possible exterior and interior finishes that are more environmentally friendly. Using reclaimed wood for structure can reduce the amount of timber that is being harvested. Wool, cork, denim, straw bales, and mineral wool are all options to replace harmful foam and bat insulation.

The 3D printing concrete process continues to use materials for the aggregate that are recycled or carbon negative. This is done by utilizing printing natural materials such as clay or recycled materials such as steel slag or fly ash. Additionally, carbon negative aggregates can be used to create a sustainable material that acts as a carbon sink. If 16% of all aggregate used was replaced with Blue Planet Aggregate, the CO2 storage needed by 2050 to keep temperature rise below 2.7F could be achieved ("Permanent Carbon Capture").

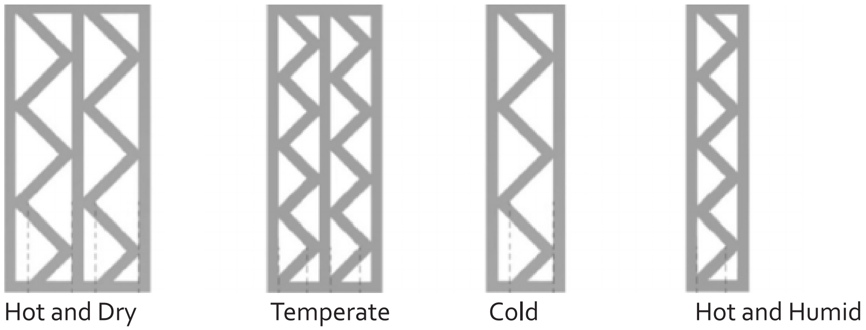


Figure 10.00 3D printed thermal resistent layers per climate conditions

Recycle

The construction industry does recycle the majority of the waste produced during construction and demolition However, because the industry is responsible for such a large amount of waste, there are still significant amounts of this waste being sent to landfills. EPA reports that of the 600 million tons of construction and demolition waste produced, approximately 455 million tons are recycled, and 145 million tons are sent to landfill ("23 Construction Waste Statistics & Tips to Reduce Landfill Debris").

3D printed walls are able to utilize recycled materials or organic materials such as clay. This allows a life cycle of the materials being able to be broken down and re-used again in the 3D printing process. Winsun has created a fast-curing concrete mixture that is suitable for 3D printing with 50% of the concrete material used from construction waste ("Winsun").

Construction

Building codes are being updated as new knowledge of designing better for the climate is gathered. As a result, the energy efficiency codes of wood frame walls have been updated to change the construction of insulation. The 2012-2018 building codes suggested a combination of in frame and outboard insulation to achieve the appropriate R-value. For the 2021 building code, outboarding insulation is being utilized as a much more materially efficient method that mitigates thermal bridging.

3D printed walls can adapt the thermal resistant layer withing the wall section to accommodate to the changing climate without major changes to the material supply chain and labor needed. More space for ventilation or insulation can be added depending on the humidity or temperature of the region. These wall compositions can be adjusted to even the most specific site or micro climate for optimal performance.

Optimization

While the construction industry may be faced with pressure to build more environmentally conscious, there is no clear way to reduce the amount of materials needed to continue the traditional stick-built wood frame construction. Additionally, there is a large increase in the number of projects that need to be completed due to general setbacks and Covid-19. Construction waste generated worldwide every year, according to Transparency Market Research, will reach 2.2. billion tons by the year 2025 ("23 Construction Waste Statistics & Tips to Reduce Landfill Debris").

The 3D printing concrete is an additive construction process that only uses the material needed when extruding a building component. Additionally, research on the stability of wall components has allowed the most efficient use of extruding material, so only the amount needed for structural support is actually printed. Many 3D printing companies, like Winsun and WASP, have saved between 30-60% on the materials used. This creates a building method that reduces waste going to landfills ("Winsun").

Labor Shift Scenario

The labor shift scenario portrays the labor shortages in the construction industry. According to this survey for the NAHB/Wells Fargo Housing Market Index, more than 55% of single-family builders reported a shortage of labor across 16 home-building trades, with the greatest shortage coming from carpentry trades ("2022 Insights: No Labor = Higher Cost to Build."). The driving forces for the construction industry would be to increase productivity of jobs, save on labor costs, and reduce the gap of laborers needed on a job. The research conducted for this scenario shows how wood frame walls and 3D printing walls react with efficiency of time on the job, the cost of labor, and the number of workers needed on the job.

Time

In order to meet tight building schedules and make up for lost time due to setbacks from Covid-19, the building industry looks to prefabricating modular construction. This allows a more efficient building process for workers to produce building components at a faster rate than stick-built homes. According to industry experts, the modular construction process is estimated to complete projects 30% to 50% faster than using traditional stick-built construction ("Modular Construction Market Size, Growth, Report, [2021-2028]").

By efficiently planning and printing multiple walls at once, the 3D printer robot is able to save time on construction. Additionally, the robot can essentially run 24/7, though it would need human supervision to ensure there is enough mix for it to continue. Winsun's technique for the construction of both the 10 houses and office building in Dubai were reported to have, on average, a 30% schedule reduction than that of similar buildings using traditional construction methods ("Winsun").

Cost

Due to the significant amount of labor shortages in the construction industy, there is a high demand for workers. This has led to an increase in labor costs as well as an increase in time for construction projects. For all of 2020, construction average hourly earnings were 7.8% higher than total private average hourly earnings ("The Construction Industry Needs to Hire").

Because 3D print technology automates much of the manual labor, less human workers need to be paid to complete a job. This can reduce the overall costs of labor on a project. Compared to traditional on-site construction methods, Winsun was able to save about 80% on construction and labor costs ("Winsun").

Jobs

The construction industry's most prevalent solution is to utilize offsite modular construction that is not 3D print related to handle this disruption that is the labor shortage. While this assists in solving the labor shortage, it limits customizability to homes. The modular construction market is projected to grow from $75.89 billion in 2021 to $114.78 billion in 2028 ("Modular Construction Market Size, Growth, Report, [2021-2028]").

3D printed concrete is an offsite modular construction that does offer customizability since utilizing the robot arm does not increase cost or labor to print a variety of shapes. Additionally, automating much of the construction process saves on labor overall. Winsun created a 2,700 square foot office building in Dubai that was printed offsite in a factory, cut in half for shipping, and assembled onsite. The entire crew consisted of 18 laborers, including one printer operator, seven laborers for assembly, and ten laborers for mechanical and electrical ("Winsun").

Limitations

All calculations are estimates. In order to find CO_2 emissions for material extraction and transportation, many areas of information had to be layered to form a conclusion. The environmental impacts of the construction phase could not be quantified as a specific calculation. The performance aspects of both wall sections are also estimates using a free software called THERM. A more in-depth analysis of envelope performance would need to be done to get an accurate conclusion. The projected climate change and labor shifts are estimates done by outside resources.

Currently Citizen Robotics is the only 3D printing company in the southeast Michigan region. The team is small and the company is new so there is still a lot of technical aspects that need to be overcome to mass produce this construction method in the area. Because it is still a niche market with few experts in the field, this construction method cannot effectively be implimented to its fullest potential.

Although 3D printed construction appeared the better option in this study, it was only compared to the type of wood frame building that is currently being used. There are many other options to build a home that is more efficient than the traditional wood frame method. SIPS panels or other prefabricated methods should be studied and compared to 3D printing to determine the most advantageous construction method for a particular project. Where no customization is needed, it is likely that a prefabricated wood structure is a more appropriate construction method to use. However, in a circumstance where a client may want a highly customized and ornate design, 3D printing offers an affordable and environmentally conscious method of doing so.

Conclusion

By using the framework to investigate this new building technology, it shows that utilizing 3D printing construction to produce residential homes in Southeast Michigan would provide multiple benefits. This method reduces carbon emissions and construction costs through efficient material use and pre-fabricated construction. This also allows the construction to be affordable in the area as well in comparison to current building methods. Furthermore, as climate change and labor shortages in the construction industry become more prevalent, new building methods that are adaptable to these circumstances are becoming necessary. 3D printing construction shows potential to mitigate these issues.

This study does not suggest that current methods of construction should be completely replaced by 3D printing construction. This thesis was intended to design a framework in which construction methods should be examined to determine whether they could be viably implemented within a region in comparison to methods that are currently being used. Examining 3D printing through this framework shows some of the benefits it has in relation to the current construction method. However, this study suggested that 3D print still work as a hybrid with stick built homes as the roof and interior walls were still suggested as being wood frame.

Next steps for examining 3D printing would be to look at the different ways the construction can be implemented and the benefits of each of these scenarios. 3D printing can be used for the footings and foundation of wood frame homes. This would still save on labor and costs and provide a more environmentally conscious construction method than the traditional concrete framework. 3D printing can also be used entirely, from foundation to roof and all the exterior and interior walls in-between. This would provide a high-end home with rich design details without heavily increasing the cost, labor, or impact on the environment.

Final Thoughts

When new technology is introduced, it is important to assess the benefits and repercussions of over or under utilizing its power. Through the creation of a framework and extensive research, this thesis determines that 3D printed is a new technology that can be beneficial to the building industry and can be introduced in the southeast Michigan region. While it faces some challenges of being implemented and is not the perfect solution to every project, 3D printed construction would provide an ecological and economical building method that performs well in this climate.

Figures

Figure 1.00 Author origional diagram
Figure 2.00 "How Does a Concrete 3D Printer Work?" 3Dnatives, 11 Jan. 2021, https://www.3dnatives.com/en/how-does-a-concrete-3d-printer-work-080120215/#!
Figure 2.01 "How Does a Concrete 3D Printer Work?" 3Dnatives, 11 Jan. 2021, https://www.3dnatives.com/en/how-does-a-concrete-3d-printer-work-080120215/#!
Figure 2.02 Based on information gathered from:
Ellis, Grace. "3D Printing in Construction: Growth, Benefits, a Challenges." Digital Builder, 21 June 2022, https://constructionblog.autodesk.com/3d-printing-construction/.
Figure 3.00 "Tecla." Mario Cucinella Architects, 27 May 2021, https://www.mcarchitects.it/tecla-2.
Figure 3.01 "Tecla." Mario Cucinella Architects, 27 May 2021, https://www.mcarchitects.it/tecla-2.
Figure 3.02 "Tecla." Mario Cucinella Architects, 27 May 2021, https://www.mcarchitects.it/tecla-2.
Figure 3.03 "Tecla." Mario Cucinella Architects, 27 May 2021, https://www.mcarchitects.it/tecla-2.
Figure 4.00 Author origional diagram
Figure 4.01 WeatherWX.com, Find Local Inc. "Southeast Mi Climate Averages, Monthly Weater Conditions." WeatherWX.com, https://www.weatherwx.com/hazardoutlook/mi/southeast.html.
Figure 4.02 WeatherWX.com, Find Local Inc. "Southeast Mi Climate Averages, Monthly Weater Conditions." WeatherWX.com, https://www.weatherwx.com/hazardoutlook/mi/southeast.html.
Figure 4.03 WeatherWX.com, Find Local Inc. "Southeast Mi Climate Averages, Monthly Weater Conditions." WeatherWX.com, https://www.weatherwx.com/hazardoutlook/mi/southeast.html.
Figure 4.04 WeatherWX.com, Find Local Inc. "Southeast Mi Climate Averages, Monthly Weater Conditions." WeatherWX.com, https://www.weatherwx.com/hazardoutlook/mi/southeast.html.
Figure 4.05 Drawing Detroit. Drawing Detroit, 5 Aug. 2021, http://www.drawingdetroit.com/gap-between-wages-and-housing-affordability-grows-in-southeastern-michigan/.
Figure 4.06 Drawing Detroit. Drawing Detroit, 5 Aug. 2021, http://www.drawingdetroit.com/gap-between-wages-and-housing-affordability-grows-in-southeastern-michigan/. ty-grows-in-southeastern-michigan/.

Figure 4.07 "Electricity Cost in Livingston County, MI: 2022 Electric Rates." EnergySage, https://www.energysage.com/local-data/electricity-cost/mi/livingston-county/#:~:text=The%20average%20electric%20rates%20in,the%20course%20of%20the%20year.
Figure 4.08 "Electricity Cost in Livingston County, MI: 2022 Electric Rates." EnergySage, https://www.energysage.com/local-data/electricity-cost/mi/livingston-county/#:~:text=The%20average%20electric%20rates%20in,the%20course%20of%20the%20year.
Figure 4.09 "Electricity Cost in Livingston County, MI: 2022 Electric Rates." EnergySage, https://www.energysage.com/local-data/electricity-cost/mi/livingston-county/#:~:text=The%20average%20electric%20rates%20in,the%20course%20of%20the%20year.
Figure 5.00 Based on information gathered from:
"Greenhouse Gas Equivalencies Calculator." EPA, Environmental Protection Agency, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
Figure 5.01 Based on information gathered from:
"Greenhouse Gas Equivalencies Calculator." EPA, Environmental Protection Agency, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
Figure 5.02 Based on information gathered from:
"Greenhouse Gas Equivalencies Calculator." EPA, Environmental Protection Agency, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
Figure 5.03 Based on information gathered from:
"Greenhouse Gas Equivalencies Calculator." EPA, Environmental Protection Agency, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
Figure 5.04 Based on information gathered from:
Google My Maps, Google, https://www.google.com/maps/d/u/0/viewer?mid=1Gy69_ozJC1mG4sHZuURB5b33G_ERXFWS&ll=42.39909380453905%2C-84.31706269480775&z=8.
"Tyvek." Wikipedia, Wikimedia Foundation, 12 Jan. 2023, https://en.wikipedia.org/wiki/Tyvek.
" Chinese Insulation Supplements Heavy U.S. Demand, Gets High Marks From Customer." Roofing, Insulation, and Composite Materials, https://ww2.owenscorning.com/worldwide/itemdetail.asp?Area=7&Language=1&ItemCode=684&System=.

Where We Are Located, https://www.rockwool.com/north-america/about/careers/where-we-operate/#:~:text=Our%20strong%20and%20growing%20presence,in%20the%20fall%20of%202020. "Steel Manufacturers in Michigan." IQS Directory, https://www.iqsdirectory.com/steel-manufacturers/michigan/.
Figure 5.05 Author origional diagram
Figure 5.06 Based on information gathered from:
"The Chafin Home Building Timeline: What to Expect." Chafin Com munities, 2 Aug. 2021, https://www.chafincommunities.com/home-buying-tools/the-chafin-home-building-timeline/.
Figure 5.07 Based on information gathered from:
"The Chafin Home Building Timeline: What to Expect." Chafin Com munities, 2 Aug. 2021, https://www.chafincommunities.com/home-buying-tools/the-chafin-home-building-timeline/.
Figure 5.08 "23 Construction Waste Statistics & Tips to Reduce Landfill Debris." BigRentz, 20 July 2022, https://www.bigrentz.com/blog/construc tion-waste-statistics.
Figure 5.09 "Tyvek, House Wrap." Croton, https://www.crotononhudson-ny.gov/recyclopedia-category/pages/tyvek-house-wrap.
"Home." Calgary.com - Justin Havre & Associates, https://www.calgary.com/home-component-recycling-guide.php.
"Can Insulation Be Reused or Recycled?" Can Insulation Be Reused or Recycled | Insulation Installation in DC, 14 Mar. 2018, https://www.accurateinsulation.com/blog/insulation-reused-recycled/#:~:text=Fi berglass%20insulation%20is%20another%20material,recycled%20into%20a%20new%20product.
Figure 5.10 Potter, Brian. "How Long Will a Home Last?" How Long Will a Home Last? - by Brian Potter, Construction Physics, 5 Oct. 2020, https://constructionphysics.substack.com/p/how-long-will-a-home-last#:~:text=The%20National%20Association%20of%20Certi fied,will%20last%20%E2%80%9Ca%20lifetime%E2%80%9D.
Figure 6.00 15 Careers in House Building (with Pay) | Indeed.com. https://www.indeed.com/career-advice/finding-a-job/careers-in-house-building.
Figure 7.00 Author origional diagram
Figure 7.01 Author origional diagram
Figure 7.02 Author origional diagram
Figure 7.03 Author origional diagram
Figure 7.04 Author origional diagram
Figure 7.05 Author origional diagram
Figure 7.06 Author origional diagram
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Figure 7.20 Author origional diagram
Figure 7.21 Author origional diagram
Figure 8.00 Geert De Schutter, Karel Lesage, Viktor Mechtcherine, Venkatesh Naidu Nerella, Guillaume Habert, Isolda Agusti-Juan, Vision of 3D printing with concrete — Technical, economic and environmental potentials, Cement and Concrete Research, Volume 112, 2018, Pages 25-36, ISSN 0008-8846, https://doi.org/10.1016/j.cemcon res.2018.06.001
Figure 8.01 Geert De Schutter, Karel Lesage, Viktor Mechtcherine, Venkatesh Naidu Nerella, Guillaume Habert, Isolda Agusti-Juan, Vision of 3D printing with concrete — Technical, economic and environmental potentials, Cement and Concrete Research, Volume 112, 2018, Pages 25-36, ISSN 0008-8846, https://doi.org/10.1016/j.cemcon res.2018.06.001
Figure 8.03 Author origional diagram
Figure 9.00 "Climate Impacts." GLISA, https://glisa.umich.edu/resources-tools/climate-impacts/.
Figure 9.01 "Climate Impacts." GLISA, https://glisa.umich.edu/resources-tools/climate-impacts/
Figure 9.02 "Climate Impacts." GLISA, https://glisa.umich.edu/resources-tools/climate-impacts/
Figure 10.00 Samudrapom DamJun 13 2022Reviewed by Susha Cheriyedath. "As sessing the Thermal Properties of 3D Printed Walls." AZoM.com, 13 June 2022, https://www.azom.com/news.aspx?newsID=59311.

References

"2022 Insights: No Labor = Higher Cost to Build." BASE4, 12 Jan. 2022, https://www.base-4.com/2022-insights-no-labor-higher-cost-to-build/.

"23 Construction Waste Statistics & Tips to Reduce Landfill Debris." BigRentz, 20 July 2022, https://www.bigrentz.com/blog/construction-waste-statistics.

"3D Concrete Printing – the Ultimate Guide." All3DP Pro, 9 June

"Climate Impacts." GLISA, https://glisa.umich.edu/resources-tools/climate-impacts/. 2022, https://m.all3dp.com/1/3d-concrete-printing-guide/.

Drew Turney, et al. "History of 3D Printing: It's Older than You Think." History of 3D Printing: It's Older Than You Think [Updated], 25 Aug. 2022, https://redshift.autodesk.com/articles/history-of-3d-printing.

Ellis, Grace. "3D Printing in Construction: Growth, Benefits, and Challenges." Digital Builder, 21 June 2022, https://constructionblog.autodesk.com/3d-printing-construction/.

Emerson, Joe. "Low Carbon Concrete – Starting from the Ground Up." Zero Energy Project, 3 Dec. 2020, https://zeroenergyproject.org/2020/11/09/low-carbon-concrete-starting-from-the-ground-up/.

Geick, Kevin. "How Long Do 3D Printed Houses Last?" SQ4D, 9 Feb. 2023, https://www.sq4d.com/how-long-do-3d-printed-houses-last/#:~:text=Based%20on%20the%20comparable%20benchmarks,the%20course%20of%20the%20build.

"How Does a Concrete 3D Printer Work?" 3Dnatives, 11 Jan.

2021, https://www.3dnatives.com/en/how-does-a-concrete-3d-printer-work-080120215/#!

"Modular Construction Market Size, Growth, Report, [2021-2028]." Modular Construction Market Size, Growth, Report, [2021-2028], https://www.fortunebusinessinsights.com/industry-reports/modular-construction-market-101662.

"Permanent Carbon Capture: Blue Planet Systems: Los Gatos." Blue Planet Systems, https://www.blueplanetsystems.com/.

Potter, Brian. "How Long Will a Home Last?" How Long Will a Home Last? - by Brian Potter, Construction Physics, 5 Oct. 2020, https://constructionphysics.substack.com/p/how-long-willahomelast#:~:text=The%20National%20Association%20of%20Certified,will%20last%20%E2%80%9Ca%20lifetime%E2%80%9D.

Sociusadmin. "How Often Does House Siding Need to Be Replaced?" American WeatherTechs, 10 Nov. 2022, https://www.americanweathertechs.com/blog/how-often-does-house-siding-need-to-be-replaced/#:~:text=Here's%20the%20average%20life%20expectancy,replaced%20every%2020%2D40%20years.

"Tecla." Mario Cucinella Architects, 27 May 2021, https://www.mcarchitects.it/tecla-2.

"The Chafin Home Building Timeline: What to Expect." Chafin Communities, 2 Aug. 2021, https://www.chafincommunities.com/home-buying-tools/the-chafin-home-building-timeline/.

"The Construction Industry Needs to Hire an Additional 430,000 Craft Professionals in 2021: News Releases." ABC, https://www.abc.org/News-Media/News-Releases/entryid/18636/abc-the-construction-industry-needs-to-hire-an-additional-430-000-craft-professionals-in-2021.

"Winsun." Future of Construction, https://www.futureofconstruction.org/case/winsun/.