# ABSTRACT


Title of Thesis: PRINTING HOPE: ADDRESSING THE AFFORDABLE HOUSING CRISIS

Aylin Garcia, Master of Architecture, 2024

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Thesis Question: How can 3D printing technology help address the shortage of affordable homes to meet the needs of low-income residents in Maryland while elevating the standards provided by code regulations of the built environment to create a sustainable and resilient future?

Abstract: In the United States, there is a shortage of 7 million affordable homes, according to the National Low Income Housing Coalition Report, and research predicts the housing crisis will worsen over time if the construction processes remain the same due to the population increase and cities' urbanization. The report also states that between 2019 and 2021, the pandemic worsened the affordable housing crisis by raising the need for homes by half a million. The current construction process is expensive and requires proper funding to develop homes to keep up with the housing demand. It also requires the need for multiple skilled laborers, which has been decreasing over time. This thesis will explore how using 3D printing could be a solution for creating more quality, affordable neighborhoods that are also sustainable and resilient. Some

benefits of 3D printing technology in the construction field are rapid construction time, lower construction costs, tight thermal envelope, less waste of materials, very few laborers required for construction, and much more. It will also investigate ways in which 3D printing dwellings can create an environment that is best for the well-being of its residents by elevating the standards provided by code regulations of the built environment.

# PRINTING HOPE: ADDRESSING THE AFFORDABLE HOUSING CRISIS

by

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# Chapter 1: Introduction

## *Aiding the Affordable Housing Crisis*

Home is a place where one lives, rests, feels comfortable, feels protected, performs daily activities, and fosters life. Having a place to call home brings one to a place of comfort and stress relief. Unfortunately, not everyone in the United States and worldwide can have a place they can call home. It is saddening to believe that such an essential part of life is not accessible to all of humanity. Attempts to help aid this issue can be seen through affordable housing development. However, the high need for affordable housing, with population growth, has led to low-quality developments of affordable housing with very limited budgets. Financing these projects has been a critical component for the development of affordable housing, but what if there was a way to construct homes for users with a lower budget while elevating the level of quality?

The construction method that has the potential to create more affordable housing is 3D printing technology. Not only is it essential to create more homes for all residents, but it is also important to maintain the level of quality regardless of the type of housing. This technology has the potential to reduce the cost of building a home significantly. First, before exploring the use of 3D printing in the construction field, it is important to understand how affordable housing has developed and changed over time. In the United States, Maryland is one of the states that is suffering the most in meeting the demand for affordable housing. It is important to understand, where the state currently stands in the affordable housing crisis, the qualifications for residents, and the benefits that could be created when providing affordable housing. As developments continue to develop rapidly, it is also essential to understand ways in which affordable housing can be improved to provide quality living conditions that surpass the building code standards. Some ways design can be improved are through sustainable

design, biophilic design, adaptable and flexible design, and through enhancing the connection within the community. It is also crucial to analyze existing construction methods to understand what might be creating drawbacks in the development of affordable housing. Some construction methods that will be analyzed are traditional stick framing, light gauge steel framing, prefabricated manufacturing, and modular construction. In the final chapters, this thesis will explore how using 3D printing technology could be a solution for creating more quality, affordable neighborhoods that are also sustainable and resilient.

# Chapter 2: History of Affordable Housing in The United States

## *Introduction to Affordable Housing*

In the United States, the great depression brought housing hardships from the crumbling economy, leading to decreased jobs and increased homelessness. In an attempt to make housing more affordable for homebuyers, the creation of the 30-year loan with a low-down payment attempted to aid this issue. However, this was not enough to help assist the affordable housing situation, leading to the development of multiple federal programs and agencies, which have significantly helped with the construction and financing of affordable housing projects.[1] Aside from the fact that the U.S. was struggling to keep up with the affordable housing demand, housing was also facing the issue of racial segregation. For African Americans and minorities, it has been and continues to be more challenging to find a home for rent or ownership. This issue occurred from white neighborhoods intentionally excluding African Americans and minorities from their communities with the belief that if they purchased property in their neighborhood, it would devalue the surrounding area. This idea of segregation in housing is known as redlining.[2] The effects of redlining created an advantage in obtaining affordable housing opportunities, which led to minorities having to be more confined towards rental housing options, creating a racial wealth gap. Another way in which housing has experienced racial segregation is through exclusionary zoning. Zoning determines the type of typology for a building, the size of a property lot, and the size constraint for a structure. Exclusionary zoning has restricted the ability to densify areas. The

[1] A Brief Historical Overview of Affordable Rental Housing. Accessed October 22, 2023. https://nlihc.org/sites/default/files/Sec1.03_Historical-Overview_2015.pdf.
[2] A history of discrimination, redlining, and affordable housing work in Washington, D.C. (n.d.). https://www.povertyusa.org/stories/affordable-housing-dc.

most common type of zoning is single-family zones, which limit the number of residents who can purchase a property in a specific location—leading to an increase in home pricing due to the high demand, creating a decrease in the ability for homeownership.[3]

*Affordable Housing in the 1930s -1940s*

Affordable housing is essential in providing housing for individuals at or below the median income level by ensuring their housing costs are attainable with their income. The history of affordable housing has changed over time, and it is crucial to understand its history and how it has evolved. It all started after World War II when soldiers were returning home from the war; when they returned, there was a limited number of homes available, leading to a rise in rapid construction to keep up with the demand for housing. This demand for housing led to some poorly constructed houses, and the U.S. created the National Housing Act of 1934 to improve the quality of housing developments.[4] Then, in 1937, the U.S. Housing Act was designed to support low-income residents in obtaining public housing. The first public housing project that was developed was the Techwood Homes in Atlanta, Georgia.

[3] Hlr. "Addressing Challenges to Affordable Housing in Land Use Law: Recognizing Affordable Housing as a Right." Harvard Law Review, Last modified March 24, 2023. https://harvardlawreview.org/print/vol-135/addressing-challenges-to-affordable-housing-in-land-use-law/#:~:text=Restrictive%20zoning%20rules%2C%20like%20single,cost%20of%20new%20housing%20projects.

[4] Kevin Leacock, MPH. "A Brief History of Housing Policy in the U.S." National Nurse-Led Care Consortium. Accessed November 5, 2023. https://nurseledcare.phmc.org/advocacy/policy-blog/item/641-a-brief-history-of-housing-policy-in-the-u-s.html.

*Figure 1: Techwood Homes Public Housing, Georgia, Atlanta Journal-Constitution, October 1950. Photograph by Tom Aldred, 1950, Atlanta, Georgia.*

Unfortunately, the development was intended for white middle-class families, in which, in a few years, they could move out and purchase a property in the suburbs with support from the

government.[5] As for minorities, segregation continued in public housing, and minimal options were available for advancing from public housing, forcing them to stay. The public housing conditions were becoming low-quality, with limited hot water, and fell into ruins.[6] Over time, public housing became a stereotype, seen as housing without maintenance, areas with high crimes, higher concentrations of poverty, reduced property values, and undesirable neighborhoods.

*Affordable Housing in the 1950s -1960s*

A few years later, the Federal Aid Highway Act of 1956 allowed for the construction of many highways in the United States. However, regarding housing, this meant the removal of many low-income homes to create new highways or the highways were constructed near low-income dwellings, leading to a disconnect from the community and amenities. As time passed, affordable housing continued to lack quality, prompting Congress to create the Department of Housing and Urban Development (HUD) in 1965.[7] HUD is a federal agency that creates elevated housing standards and supports fair housing for all.

As more options for affordable housing grew, landlords were having difficulty keeping up with the costs of operating public housing, causing increased rent prices, which led to Congress having to pass the Brooke Amendment. This amendment allowed for rent prices to adapt to individuals' needs by charging them based on a percentage of the tenants' incomes. Shortly after, the Fair Housing Act was created in 1968, which prevented discrimination when purchasing, leasing, and financing a home.[8] Although this act was

[5] *East Lake Meadows: A Public Housing Story*. Directed by Sarah Burns and David McMahon, PBS, 2020.
[6] A Brief Historical Overview of Affordable Rental Housing.
[7] Ibid.
[8] Leacock, "A Brief History of Housing Policy in the U.S."

created for equal opportunity housing, one can see how seniors, the disabled, the labor force, and minorities continue to suffer from racial disparities created in previous decades, as illustrated in the figures below from up-to-date data. The effects of racial discrimination in housing can be seen to this day, which prevented minorities from owning their home and acquiring wealth.

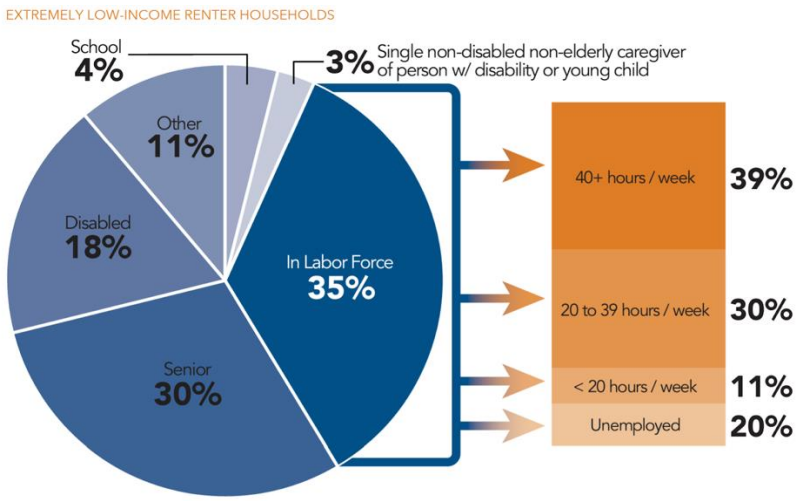


*Figure 2: Most Extremely Low-Income Households Are In Labor Force, Are Seniors, or Have A Disability. A Shortage of Affordable Homes - National Low Income Housing Coalition, 2021.*

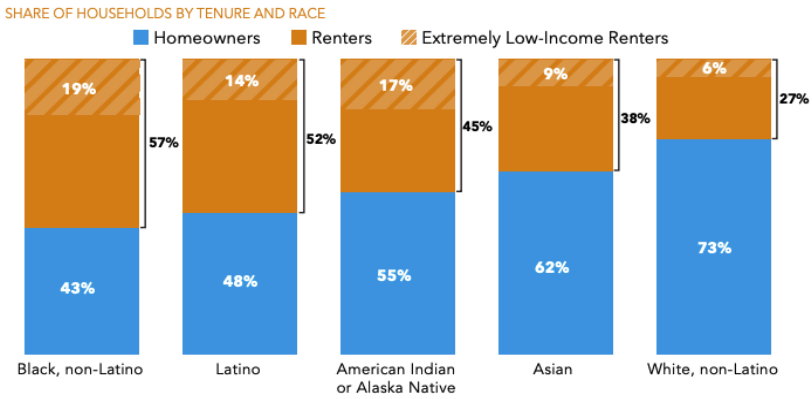


*Figure 3: Households of Color More Likely Than White Households To Be Renters and Have Extremely Low Incomes. A Shortage of Affordable Homes - National Low Income Housing Coalition, 2021.*

*Affordable Housing in the 1970s - Present Day*

Then, in 1974, the Section 8 Amendment replaced the Housing Act of 1937, which allowed federal vouchers for low-income residents to rent from a private landlord. Although this amendment was created to help prevent homelessness, due to the number of residents looking for affordable housing, finding a private landlord who would allow one to join the waitlist was nearly impossible. Then, ever since 1998, the Faircloth Amendment has not allowed for the construction of more affordable units by placing a cap on the number of housing units that can be redeveloped. The number of housing units that can be redeveloped must match the previously developed amount, not allowing for further development in the number of affordable units, creating a higher strain on the affordable housing crisis.

Finally, in 2012, the Rental Assistance Demonstration (RAD) was developed and is used to this day, in which federal and public partnerships help subsidize public housing. RAD was created to help HUD meet the demand for affordable housing since they have a backlog of $26 million in housing needs.[9] In 2022, the Biden Administration is attempting to aid the affordable housing crisis by implementing multiple actions to help meet the housing supply within five years. One of its actions to help the affordable housing crisis is by promoting different construction methods for faster production, like modular construction, panelized construction, manufactured housing, and 3D printing construction.[10] Although the Federal government has made all these changes, there is still a significant need for affordable housing, and there is more work to be done by the advocates and the government to meet the

[9] Leacock, "A Brief History of Housing Policy in the U.S."

[10] "President Biden Announces New Actions to Ease the Burden of Housing Costs." The White House. Last modified May 16, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/16/president-biden-announces-new-actions-to-ease-the-burden-of-housing-costs/.

housing demand. Currently, the United States continues to struggle with the demand for affordable housing and with the removal of the effects produced by racial segregation.

# Chapter 3: Affordable Housing in Maryland

## *Maryland Affordable Housing Crisis*

Maryland is one of the states facing the most need for affordable housing, it currently has less than the national level of affordable and available housing units per 100 households classified at or below the extremely low-income threshold. In Maryland, data states that for every 100 extremely low-income renter households, there are only 30 available homes for rent.[11] Currently, the state needs more than 146,085 homes for rent. To afford a two-bedroom apartment, a resident must earn approximately $31.08 an hour (a yearly salary of $64,646.40). However, the minimum wage for Maryland is $13.25 (a yearly salary of $27,560). This would require the salary of 2.3 jobs at minimum wage to pay for the household rent. Due to this, 75% of extremely low-income renters have a severe cost burden.[12] Housing is considered to be unaffordable when it makes up for more than 30% of one's income, leading to not having enough to support other expenses like healthcare, food, and transportation.[13] In Maryland, 178,000 families spend more than half their income on rent.[14] The figure below indicates which income groups are cost-burdened and severely cost-burdened.

[11] *A Shortage of Affordable Homes - National Low Income Housing Coalition*. Accessed September 6, 2023. https://nlihc.org/sites/default/files/gap/Gap-Report_2023.pdf.
[12] "Maryland." National Low Income Housing Coalition. Accessed October 22, 2023. https://nlihc.org/housing-needs-by-state/maryland#:~:text=Across%20Maryland%2C%20there%20is%20a,of%20their%20income%20on%20housing.
[13] More Housing for Maryland's Working Families. Accessed November 15, 2023. https://mgaleg.maryland.gov/cmte_testimony/2020/ent/3639_03032020_10478-704.pdf.
[14] Ibid.

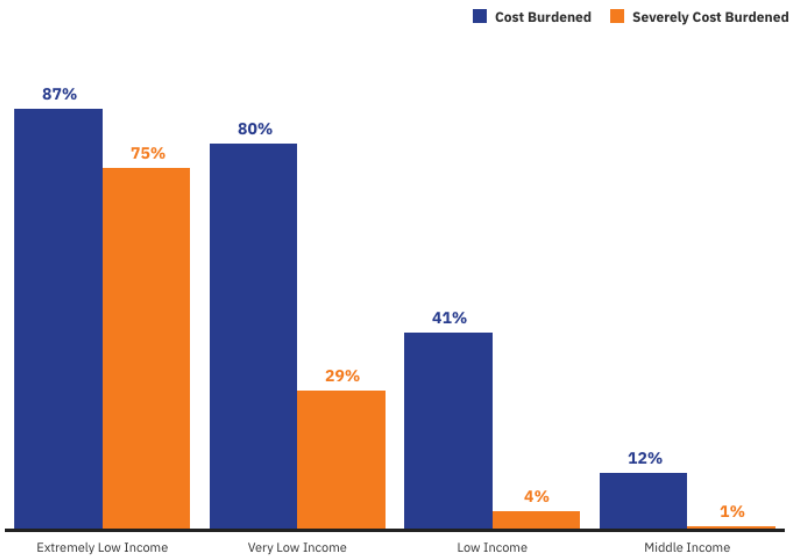


*Figure 4: Housing Cost Burden By Income Group. A Shortage of Affordable Homes - National Low Income Housing Coalition, 2021.*

*Qualifications for Affordable Housing in Maryland*

The qualifications required for a resident to obtain Affordable Housing in Maryland are essential to understand because although residents might have a need for affordable housing, they may be unqualified by some of the criteria that Maryland has created. Maryland Section 8 Housing is a federal program designed to help low-income families, seniors, and people with disabilities obtain affordable housing within the private market. The federal agency HUD administers this program. In order to qualify for affordable housing, households must have an income below a certain average income threshold that is location-based (the figure below illustrates an example of a threshold range for residents to qualify for affordable housing), the resident must be U.S. Citizens or have eligible immigration status, a background check must be conducted (criminal convictions can disqualify the qualification), an

excellent rental history (no previous debt or evictions), and proof of housing need.[15] Income limits in Maryland are determined by Area Median Income (AMI), which is subject to change according to the housing unit's location and the area's average income.[16]

| Household Size | Very Low Income | Low Income |
|---|---|---|
| 1 | $29,250 | $46,800 |
| 2 | $33,400 | $53,500 |
| 3 | $37,600 | $60,200 |
| 4 | $41,750 | $66,900 |
| 5 | $45,100 | $72,300 |

*Table 1: Threshold Considered for Affordable Housing Dependent Upon Household Size in Maryland based on DHCD's guidelines. "Maryland Section 8 Housing," 2023.*

Although some residents do not qualify for affordable housing because they earn over the low-income threshold, they are still struggling to pay their home rent or mortgage due to significant rent increases over the years, as seen in the figure below.

[15] Carol, B. "Maryland Section 8 Housing." Affordable Housing Hub. Last modified May 6, 2023. https://affordablehousinghub.org/state-section-8-guides/maryland-section-8-housing#.
[16] B. "Maryland Section 8 Housing."

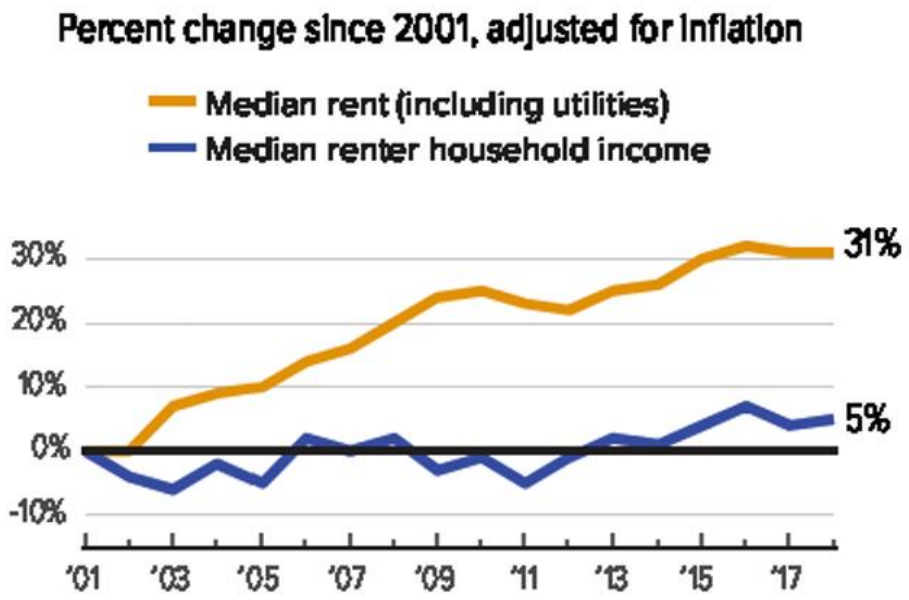


*Figure 5: Rents Have Risen Dramatically; Income Has Not. More Housing for Maryland's Working Families, Center on Budget and Policy Priorities (CBPP), tabulations based on the Census Bureau's American Community Survey, 2020.*

The concept of house-induced poverty is when a resident focuses on paying their housing rent or mortgage and then becomes unable to pay for other needs; this type of poverty in the US has been increasing.[17] Creating assistance in housing can significantly decrease the chances of residents entering house-induced poverty. In the analysis provided by the author Nandinee K. Kutty, she found that this concept of house-induced poverty classifies 3.8 million households in the US that are above the poverty line, not allowing them to obtain affordable housing, creating a burden for families.[18] So, to develop affordable housing, one must be able

[17] Nandinee K. Kutty (2005) A new measure of housing affordability: Estimates and analytical results, Housing Policy Debate, 16:1, 113-142, DOI: 10.1080/10511482.2005.9521536.
[18] Ibid.

to build housing for residents who are qualified as low-income, as well as those who do not qualify as low-income.

*Benefits of Providing Housing for All*

Regardless of income level, providing housing for all has multiple benefits. The first benefit is that it raises the residents' self-esteem because affordable homes develop a sense of control over the physical environment.[19] Creating a sense of stability in housing relieves stress for residents and improves their well-being. Another benefit is that creating affordable homes provides stability, allowing children to enhance their education.[20] This will enable people to focus more on their careers, making a better labor market. The third benefit is that it reduces the amount of homelessness, providing a decrease in crime, public health problems, and economic consequences.[21] Finally, creating affordable housing allows for creating new maintenance jobs required for the maintenance of housing, decreasing unemployment within the U.S. As residents of the United States, all individuals need access to housing because it is fundamental to human beings and their health.

[19] Jeffrey, Lubell, Rosalyn Crain, and Rebecca Cohen. "Framing the issues—the positive impacts of affordable housing on health." *Center for Housing Policy* 34 (2007): 1-34.
[20] "The Benefits of Affordable Housing." Midlands Housing Trust Fund, Last modified November 10, 2022. https://midlandshousing.org/the-benefits-of-affordable-housing/.
[21] Ibid.

# Chapter 4: Ways to Improve Affordable Housing

## *Designing Affordable Housing*

Everyone should have the right to affordable housing because it is fundamental to their health. Housing provides shelter for residents and supports activities of daily living. However, not all housing designs are created equally, creating a gap for equality in housing. Architects have a role to create a balance between meeting the needs and values of the community, while at the same time meeting building codes. Unfortunately, buildings designed just to meet building codes only achieve minimum standards in design. Designing beyond building codes can yield a more sustainable, resilient, and better user experience home. Some modes in which affordable housing can be improved are through sustainable design, biophilic design, adaptable design, and enhancing the connection within the community.

## *Sustainable Design*

Specialists in energy systems found that almost 40% of greenhouse emissions come from buildings.[22] It is also important to consider that residential buildings are one of the largest uses of energy consumption compared to other types of energy producers, as illustrated in the figure below.

[22] Denia Kolokotsa, Gloria Pignatta, and Giulia Ulpiani. "Nearly Zero-energy and Positive-energy Buildings: Status and Trends." *Technologies for Integrated Energy Systems and Networks* (2022): 239–273.

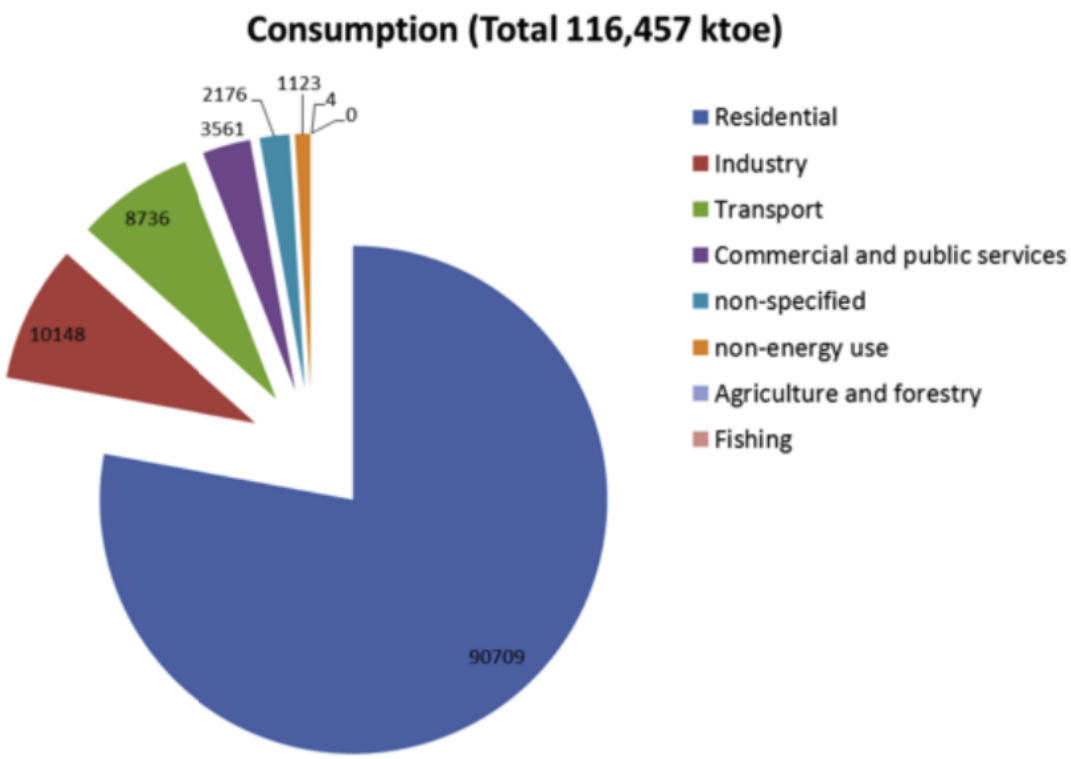


*Figure 6: Energy Consumption by Economic Sector in ktoe – International Energy Agency, 2013.*

Sustainable design is essential for affordable housing because not only is it helping the environment, but it also provides more benefits for residents. The first benefit of implementing sustainable design in housing is that residents' operating costs are decreased because of the ability to create more self-sustaining homes.[23] This leads to families being able to keep up with the costs associated with housing and creates opportunities for residents, mitigating the wealth disparities that were generated earlier in history. Another benefit is the use of renewable energy and energy efficiency permits residents to not depend too heavily on the grid. The result of breaking this dependency creates more resilient housing because of the

[23] Environmental and Energy Study Institute (EESI). "Building Green: How Affordable Housing Can Tackle Justice and Sustainability." EESI. Accessed October 12, 2023. https://www.eesi.org/articles/view/building-green-how-affordable-housing-can-tackle-justice-and-sustainability.

ability to control costs for energy. The final benefit of sustainable design is seen through the use of environment-friendly materials, which help decrease the amount of off-gassing that is created compared to conventional building materials.[24] This is important for creating a healthy indoor environment since most of one's time is spent indoors. Better air quality in buildings helps prevent users from becoming ill in the near future. The benefits of sustainable design are necessary for developing future affordable housing to create resilient communities.

*Biophilic Design*

People spend about 90% of their time indoors, meaning that indoor environments are essential for fostering a healthy life.[25] Another way in which affordable housing can be improved is through biophilic design. Biophilic design creates a user connection with the natural environment. Incorporating this connection between the user and the environment creates better housing by enhancing human health and indoor air quality. Having access to biophilic design elements in affordable homes creates equity because of the ability to experience all the health benefits it provides.[26] It allows residents to have equal access when connecting with the natural environment. The most important benefit is that it improves physical and mental health and improves productivity. A hospital study found that biophilic design improved the health of the patients by 26-41%.[27] Another study found that the use of biophilic design improved the productivity of its employees by 101%.[28] The use of natural ventilation also plays a crucial role in biophilic design. Access to natural ventilation allows

[24] "Sustainable Design & Affordability." Affordable Housing + Sustainable Communities. Accessed October 12, 2023. https://outreach.design.ncsu.edu/ah+sc/resources/white-papers/sustainable-design-affordability/.
[25] "Biophilic Design as a Holistic Approach to Healthier Buildings." BlueGreen Alliance Foundation. Accessed October 12, 2023. https://www.bgafoundation.org/news/biophilic-design-as-a-holistic-approach-to-healthier-buildings0/.
[26] Anne, Debertin. Biophilic Design, Regenerative Design, and Equity: An Intersection. Accessed October 12, 2023. https://pubs.lib.umn.edu/index.php/muraj/article/download/3618/2783/18518.
[27] "Biophilic Design as a Holistic Approach to Healthier Buildings." BlueGreen Alliance Foundation.
[28] Gong, Yu, Erzsébet Szeréna Zoltán, and Gyergyák János. 2023. "Healthy Dwelling: The Perspective of Biophilic Design in the Design of the Living Space" *Buildings* 13, no. 8: 2020. https://doi.org/10.3390/buildings13082020

for a decrease in VOCs, creating better indoor air quality. Researchers have found that natural ventilation has improved asthma in occupants by 69%.[29] Biophilic design is best for creating better indoor environments and can enhance affordable housing significantly.

*Adaptable and Flexible Design*

The third method to improve affordable housing is through adaptable design. At the city scale, being able to plan land use more effectively can help develop neighborhoods by being able to adapt and change to the needs of the public.[30] Smart Growth aims to create more robust and resilient communities through efficient land development. Another critical element in the adaptable design is a flexible design. Having the ability to change a space for multiple uses allows homes to grow and re-adapt to each family's needs. Creating more flexible housing is a solution that is best for different user's needs and has the ability to solve part of the economic aspect of affordable housing issues.[31]

*Enhance Connection with Community*

Creating a connection with the community is crucial when designing affordable housing. Creating a connected community allows residents to be engaged and supportive within the community. The community can enable the growth of its neighborhood and its individuals. It provides resources and support for its residents and is crucial for creating a resilient

[29] "Biophilic Design as a Holistic Approach to Healthier Buildings." BlueGreen Alliance Foundation.

[30] Anih, E K, C Sam-Amobi, C E Okere, P E Odoh, N N Andy, I P Onubeze, and C C Ugwu. "Design Adaptability as a Tool for Achieving Affordable Housing in Developing Economies." *IOP Conference Series: Materials Science and Engineering* 640, no. 1 (2019): 012008. doi:10.1088/1757-899x/640/1/012008.

[31] Micaela R. Danko, "Designing Affordable Housing for Adaptability: Principles, Practices, & Application." (2013).

community.[32] The figure below also illustrates more advantages that are created with a connected community.

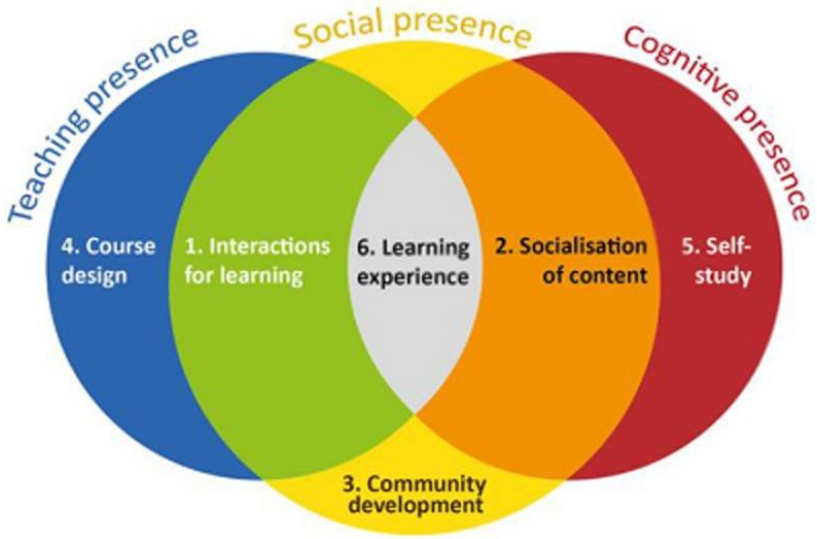


*Figure 7: Suggested Update of the Communities of Inquiry by Armellini and De Stefani – "Social Presence in the 21st Century: An Adjustment to the Community of Inquiry Framework," , 2016.*

The community can come together either physically or remotely. Community participation allows for inclusiveness and diversity by understanding the community's needs and the ability to adapt and change. Overall, this element is one of the most important ways to foster growth for the neighborhood and individuals.

[32] "Benefits of Be You Connected Communities for Early Learning." Be You. Accessed October 12, 2023. https://beyou.edu.au/resources/sessions-and-events/be-you-connected-communities-for-early-learning/benefits.

*Equity in Design*

Sustainable design, biophilic design, flexible design, and creating a connected community are all ways in which affordable housing can be improved. Designing with these improvements can help alleviate the historical issues that affordable housing has experienced, regarding equity in design. Implementing these strategies can build equity for all residents and reduce the racial disparities caused by redlining. These are all ways in which housing could improve, but it is also essential to consider how current housing construction plays a role in providing affordable housing.

# Chapter 5: Current Construction Methods for Housing

## *Types of Construction Methods*

The United States is one of the wealthiest economies, yet it cannot keep up with the demand for affordable housing for low-income residents.[33] This might be occurring due to the current construction methods available. Is the construction method taking too much time? Is there a reason why a construction method is more favorable than others? This chapter will review the most common current construction methods: traditional stick framing, light gauge steel framing, prefabricated manufacturing, and modular construction. The purpose of this chapter is to understand the advantages of each method and why possible drawbacks are causing the housing crisis in the United States.

## *Traditional Stick Framing*

Traditional stick framing uses lumber materials assembled on-site to construct walls, roofs, and sometimes trusses. This method is the most used in the industry for home construction due to its performance, availability of the material, and relatively low cost to construct.[34]

[33] "Top 10 Largest Economies in the World." Business Insider, Last modified October 10, 2023. https://www.businessinsider.in/top-10-largest-economies-in-the-world/articleshow/70547252.cms.
[34] Chini, Abdol S., and Kavita Gupta. "A comparison between steel and wood residential framing systems." *Nation* 700, no. 12,208 (1997): 4-880.

*Figure 8: Stick Built Construction. Photograph by Dominick Blocchi, June 07, 2013, Moore, Oklahoma.*

The typical time frame for building a stick-built home can range between six and twelve months. However, in recent years, there has been a significant price increase in timber costs, increasing to four times as much, and there are multiple fluctuations in the pricing. The price of framing a thousand board feet on average cost approximately $400 in 2020 and increased significantly to as high as $1,500.[35] To place this into perspective, the typical amount of board feet that an average home of 2,200 square feet would need is 15,000 board feet, which would mean that the lumber costs in 2020 would be about $6,000, and in recent years, the price has fluctuated up to $22,500. This increase in pricing is creating higher costs for homeowners and renters. The major disadvantage of this material is that pricing can become

[35] Paul, Emrat,. "Since Pandemic Onset, Lumber Products Have Added $14K to House Price, $51 to Rent: Eye On Housing." Eye On Housing | National Association of Home Builders Discusses Economics and Housing Policy, Last modified July 15, 2022. https://eyeonhousing.org/2022/07/since-pandemic-onset-lumber-products-have-added-14k-to-house-price-51-to-rent/.

undependable over time. Although this construction method is the most typical when constructing a home, there might be other options to explore that are more stable in costs and do not rely directly on deforestation to acquire lumber.

*Light Gauge Steel Framing*

Another method for housing is light gauge steel framing. It is similar to traditional stick framing, except the construction elements are created from cold-formed steel. This type of construction method became more common since the 1970s by 300% and is used for the construction of single-family homes, high-density housing, and commercial uses.[36] The rise in the construction method occurred due to the demand for housing after World War II. Some advantages of the material include higher strength compared to wood (best used for locations that experience natural disasters), stable pricing, insect resistance, recyclable, and exact sizing with consistent quality.[37] Another significant advantage is that the timeframe to build a home from light gauge steel is only three months.[38] Although there are multiple benefits, there are some drawbacks to this method. Some disadvantages are that this construction method's price is slightly higher than wood per foot, it loses strength when it is on fire, and creates thermal bridging. Steel gauge framing might have a more stable price for a home and is faster to construct, but it lacks some performance abilities.

[36] Bruce, Bateman W. "Light gauge steel verses conventional wood framing in residential construction." *Journal of construction education* 2, no. 2 (1997): 99-108.

[37] Chini, "A comparison between steel and wood residential framing systems." 4-880.

[38] Association, Steel Framing Industry. "Steel Framing Saves 9 Months on Construction, Beats Monsoon Season." BuildSteel.Org, Last modified September 22, 2022. https://buildsteel.org/projects/multi-family-residential/steel-framing-saves-9-months-construction-time/#:~:text=%E2%80%9CTo%20build%20a%20conventional%20concrete,founder%20of%20the%20ODF%20Group.

*Prefabricated Manufacturing*

The prefabricated manufacturing method involves bringing pre-constructed elements to the site and connecting the overall pieces to build a home faster and more efficiently. The advantages of this type of method include cost savings in labor and materials, less waste, and quicker construction time.[39] Although prefabricated has become very popular in recent times due to the rapid construction time, there are several disadvantages that this method encounters. First, the time it takes to repair parts is more time-consuming because sometimes the manufacturer uses unique materials.[40] Second, the material quality could be lower due to the companies saving some money on the cost of materials. Finally, the transportation of all the elements to the site releases significant amounts of carbon emissions. Although prefabricated manufacturing produces faster homes, the increased carbon emissions are a major drawback of this method.

*Modular Construction*

The modular construction method brings pre-developed components built from multiple elements assembled to the site and joined with other modules. This method allows for the production process to cut traditional stick framing by half the amount of time due to its ability to mass-produce the modules.[41] The figure below illustrates how the modules are assembled on site.

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[39] Jordan A. Rippon. "The Benefits and Limitations of Prefabricated Home Manufacturing in North America." G. Undergraduate Research. Last modified April 11, 2011. Accessed October 19, 2023. https://open.library.ubc.ca/collections/undergraduateresearch/52966/items/1.0103127.

[40] Stephen Tse-Lun, Chiu. "An Analysis on : The Potential of Prefabricated Construction Industry." G. Undergraduate Research. Last modified April 9, 2012. Accessed October 19, 2023. https://open.library.ubc.ca/collections/undergraduateresearch/52966/items/1.0103132.

[41] Dita Hořínková 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* 1203 032002.

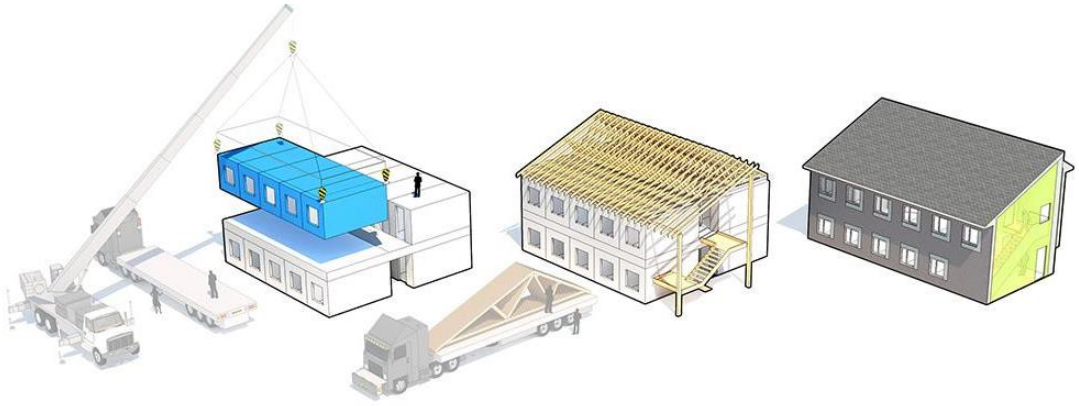

*Figure 9: Argyle Gardens, Modular Construction Assembly, drawn by Holst Architecture, 2020. https://www.world-architects.com/en/architecture-news/reviews/argyle-gardens.*

Allowing for the development of more construction to occur over a shorter period. However, faster construction is only sometimes better. Creating these large modules requires larger transportation systems to transport them to the site, which releases more carbon emissions.[42] Modular Construction so far has been seen as the best alternative to creating faster production of homes. A drawback of this method is that it limits customization in design. This construction method starts to pave the path for creating rapid developments of housing in the

[42] J., Quale, Eckelman, J.M., Williams, W.K., Sloditskie, G. and Zimmerman, B.J. (2012), Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. Journal of Industrial Ecology, 16: 243-253. https://doi.org/10.1111/j.1530-9290.2011.00424.

construction field but is currently releasing high amounts of carbon emissions and limits design customization.

*Conclusion*

After reviewing all these construction methods, which include traditional stick framing, light gauge steel framing, prefabricated manufacturing, and modular construction, it is clear that each method has its advantages and disadvantages. To keep up with the demand for affordable housing, one must not only produce a house rapidly but must also provide the best space for living. The current examples all indicate that while one solution might be more cost-effective, it might create more carbon emissions, or if one solution creates homes faster, it might limit design flexibility. If only there could be a solution for constructing affordable homes that can accomplish both low construction costs with quality-built homes than the construction processes indicated above and reducing the carbon footprint that these methods are currently producing.

# Chapter 6: Using 3D Printing Technology for Home Construction

## *3D Printing Technology in the Construction Field*

The US has seen significant advances in technology, yet it is struggling to provide affordable housing for low-income working-class residents.[43] The construction industry has seen very little change in its construction methods over time, but the implementation of technology in the construction field could lead to an improved construction method. The use of 3D printing systems provides benefits to help aid the housing problems currently occurring. 3D printing technology is created by additive manufacturing, which uses digital models to create a product by printing the material layer by layer. Some benefits of the technology include mass production, mass customization, affordability, efficiency, reduction in the number of injuries on job sites, and the reduction of carbon emissions associated with the construction and transportation of materials.[44]

The different ways in which the technology is being used for affordable housing is by creating micro-apartments, tiny houses, modular, and prefabricated housing.[45] 3D printing can be implemented at low-density or high-density scales of construction. This chapter aims to create an understanding of 3D printing technology in the construction field and how it compares to current construction methods by understanding the types of materials that are being used for 3D printing, the system integration of the construction process, the costs

[43]Rachel Monroe. "Can 3-D Printing Help Solve the Housing Crisis?" *The New Yorker*. Last modified January 16, 2023. Accessed September 6, 2023. https://www.newyorker.com/magazine/2023/01/23/can-3-d-printing-help-solve-the-housing-crisis.
[44]Mehmet Sakin, and Yusuf Caner Kiroglu. "3D Printing of Buildings: Construction of the Sustainable Houses of the Future by Bim." *Energy Procedia* 134 (2017): 702–711.
[45] Lojanica V., V. -M. Colic-Damjanovic and N. Jankovic, "Housing of the Future: Housing Design of the Fourth Industrial Revolution," 2018 5th International Symposium on Environment-Friendly Energies and Applications (EFEA), Rome, Italy, 2018, pp. 1-4, doi: 10.1109/EFEA.2018.8617094.

associated with the construction, the timeframe for the construction of a home, and the sustainable and resilient capabilities.

*System Integration in the Construction of 3D Printed Structures*

One of the most important benefits of utilizing 3D printers in the construction field is the ability to have an integrated design and construction process. This results in less wasted materials, disciplines being able to work together simultaneously to accomplish a faster-finished product, and fewer errors. The foundation is typically printed on-site with the 3D printer, and the next step would be locating any drainage locations that need to be created for the construction. Then, the walls would be printed following the BIM model.[46] The figure below indicates some of the components from the 3D-printing machine that allows for the creation the 3D-printed homes.

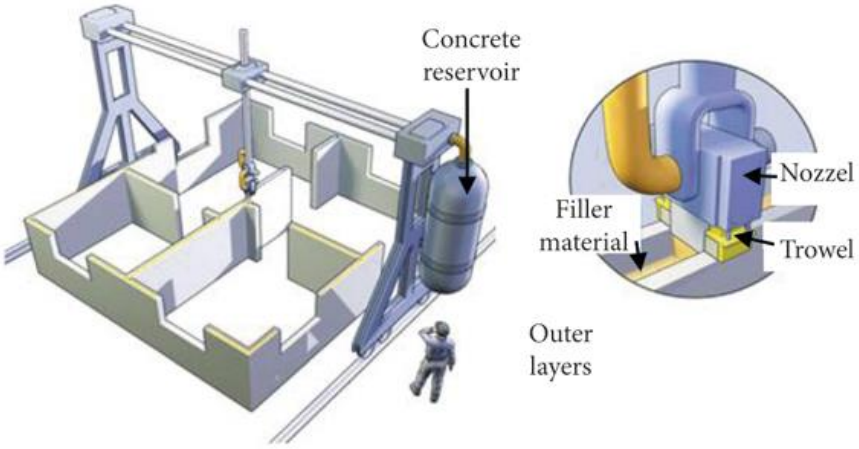


*Figure 10: Automation in Construction, vol. 29, pp. 50–67, 2013. J. Zhang and B. Khoshnevis, "Optimal machine operation planning for construction by contour crafting."*

[46] Ibid.

The plumbing, electrical, and HVAC would be placed within the walls once cured and the cutouts required for installation would be created either while the structure is printing or when the walls have cured. [47]At the same time, the wall openings for doors and windows would be created to avoid material waste. Once the plumbing is installed, the walls are filled with insulation, and the roof can either be 3D printed or constructed like a conventional roof. To finish off the house, all finishes on the interior are created, and the house is ready for occupancy.

*Materiality, Sustainability, and Resiliency of 3D Printed Structures*

The most common material that is currently being used for 3D printing structures in the construction industry is concrete due to the flexibility of the material, which can be adjusted according to the printer's needs. It can create pre-molded concrete homes, which can be assembled or constructed on-site for in-place printing. To create a more sustainable structure, a study conducted suggests the use of recycled concrete composites for the production of new concrete, which can even reduce the cost of construction by 30%.[48] The figure below indicates the life cycle of 3D-printed structures and how the material can create a closed loop that allows for a more sustainable product.

[47] "R+D Concept: Hexagon House." *KTGY*. Last modified September 15, 2023. Accessed September 05, 2023. https://ktgy.com/work/hexagon-house/.
[48] Anielle Guedes. "3D Printing Ready to Reshape Home Building." *Proquest*, November 23, 2015. Accessed August 30, 2023. https://www.proquest.com/openview/994bf418377c3989263e4069ed1345de/1?pq-origsite=gscholar&cbl=5572318.

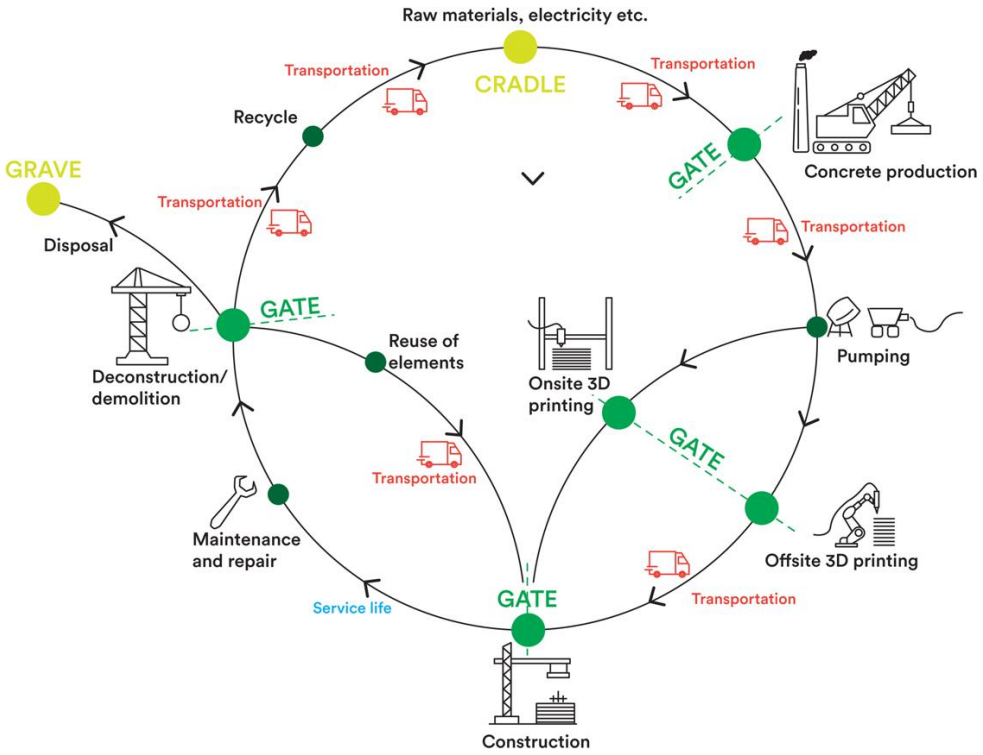


*Figure 11: Sustainability and 3D concrete printing: identifying a need for a more holistic approach to assessing environmental impacts, Kate Heywood and Paul Nicholas, 2023. Adapted from Bhattacharjee et al, 2021.*

A new material that is currently leaving a mark in the 3D printing construction industry is the usage of bio-based materials. The printer uses mud, clay, and plant fibers for raw materials to print structures, creating a more environmentally friendly printer. Removing the need to use cement allows for structures to be more thermally insulated.[49] Another method for creating biobased materials for 3D printed structures is using 3D printing wood, which emulates wood biogenesis by making an assembly of wood-like objects. The assembly of the wood-printed structure is held up similarly using a reaction to mimic the structure of cells found in wood.[50]

[49] Beaups. "Can a 3D Printer Solve the World's Housing Crisis?" *Technology and Operations Management*. Last modified November 20, 2016. Accessed August 30, 2023. https://d3.harvard.edu/platform-rctom/submission/can-a-3d-printer-solve-the-worlds-housing-crisis/.

[50] Kajsa Markstedt, Karl Håkansson, Guillermo Toriz, and Paul Gatenholm. "Materials from Trees Assembled by 3D Printing – Wood Tissue beyond Nature Limits." *Applied Materials Today* 15 (2019): 280–285.

The use of bio-based materials is revolutionizing the way 3D printers can be more environmentally friendly, creating a sustainable and circular economy.[51]

Another aspect of 3D-printed structures is that they are not only more cost-effective but are also more sustainable than current construction methods. 3D printing with concrete as the material can produce more sustainable structures with slight adjustments to the cement ratios and could yield the potential of being able to reduce carbon emissions by up to 90%.[52] A new 3D-printed cement material called green cement is starting to appear in the 3D-printed industry and is being utilized on several projects for Mighty Buildings. Green Cement claims to reduce carbon emissions by 99% compared to Portland cement due to the material not needing to rely on a kiln.[53]

Another way structures are more sustainable is due to their thermal performance, and research has been done on how it could improve. Incorporating biomimicry into the interior of the structures can increase thermal and acoustic performance while giving the structure more strength. The article on 3D-printing research provided three ways in which 3D-printed structures could improve their thermal performance: adding insulation in the voids of the walls, printing using different extrusion nozzles for various layers, or changing the composition of the concrete mix makeup.[54] Creating homes to be more thermally insulated allows for reduced utility expenses, which also relieves some of the burden costs associated with the operating costs of the home while relieving some of the carbon footprint generated by the construction and usage of the home.

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[51] Wijk, Ad van, and Iris van Wijk. *3D Printing with Biomaterials towards a Sustainable and Circular Economy*. Amsterdam: IOS Press, 2015.

[52] Hadeer Abdalla, Kazi Parvez Fattah, Mohamed Abdallah, and Adil K. Tamimi. "Environmental Footprint and Economics of a Full-Scale 3D-Printed House." *Sustainability* 13, no. 21 (2021): 11978.

[53] "Green Cement Products Feedstock from Pozzolanic Minerals or Fly Ash." Green Cement. Accessed December 16, 2023. https://greencement.com/sustainability/.

[54] Pessoa, S., A.S. Guimarães, S.S. Lucas, and N. Simões. "3D Printing in the Construction Industry - a Systematic Review of the Thermal Performance in Buildings." *Renewable and Sustainable Energy Reviews* 141 (2021): 110794.

The use of concrete in 3D-printed structures allows for the creation of more resilient homes. Adding vertical rebar or meshes within the 3D-printed structures creates more reinforcement in the structure, allowing for more resistance from lateral forces brought by winds or earthquakes.[55] The figure below indicates the different types of walls that can be printed and reinforced to provide more strength in constructing 3D-printed structures.

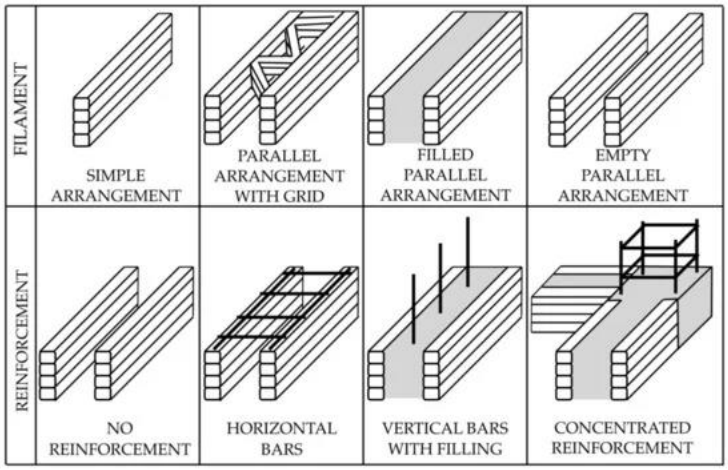



*Figure 12: Types of Walls And Types of Reinforcement in the 3D-Printed Constructions Recorded, 2021.García-Alvarado, Rodrigo, Ginnia Moroni-Orellana, and Pablo Banda-Pérez. 2021. "Architectural Evaluation of 3D-Printed Buildings" Buildings 11, no. 6: 254. https://doi.org/10.3390/buildings11060254.*

The use of 3D printing technology construction can also withstand droughts, floods, and fires.[56] Concrete combined with other biobased materials has the potential to withstand extreme climate situations being able to adjust to extremely cold or hot climates. Creating

[55] Alvarado García, Rodrigo, Ginnia Moroni-Orellana, and Pablo Banda-Pérez. 2021. "Architectural Evaluation of 3D-Printed Buildings" *Buildings* 11, no. 6: 254. https://doi.org/10.3390/buildings11060254.
[56] Ibid.

3D-printed structures allows for a more sustainable and resilient future in the construction industry compared to conventional construction methods.

*The Costs and Time of 3D Printing Homes*

Technological advancements have made products more affordable for all users. For example, when televisions were first sold, the cost to purchase a TV was high, limiting the ability for multiple income users to buy the product. However, as the advancements in technology increased, the pricing decreased and allowed for the same quality results of televisions to be available for all income users. In 2018, the first permitted 3D-printed home was constructed in 48 hours and was 350 square feet, costing only $10,000. New printers are advancing in technology and can produce a 500 sqft home in less than 24 hours, costing less than $4,000. To understand the pricing of 3D-printed structures compared to traditional stick-built framing, one must understand the square foot price for each. According to the National Association of Home Builders, the average size of a home is 2,500 square feet, and the cost of the materiality is $237,760, meaning that the average price per square foot to build a traditional stick-built home would cost $95.10.[57] The figure below compares the construction of stick-built vs. 3D-printed structures, which also highlights that the material cost, time of construction, and safety of employees are better options with 3D-printed construction.

[57] Kelly Bertog. "Why 3D Printed Homes Might Actually Work." Medium. Last modified March 5, 2020. https://kellybertog.medium.com/why-3d-printed-homes-might-actually-work-d71fef286080.

Construction Comparison of Stick Built Construction and 3D Printed Construction

*Comparing the construction of an average 2,500 square foot home.

| | Stick Built Construction | 3D Printed Construction |
|---|---|---|
| Material Costs | Materials: $95.10<br>Total Material Costs: $237,760<br>*Price per square foot | *Depends upon type of material, concrete was used for this instance.<br>Materials: $8.00<br>Total Material Costs: $20,000<br>*Price per square foot |
| Time Needed for Construction of Structure | Approximately 7 days with 3-4 laborers | Approximately 2 days with 2-3 laborers |
| Level of Safety for Employees to Constructure the Structure | High Level Risk | Medium Level Risk |

Information from sources:

"National Association of Home Builders." NAHB. Accessed December 06, 2023. https://www.nahb.org/.

"The Real Cost of a 3D Printed House." YouTube. Last modified January 21, 2022. https://www.youtube.com/watch?v=ddesI3HDDe0.

Kelly Bertog. "Why 3D Printed Homes Might Actually Work." Medium. Last modified March 5, 2020. https://kellybertog.medium.com/why-3d-printed-homes-might-actually-work-d71fef286080.

*Figure 13: Construction Comparison of Stick Built Construction and 3D Printed Construction, drawn by author.*

The National Association of Home Builders also determined that the time it takes to construct a new home can range anywhere between 7 and 13.5 months.[58] To understand the pricing of the most up-to-date printer, a 500 sqft home could be built for $4,000, meaning the cost per square foot would only be $8.00. This technology can decrease the construction cost for homes by approximately 92%. The ability for the construction process to be automated allows for the construction of homes to be built at a lower price. It can also reduce costs associated with human errors and the number of skilled laborers required for the project. Even if the cost of land is high, 3D printing technology helps create affordable homes that allow for a decrease in rent or sale prices, helping foster the idea of the American Dream by providing the opportunity for home ownership for all income levels.

[58] "How Long Does It Take to Build a Single-Family Home?" NAHB. Accessed October 29, 2023. https://www.nahb.org/blog/2020/09/How-Long-Does-it-Take-to-Build-a-Single-Family-Home.

*Conclusion*

After reviewing some benefits of 3D printing technology in construction, it yields the possibility of revolutionizing how the future could be constructed. The materiality and use of the product can deliver excellent results in regards to having a sustainable and resilient structure. The timeframe it takes to produce a home is efficient and has the potential to keep up with the need for affordable housing. Finally, the most remarkable benefit is that it can cut costs significantly compared to traditional stick-built homes. Overall, to keep up with the demand for housing, current construction methods are insufficient to keep up with urbanization and population growth as seen with the continuation in the demand for affordable housing. The ability to use 3D printing technology in the construction field not only provides a way to create more affordable homes but can also create more opportunities for achieving the American Dream of home ownership.

# Chapter 7: Program

*Program Abstract*

Printing Hope is a community that creates affordable housing with the principles Living, Growth, and Community. Living creates an equal opportunity in a space best suited for living that disregards income and race. Growth creates spaces that encourage growth for the community as individuals and growth for the community as a whole. Community creates spaces to provide a connected and engaged neighborhood. All these zones combined allow for the successful development of a community to prosper regardless of the material used to construct the community; these are the essential elements required to create a strong, sustainable, and resilient community.

The Living Zone consists of home space comprising bedrooms, bathrooms, a kitchen, living spaces, flexible spaces, and storage space. It provides multiple options for individuals and families for units. The unit types are individual units, family units, and coliving units. The Growth Zone comprises education spaces, workspaces, which is located both within the indoor/outdoor pavilion and within the co-living unit. For education spaces, one can find collaborative spaces, individual spaces, makers spaces, and a gallery display within the units and the indoor/outdoor pavilion. The Community Zone consists of indoor and outdoor amenities, which include a community multipurpose space and community garden, this type of program is located within all the unit blocks being proposed. All these zones can overlap and create a connection of combined spaces to enhance the neighborhood created.

*Zones and Program*

The zones were developed to best support the user's needs and provide equality in living. The living zone creates an equal opportunity space that is best suited for living that disregards income and race. An attempt to help foster this idea through the program is by providing access to coliving units as seen in the reverse engineering precedent below, in which the cost of a unit is less than an individual unit; by sharing utility costs, this reduces the cost burden brought from housing while also creating a community. The next zone that helps support users is growth. This zone focuses on creating spaces for users that aid the growth of its users and the community. This can be seen in the program through education spaces and workspaces. An example precedent is the Manifesto Market and Andel, in which the market is being utilized for community-based retail spaces. These spaces allow individuals access to more growth opportunities helping bridge the income inequality gap created through the history of housing. Finally, the last zone is the community zone, which helps create spaces for residents to experience an engaged neighborhood while also providing a space for the community's well-being. An example of a space that can adapt to the user's needs for usage in growth can be seen in the precedent named PJKita Community Centre, in which the space is created for flexible usage by the community. This zone ensures that residents can have access to a high quality of life as it pertains to their mental, social, and physical well-being, an issue that has occurred in multiple affordable housing projects.

*Thesis Program Tabular and Graphic*

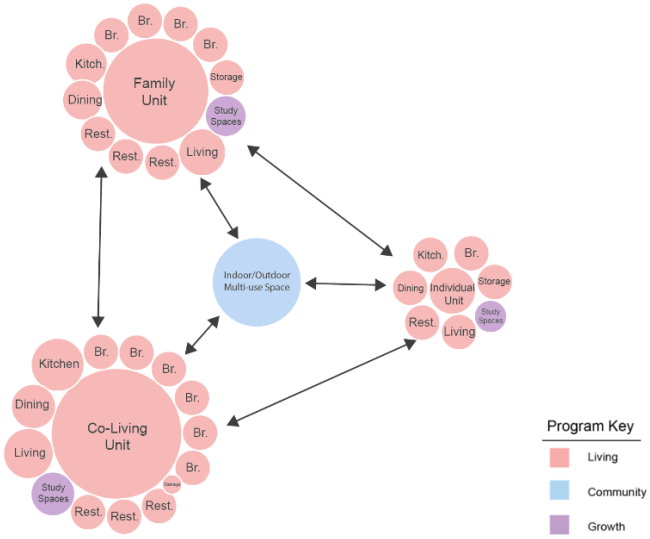



*Figure 14: Bubble Diagram of Program, drawn by author.*

In Figure 14, the bubble diagram illustrates the idea of creating a connection and overlap with different areas of zones that enhance the experience for the user. Allowing more connections within the spaces allows for an increase in community engagement.

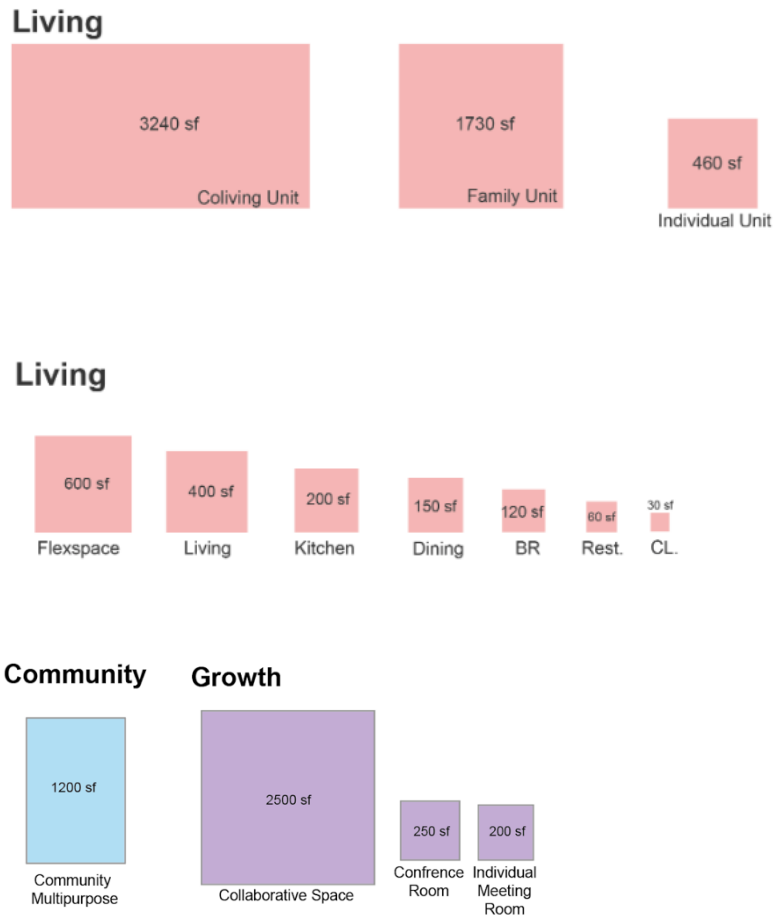



*Figure 15: Graphic Tabulation of Program, drawn by author.*

| Room / Space | Quantity | SF | Total SF |
|---|---|---|---|
| **Living** | | | |
| **Individual Unit** | | | |
| Bedroom | 1 | 120 | 120 |
| Kitchen | 1 | 100 | 100 |
| Dining | 1 | 50 | 50 |
| Restroom | 1 | 60 | 60 |
| Living Space | 1 | 100 | 100 |
| Closet | 1 | 30 | 30 |
| Total Per Unit | | | 460 |
| Unit Totals | 74 | 460 | 34040 |
| **Family Unit** | | | |
| Bedroom | 3 | 120 | 360 |
| Kitchen | 1 | 100 | 100 |
| Dining | 1 | 150 | 150 |
| Restroom | 3 | 60 | 180 |
| Living Space | 1 | 400 | 400 |
| Closet | 4 | 30 | 120 |
| Flexible Space | 1 | 300 | 300 |
| Total Per Unit | | | 1610 |
| Unit Totals | 74 | 1610 | 119140 |
| **Coliving Unit** | | | |
| Bedroom | 10 | 120 | 1200 |
| Kitchen | 1 | 200 | 200 |
| Dining | 1 | 300 | 300 |
| Restroom | 4 | 60 | 240 |
| Living Space | 1 | 400 | 400 |
| Closet | 10 | 30 | 300 |
| Flexible Space | 1 | 600 | 600 |
| Total Per Unit | | | 3240 |
| Unit Totals | 30 | 3240 | 97200 |

*Figure 16: Tabulation of Living Zone of Program, drawn by author.*

| Room / Space | Quantity | SF | Total SF |
|---|---|---|---|
| **Growth** | | | |
| **Education/Work** | | | |
| Collaborative | 1 | 2500 | 2500 |
| Conference Rooms | 1 | 250 | 250 |
| Individual Meeting Room | 2 | 200 | 400 |
| Total | | | 400 |

*Figure 17: Tabulation of Growth Zone of Program, drawn by author.*

| Room / Space | Quantity | SF | Total SF |
|---|---|---|---|
| **Community** | | | |
| **Indoor Amenities** | | | |
| Community Multipurpose | 1 | 1200 | 1200 |
| **Outdoor Amenities** | | | |
| Kids Playground | 1 | 1000 | 1000 |
| Community Garden | 1 | 1000 | 1000 |
| | | | 3200 |

*Figure 18: Tabulation of Community Zone of Program, drawn by author.*

*Reverse Engineering*

Summary: From this reverse engineering exercise, one can learn how coliving spaces are created and understand the required program for creating a coliving space. It was also an excellent example of understanding the scale of spaces and how different types of units can coexist. This project is also a modular construction-based project and was a good precedent to study the assembly of the project and how it was able to provide housing in such a short period. Having a coliving space allows for users to split the costs of living creating less of a cost burden and also allowing for more of a subcommunity to develop.

**Argyle Gardens | Holst Architecture**
**Portland, Oregon | 2020 | Focus: Modular Construction and Coliving**

Argyle Gardens is the first LISAH (Low Income Single Housing) to create a coliving space for individual residents. The goal is to foster community and provide support for formerly homeless, working class, student housing, or intergenerational families. Some program elements include community room, laundry facilitis, and support service offices, which are utilized as central hub or gathering space. The units are made up of both individual units and coliving units. Some exterior amenities are a garden, plaza, covered bike parking, and parking. The buildings aare constructed using prefabricated modules that were brought to the site for assembly, creating a rapid and efficient construction of the project.

*Figure 19: Aerial Image of Argyle Gardens, photograph by Portlandrone, 2020. "Argyle Gardens. https://www.world-architects.com/en/architecture-news/reviews/argyle-gardens.*

*Figure 20: Google Earth (2024), Portland, Oregon.*


*Figure 21: Argyle Gardens Ground Floor Plan*, drawn by Holst Architecture, 2020. https://www.world-architects.com/en/architecture-news/reviews/argyle-gardens.

*Figure 22: Underlay - Figure 21: Argyle Gardens Ground Floor Plan*, drawn by Holst Architecture, 2020. https://www.world-architects.com/en/architecture-news/reviews/argyle-gardens. *Overlay - drawn by author.*

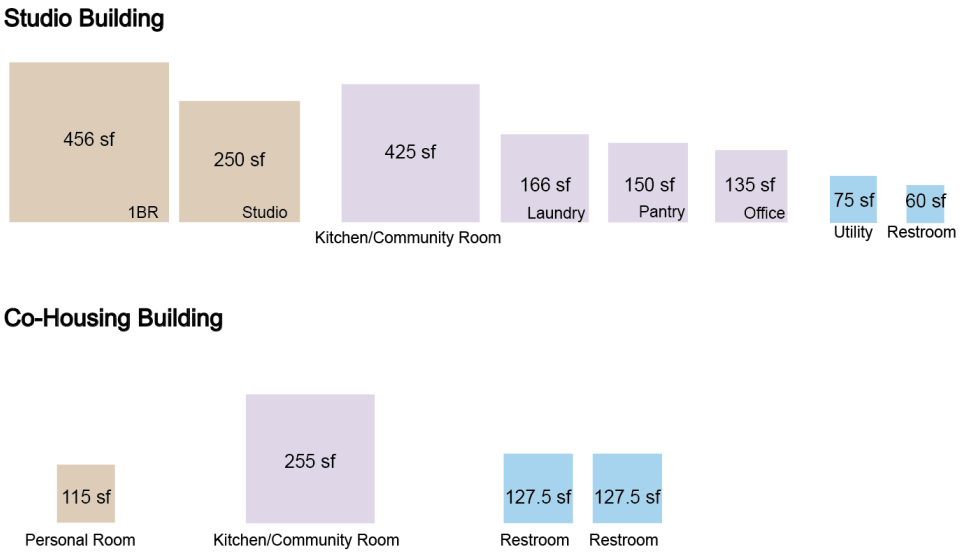



*Figure 23: Graphic Tabulation of Program for Argyle Gardens, drawn by author.*

| **Studio Building** | **Total (including unused space)** | | **4685** |
|---|---|---|---|
| Room/ Space | Quantity | SF | Total SF |
| Living | | | |
| Studio | 7 | 250 | 1750 |
| 1 BR | 1 | 456 | 456 |
| Total | | | 2206 |
| | | | |
| Community | | | |
| Pantry | 1 | 150 | 150 |
| Laundry | 1 | 166 | 166 |
| Office | 2 | 135 | 270 |
| Kitchen / Community Room | 1 | 425 | 425 |
| Total | | | 1011 |
| | | | |
| Service | | | |
| Utility | 2 | 75 | 150 |
| Restroom | 1 | 60 | 60 |
| Total | | | 210 |
| | | TOTAL | 3,427 |

| **Co-Housing Building** | **Total (including unused space)** | | **1706** |
|---|---|---|---|
| Room/ Space | Quantity | SF | Total SF |
| Living | | | |
| Personal Room | 6 | 115 | 690 |
| Total | | | 690 |
| | | | |
| Community | | | |
| Kitchen / Community Room | 1 | 255 | 255 |
| Total | | | 255 |
| | | | |
| Service | | | |
| Restroom | 2 | 127.5 | 255 |
| Total | | | 255 |
| | | TOTAL | 1,200 |

*Figure 24: Tabulation of Program for Argyle Gardens, drawn by author.*

*Precedent Analysis*

**3D Print House Zero | Lake Flato Architecture**
**Austin, Texas | 2022 | Focus: Sustainability**

House zero creates a space to reconnect with the landscape, while providing a sustainable and relisient home. The materials of the home consist of concrete 3D printed walls and wood roof structure. The use of wood and natural daylight a few biophilic principles that are implemented to this home. This houses pushes the boundries of 3D printing technology by producing a new statement for what 3D printed homes could look like, allowing for more designs to evolve. Some sustainable strategies include: maximizing indirect sunlight, renweable reaources, high efficientcy appliances, overhangs, 3 wythe printed wall (thermal insulation layer), and Xeriscaping.

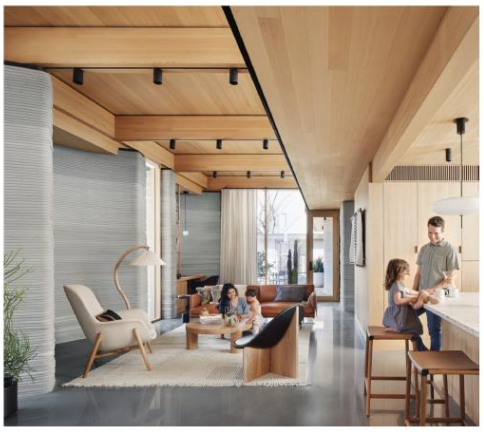


*Figure 25: "House Zero." Lake Flato, Last modified June 20, 2023.*

*https://www.lakeflato.com/houses/house-zero.*

**Coachella Valley Net-Zero Energy 3D Printed Neighborhood | Mighty Buiildings**
**Rancho Mirage, CA | 2022 | Focus: 3D Printed Homes and Sustainability**

Coachella Valley 3D printed neighborhood is the first net-zero energy community. The community is made of 15 homes that are 1,450 sqft consisting of 3 bedrooms, 2 baths, a terrace, and a swimming pool. It is l ocated in the city of Rancho Mirage in Coachella Valley. The homes are 3D printed using concrete additive manufacturing. This is the first net-zero 3D printed community and its mission is to provide housing in which costs remain stable.

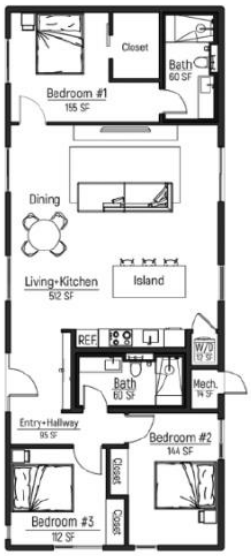



*Figure 26: Cochella Valley Net-Zero Energy 3D Printed Neighborhood, Mighty Buildings/EYRC Architects, "In California, a 3D Printed Neighbourhood in Mid-Century Modern Style." DOMUS. https://www.domusweb.it/en/sustainable-cities/gallery/2021/03/24/in-california-the-first-3d-printed-neighbourhood.html.*

**Bio-Based 3D Printed Home | University of Maine**
**Greater Bangor, Maine | 2023 | Focus: 3D Printed Homes with Bio-Based Materials**

In Bangor, Main there will be a community of the first bio-based 3D printed homes. Maine plans to use these homes to help the affordable housing crisis in their state. The bio-based affordable homes are made of 50% wood and 50% bio-resin. The state plans to use wood residuals from the state to create the homes, the total waste allows for the production of 100,000 600 sqft homes per year. The University of Maine is also planning on creating a research and learning facility that will help with the manufacturing of the homes.


*Figure 27:* "BioHome3D." Advanced Structures & Composites Center, Last modified October 25, 2023. University of Maine. https://composites.umaine.edu/biohome3d/.

**La Borda | Lacol**
**Barcelona, Spain | 2018 | Focus: Community and Gathering**

La Borda is a housing cooperative, allowing all residents to be owners of the property. The building was designed to enhance the aspect of community and would create spaces that are typically found inside each unit and would be placed outside their units to create a common place for people to interact. Some of the program found in this project include kitchen-dinning room, laundry room, multipurpose space, space created for guests, health and care space, storage space, and patio and roof access. When the building was designed it focused it efforts to also reduce the demand for energy, water, materials, and waste. The building was designed using passive strategies to reuse extisting reasources.

*Figure 28: La Borda, floor plan drawn by Lacol, photographs by Lluc Miralles, Barcelona, Spain, 2018.*

**Baiziwan Social Housing | MAD Architects**
**Beijing, China | 2021 | Focus: Connection to Nature, Human Health, and Community**

The Baiziwan Social Housing in Beijing, China is located in the central business district of the city. It is made up of 12 residentials building providing housing for 4,000 residents. They are main for depend residents and young professionals. The architects wanted to create a neighborhood within the city connecting six plots of land. The first floor is composed of commercial spaces like shops, cafes, resturants, kindergartens, pharmacies, bookstores, and elder care facilities. While the second floor is made up of community spaces that are only occupied by the residents, which include a gym, community gardens, badminton court, children's playground, ecological sanctuary, and commual support services.


*Figure 29: Baiziwan Social Housing, drawn by MAD Architects, Beijing, China, 2021.*

**Manifesto Market Andel | CHYBIK + KRISTOF**
**Prague 5, Czech Republic | 2021 | Focus: Community Hub**

Manifesto Market Andel is located in a high populated area and located near multiple retail shops, businesses, and entertainment. It focus is to create a community hub for a meeting spot within the area. It was designed to mimic characteristics of courtyards that have different characteristics like furniture, lighting, and greenery. The project attempts at connecting within the streets for access. It was designed using a modular unit approach that would consist of corrugated metal sheets to enclose the spaces. The energy used on site is all clean energy from renewable sources.

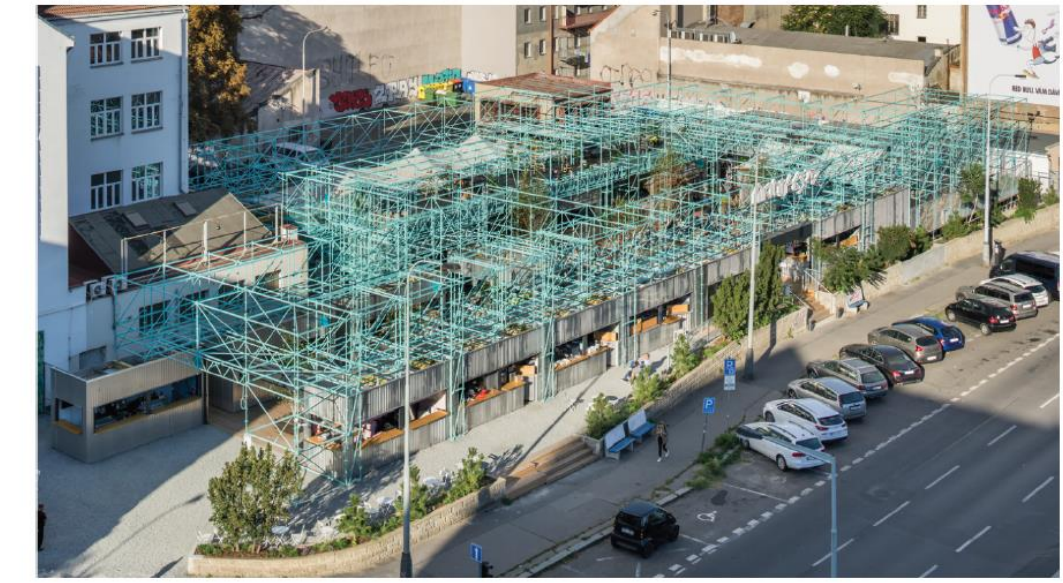


*Figure 30: Manifesto Market and Andel, CHYBIK + KRISTOF, Photographs by Studio Flusser, Vaclav Miskovsky, Alexandra Siebenthal, Czech Republic, Axon drawn by CHYBIK + KRISTOF, 2021.*

**PJKita Community Centre | DTLM Design Group**
**Petaling Jaya, Malaysia | 2021 | Focus: Multifunctional Spaces**

PJkita Community Center is located in a park within the city and aims to bring the community together in order to have a sustainable, creative, and community-driven city. The community center consists of two levels creating multiple sized spaces for users that can adapt for any use. The space itself is there and the community adapts its usage of the space for its needs. It connects to a shopping street that hosts community festivals, food stalls, and shops. The structure was designed to obtain the best sustainable strategies like controling sunlight and maximizing natural ventilation.

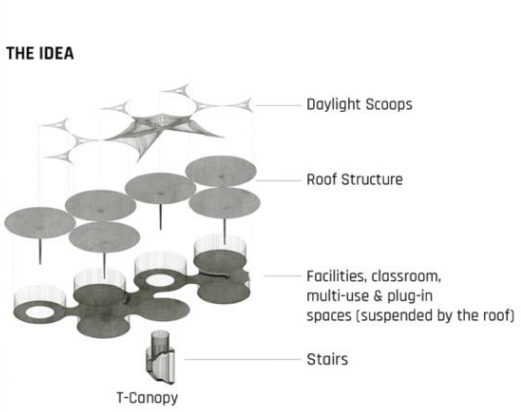



*Figure 31: PJKita Community Centre, DTLM Design Group, photographs by H. Lin Ho, diagram drawn by DTLM Design Group, Petaling Jaya, Malaysia, 2021.*

# Chapter 8: Site Selection and Analysis

*Site Selection Abstract*

The project Printing Hope looks toward Maryland locations to select a site for this thesis. Maryland is one of the 13 states with less than the national affordable and available units per 100 households at or below the low-income threshold. Maryland currently has a deficit of 146,085 affordable and available units and suffers more from this deficit in more dense metropolitan areas. Some locations that were analyzed within the state of Maryland are Baltimore City, Towson, Silver Spring, and Greenbelt. The ideal location for this project would be a location with the most need for affordable housing, but that also contains the potential for growth within the community. Some criteria used to compare the site locations are the number of affordable units in deficit, the number of households suffering from severe cost burden, job growth employment opportunities, connection to greenspaces, access to public transportation, and community ambiance.

After analyzing the regional locations, Greenbelt was the ideal candidate to locate this thesis project. Within Greenbelt, 3 site-specific locations were chosen for candidates for this thesis. The site selection matrix focused on the community's needs and values for these criteria. The criteria that were evaluated for each site were transportation, proximity to schools, proximity to essential amenities, connection to green spaces, availability of utilities, size of the site, connection to the surrounding context, access to water, level of disturbance to the community, proximity to existing affordable housing. After reviewing the sites, option 3 is the best-located site for this project. This project can utilize the same technique of 3D printing for a similar application in other locations to help aid the construction of a community.

## *Regional Site Selection*

| Selection Matrix | Baltimore City, MD | Towson, MD | Silver Spring, MD | Greenbelt, MD |
|---|---|---|---|---|
| Deficit of Needed Adequate, Affordable, and Available Units | 21, 812 units are in decifict from the total population of 569,931 | 14,127 units are in decifict from the total population of 846,161 | 14,298 units are in decifict from the total population of 1,052,521 | 18,020 units are in decifict from the total population of 946,971 |
| Rate of Change From 2000 - 2014 For The Number of Adequate, Affordable, and Available Units | -11% | -3% | 0.05% | -1% |
| Suffering to Obtain a High Quality of Life | The University of Wisconsin Population Health institute ranked this location #24 for the quality of life based on the well-being of the community | The University of Wisconsin Population Health institute ranked this location #12 for the quality of life based on the well-being of the community | The University of Wisconsin Population Health institute ranked this location #1 for the quality of life based on the well-being of the community | The University of Wisconsin Population Health institute ranked this location #14 for the quality of life based on the well-being of the community |
| Households Suffering From Severe Cost Burden | The University of Wisconsin Population Health institute states this location has 47,248 residents who are suffering from severe cost burden | The University of Wisconsin Population Health institute states this location has 44,225 residents who are suffering from severe cost burden | The University of Wisconsin Population Health institute states this location has 52,806 residents who are suffering from severe cost burden | The University of Wisconsin Population Health institute states this location has 48,986 residents who are suffering from severe cost burden |
| Owner-Occupied Housing Unit Rate | 47.90% | 66.50% | 65.40% | 62.20% |
| Job Growth Employment Opportunities | Over a year job growth opportunities have decreased by 1.75% | Over a year job growth opportunities have increased by 1.90% | Over a year job growth opportunities have increased by 0.05% | Over a year job growth opportunities have increased by 2.31% |
| Income Inequality | The University of Wisconsin Population Health institute compared the ratio of household income at the 80th percentile to income at the 20th percentile | | | |
| | 6.3 | 4.2 | 4.5 | 3.8 |
| Connection to Greenspaces | Compared by the density of green spaces found for each location and its surrounding area | | | |
| | C | D | B | A |
| Link to Public Transportation | Best connection using various types of transportation | Connection is lacking for using various types of transportation | Good connection using various types of transportation | Creates connection using various types of transportation, but needs more development |
| | A | D | B | |
| Severe Housing Problems | The University of Wisconsin Population Health institute identified the percent of households with servere housing problems, which include overcrowding, high housing costs, lack of kitchen facilities, or lack of plumbing | | | |
| | 23% | 16% | 17% | 19% |
| Community Ambiance | Community ambience was ranked based on community rankings from NICHE | | | |
| | C+ | C+ | A | A |
| Ability to Create Denser Populated Neighborhoods | Analyzed map for possible expansion of development for future development to account for city and population growth | | | |
| | B | D | C | A |

*Figure 32: Regional Site Selection Matrix Research, drawn by author.*

| Selection Matrix (1 Worst fitted for the project — 5 Best fitted for the project) | Baltimore City, MD | Towson, MD | Silver Spring, MD | Greenbelt, MD |
|---|---|---|---|---|
| Deficit of Needed Adequate, Affordable, and Available Units | 5 | 2 | 3 | 4 |
| Rate of Change From 2000 - 2014 For The Number of Adequate, Affordable, and Available Units | 4 | 3 | 1 | 2 |
| Suffering to Obtain a High Quality of Life | 5 | 3 | 2 | 4 |
| Households Suffering From Severe Cost Burden | 5 | 4 | 2 | 3 |
| Owner-Occupied Housing Unit Rate | 5 | 2 | 3 | 4 |
| Job Growth Employment Opportunities | 2x 2*1 | 2*4 | 2*3 | 2*5 |
| Income Inequality | 5 | 3 | 4 | 2 |
| Connection to Greenspaces | 3 | 1 | 2 | 5 |
| Link to Public Transportation | 5 | 2 | 4 | 3 |
| Severe Housing Problems | 5 | 2 | 3 | 4 |
| Community Ambiance | 2 | 2 | 5 | 5 |
| Ability to Create Denser Populated Neighborhoods | 4 | 2 | 3 | 5 |
| TOTAL | 50 | 34 | 38 | 51 |

*Figure 33: Regional Site Selection Matrix, drawn by author.*


*Figure 34: Regional Site Selection Locations, Google Earth (2024), Baltimore City, MD, Towson, MD, Silver Spring, MD, and Greenbelt, MD.*

Site Selection

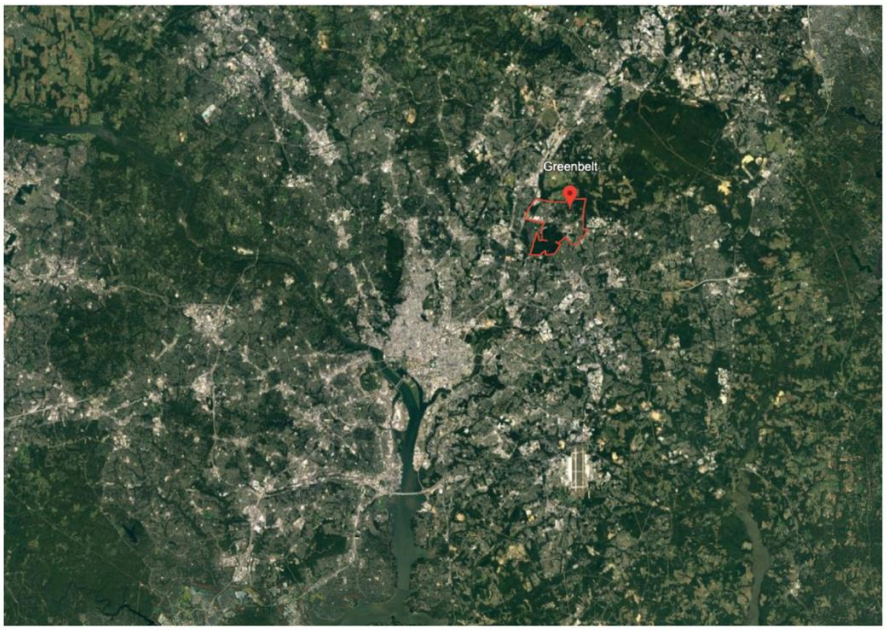



*Figure 35: Greenbelt, MD Boundary, Google Earth (2024).*

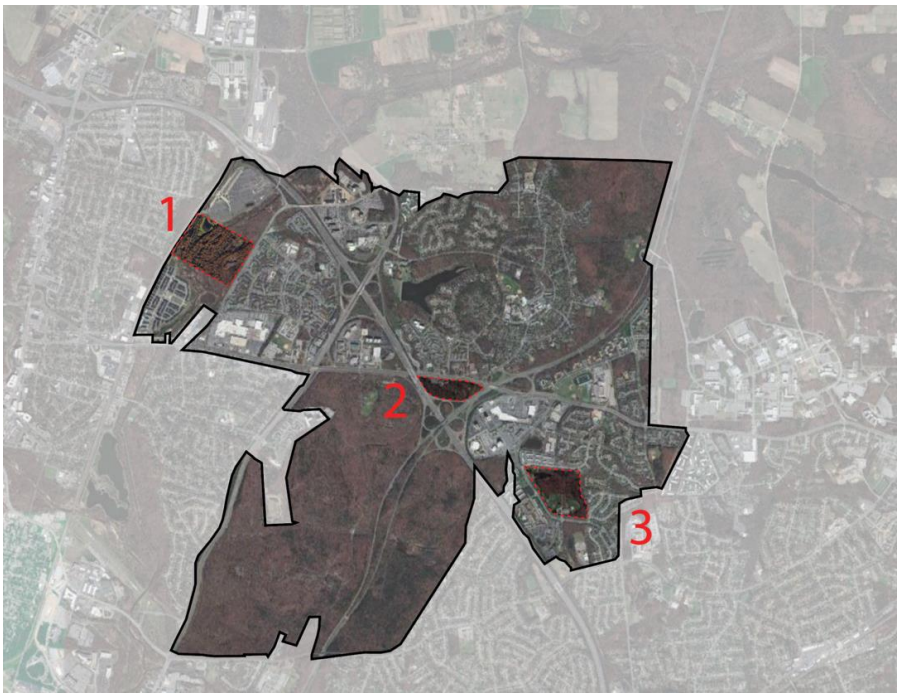



*Figure 36: Greenbelt, MD Site Options, Underlay from Google Earth (2024), Overlay drawn by author.*

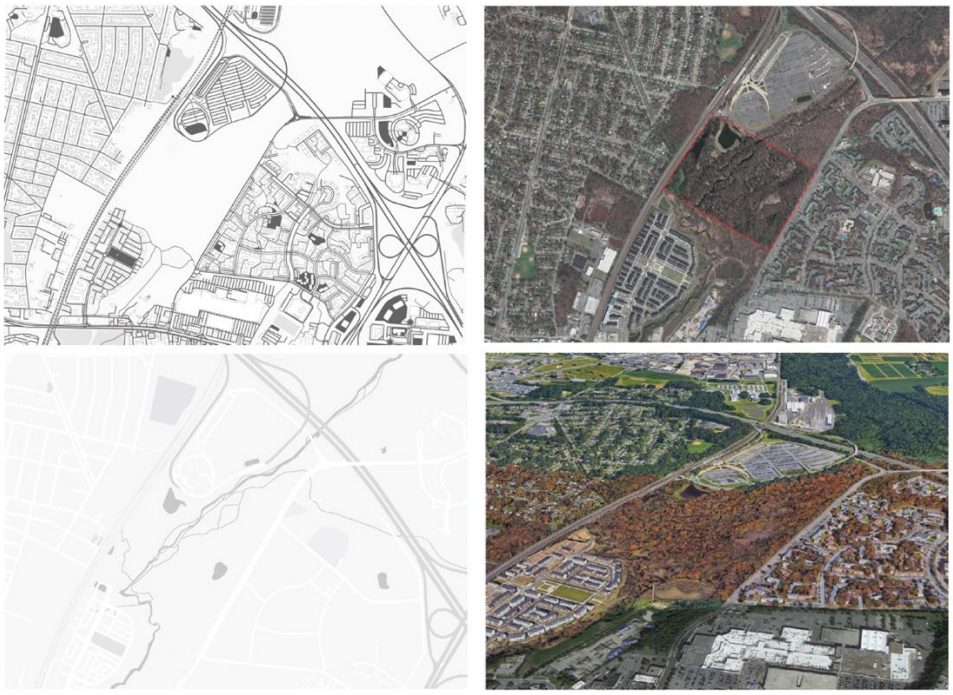


Figure 37: Site Option One, Google Earth (2024).

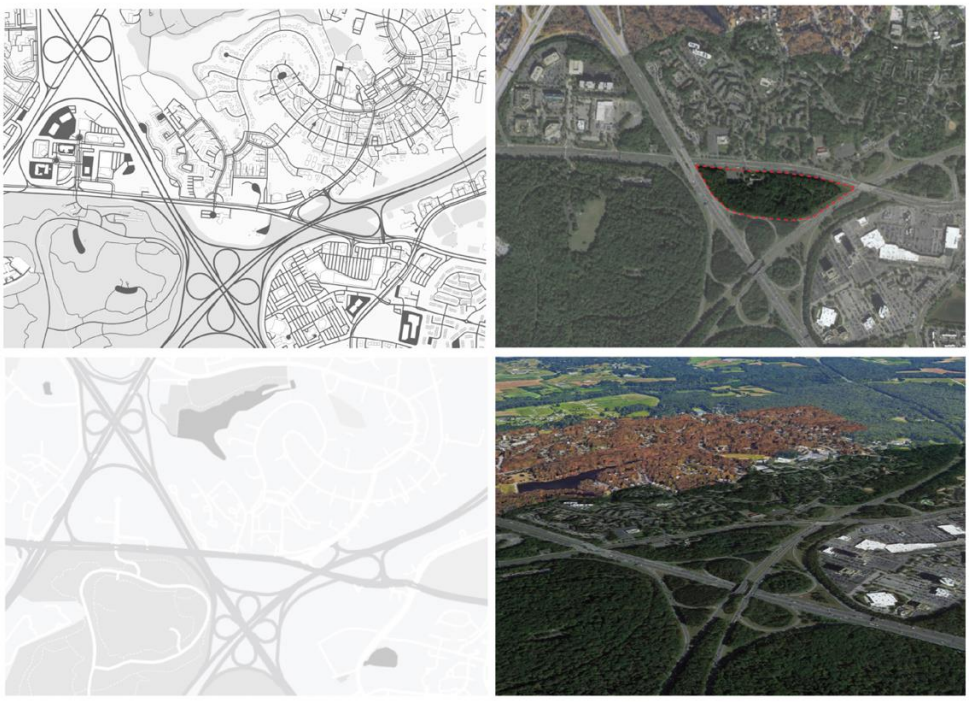


*Figure 38: Site Option Two, Google Earth (2024).*

*Figure 39: Site Option Three, Google Earth (2024).*


| Selection Matrix<br>1 (Worst fitted for the project) – 5 (Best fitted for the project) | Option 1 | Option 2 | Option 3 |
|---|---|---|---|
| Transportation | Located next to Metro and Marc station, there are 4 bus stations in front of site | Located near 13 bus stations within 15 minute walking radius | Located near 15 bus stations within 15 minute walking radius |
| Proximity to Schools | All ES, MS, and HS are located within 2 miles | All ES, MS, and HS are located within 1 mile | All ES, MS, and HS are located within less than 1 mile |
| Proximity to Essential Amenities | Explores the number and types of amenties available to users (amenity types include: grocery stores, resturants, shopping centers, etc.) | | |
| | B | C | C |
| Connection to Green Space | A- | C | B |
| Availability of Utilities | No | Yes | Yes |
| Size of Site | 74 Acres | 23 Acres | 48 Acres |
| Connection to Surrounding Context | C | B | A |
| Access to Water | Yes | No | Yes |
| Level of Disturbance to the Community | Highest Level | Least Level | Mid-Level |
| Proximity to Existing Affordable Housing | None within 5 min walking Radius | 4 within 5 min walking Radius | None within 5 min walking Radius |

*Figure 40: Site Selection Matrix Research, drawn by author.*


| Selection Matrix<br>1 (Worst fitted for the project) – 5 (Best fitted for the project) | Option 1 | Option 2 | Option 3 |
|---|---|---|---|
| Transportation | 4 | 3 | 4 |
| Proximity to Schools | 3 | 4 | 5 |
| Proximity to Essential Amenities | 4 | 3 | 2 |
| Connection to Green Space | 4 | 2 | 3 |
| Availability of Utilities | 1 | 5 | 5 |
| Size of Site | 2 | 3 | 4 |
| Connection to Surrounding Context | 3 | 4 | 5 |
| Access to Water | 4 | 1 | 5 |
| Level of Disturbance to the Community | 1 | 5 | 3 |
| Proximity to Existing Affordable Housing | 3 | 2 | 5 |
| Total | 29 | 32 | 41 |

*Figure 41: Site Selection Matrix, drawn by author.*

# Chapter 9: Conclusion

## *3D Printing Construction Analysis*

The first step in commencing this thesis was to create a further Analysis of the 3D printing construction before application. For further analysis, the typical timeframe of construction of a 2,500 sqft home for both stick-built construction and 3D printing construction was broken down by the construction phases. In a stick-built home, the core & shell phase is currently taking the longest time to complete, since it relies on multiple disciplines being involved and relying on one another to move the construction forward, as illustrated in the figure below. However, if one looks towards 3D printing construction, the timeframe decreases significantly due to the core & shell process occurring all at once allowing all the disciplines being on-site to finish construction, while the structure is printing.

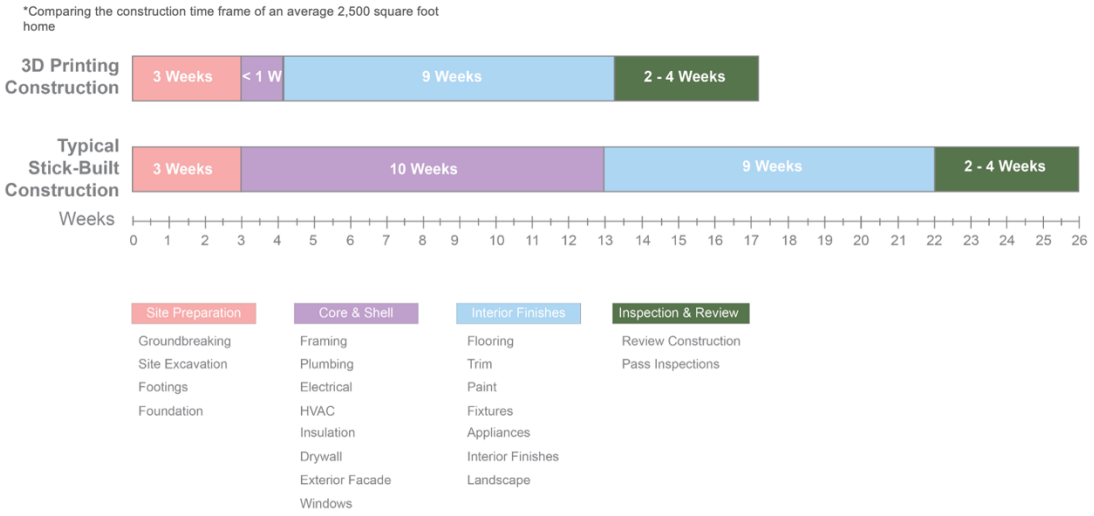



*Figure 42: 3D Printing Construction vs. Stick-Built Construction Timeframe, drawn by author.*

The next analysis was to determine how much cost savings would occur for both construction costs and operation costs, to determine whether 3D printing technology could help lessen the costs of construction and operation for its residents. The figure below illustrates that there was a cost savings of $8.23 per square foot due to the fact that the foundation and framing were cheaper to construct in 3D printing construction. Also, 3D printing construction did not require the development of exterior walls reducing the costs further, according to the data provided by Xtreme Habitats Institute and the Alaska Housing Finance Corporation.

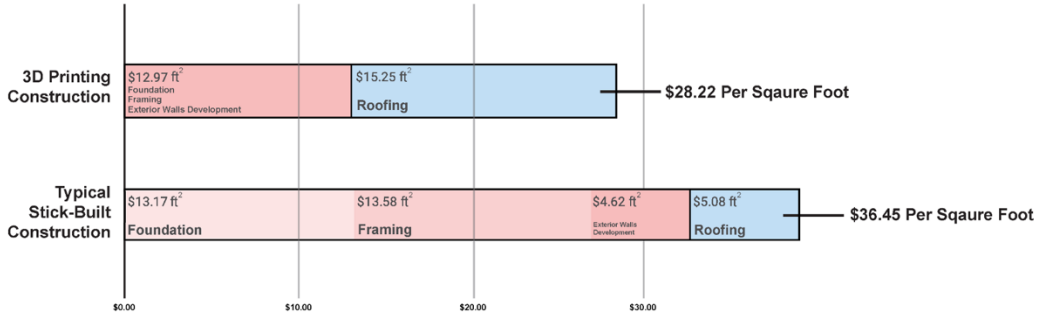



*Figure 43: Construction Costs Comparison, drawn by author.*

Then, a study of the operation costs was compared with the minimum code standard construction. The proposed units were utilized to study this comparison. In the proposed units with the utilization of the roof being 80% solar panel and the walls having a higher R-Value, the costs of operations compared to a code minimum construction allowed for a decrease of 70% in costs relieving residents from being cost-burdened, as illustrated in figure 44.

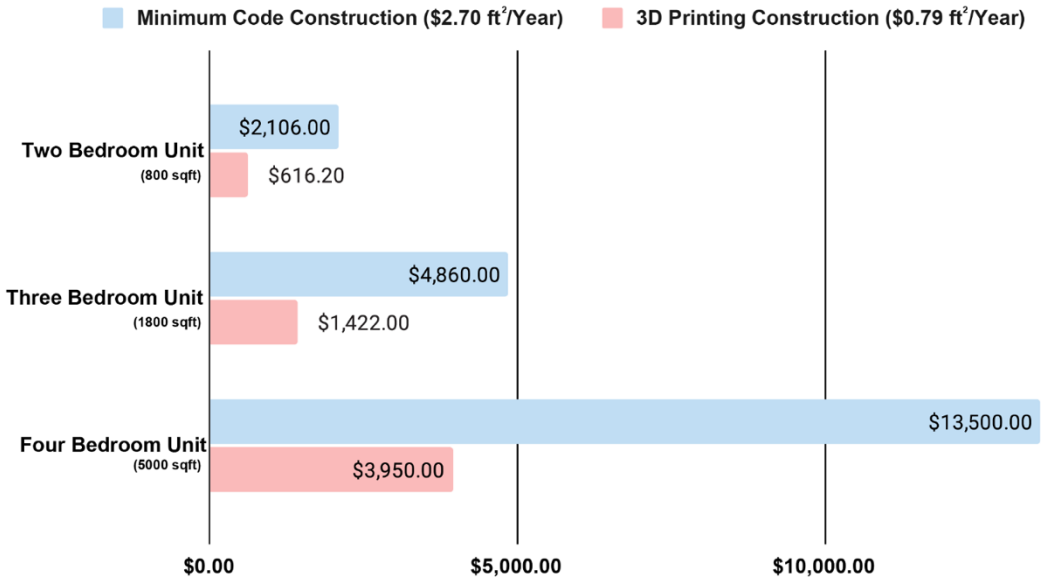



*Figure 44: Operational Costs Comparison, drawn by author.*

Finally, the last step before starting design was to determine the printer's constraints and limitations. Currently, the printer requires a 4ft spacing around the construction and is only able to print up to 3 stories, as shown in the figure below.

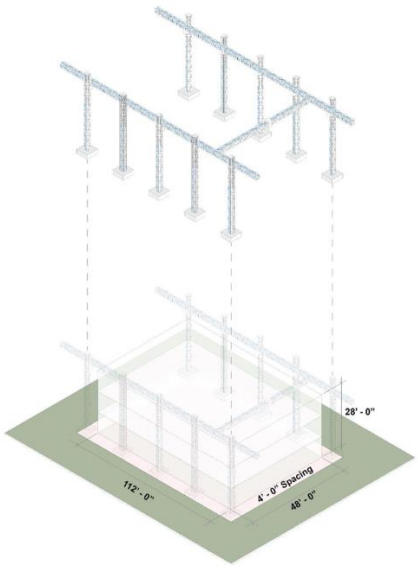



*Figure 45: 3D Printer Constraints, drawn by author.*

The construction would begin with the pouring of the foundation, then moving up with the development of a 3-layer walls of concrete and as it is being printed the plumbing, electrical, and HVAC is also being installed. As it finishes the first floor, the walls are infilled with insulation and a prefabricated concrete floor slab is added to continue the printing of the next level. The wall breakdown below, illustrates the different components that create a 3D-printed wall.

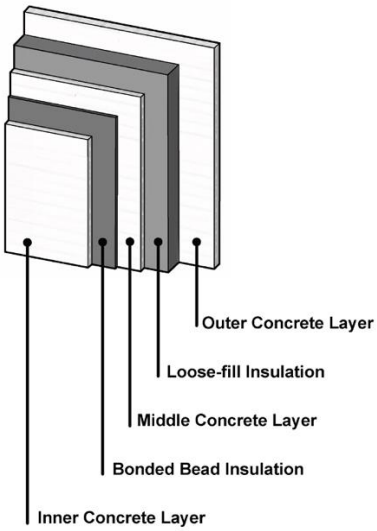



*Figure 46: 3D Printed Wall Assembly, drawn by author.*

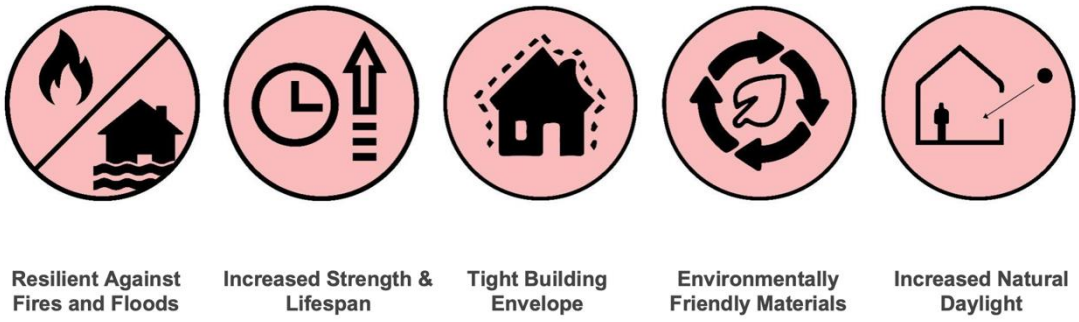



*Figure 47: 3D Printing Elevating the Standards, drawn by author.*

Overall, 3D printing Construction is elevating the standards of code construction by being able to withstand strong earthquakes and fires, increasing its strength and lifespan, creating a tight building envelope that reduces operation costs, utilizing environmentally friendly materials like green cement, and increasing daylight by having the ability to add more natural light on all 4 sides of a building.

*Analysis of Greenbelt Historic District*

The site selected for this thesis was Greenbelt because as one of the first three green cities created it had similar beliefs as this thesis to look towards new construction methods like modular construction, that were faster and budget-friendly, while still allowing the natural curves of technology to blend in nicely to the art deco style that currently exists on site. Although this thesis is within Greenbelt, it is designed to be able to be implemented in any suburban development. Some values in the figure below are from the green cities initiatives and some were added to consider moving forward with this project.


*Figure 48: Site Values, drawn by author.*


*Figure 49: Greenbelt Divisions, drawn by author.*

As illustrated in Figure 49, Greenbelt is mainly divided by the highway. The original development of the green city is located in Old Greenbelt, just north of the site. The site is located in Greenbelt East being disconnected from Old Greenbelt by Greenbelt Road. To understand the ideas of green city development, a further analysis of Old Greenbelt was developed. The blocks of the city were divided to become large "Super Blocks" that would limit the amount of vehicle access as illustrated in Figure 50. In Figure 51, one can see that all the amenities are located at the center of the original city to allow for easier access being close proximately to the living spaces. Finally, in Figure 52, the reason for creating these "Super Blocks" was to create more walkable paths creating a very interwoven pedestrian-friendly network, that would encourage more connection to nature.

Zooming more into the analysis of a "Super Block" in Figure 53, one can notice the housing units are divided by creating a garden side and a housing side. However, viewing Figure 54, the privacy for the units is very limited, since only the garages are the areas with the most privacy. So, this is something to consider when designing this thesis project. It is

also important to consider that these large blocks are not easy to implement into other suburban developments and would have to change to become more standardized.


*Figure 50: Greenbelt Historic District – "Super Blocks", drawn by author.*


*Figure 51: Greenbelt Historic District – Amenities, drawn by author.*


*Figure 52: Greenbelt Historic District – Walking Trails, drawn by author.*


*Figure 53: Greenbelt Historic District – Garden vs. Housing, drawn by author.*


*Figure 54: Greenbelt Historic District – Privacy, drawn by author.*

*Site Analysis*

The site is located in Greenbelt East, where it is surrounded by the highway and mostly residential development, as seen in Figure 55. At the center of the site is a park, where the community has generated its own community garden, so this is a good indication that the community is already looking for more community spaces. This is due to the fact the closest recreation center is a 40-minute walk or a bus ride. North of the park there are a few amenities for the people living in the area.


*Figure 55: Existing Site Plan, drawn by author.*

In Figure 56, the drawing below illustrates the development of the site over time. The site was developed between 1970s – 2010s. However, the developments that occurred over time were designed to be very disconnected and some have even fenced off the areas of housing. The site of Greenbelt East loses the ideals of creating a green city, this thesis will aim to reconnect the existing developments to create a more connected community similar to the Historic District. Another item to consider is that the main road adjacent to the park is the

most trafficked street within the development with several bus stops along the route, as illustrated in Figure 57, this is important to consider when redesigning,

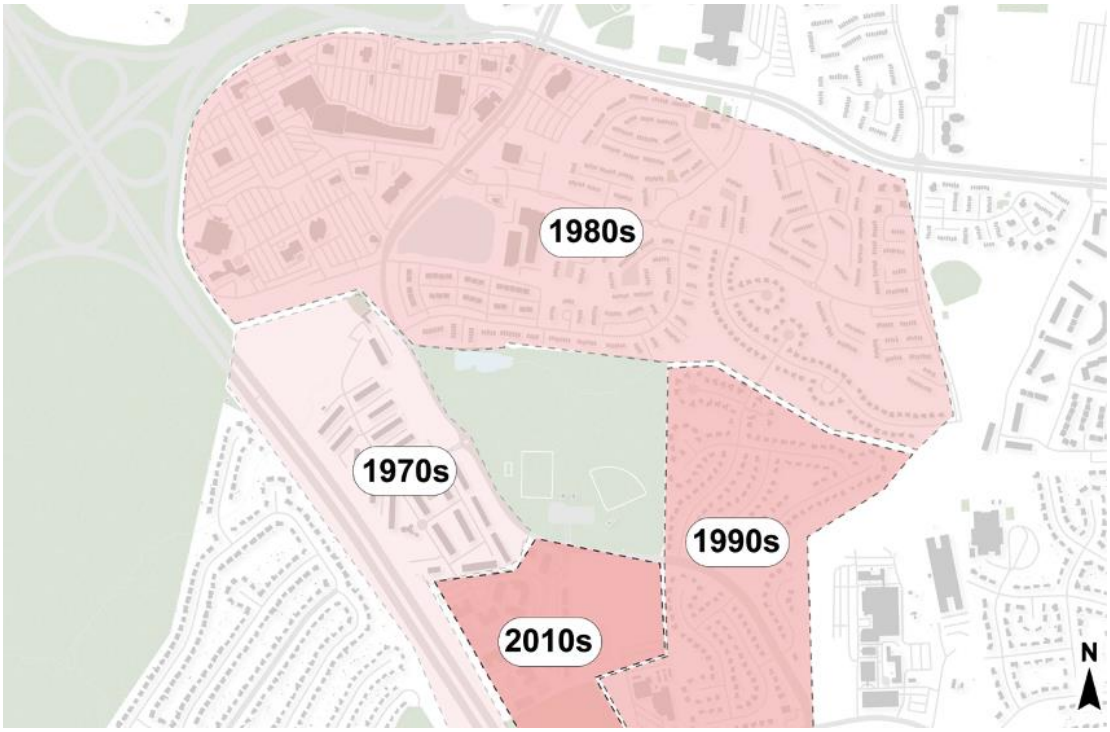



*Figure 56: Site Development, drawn by author.*


*Figure 57: Transportation, drawn by author.*

*Design Proposal*

The first step taken in the design process was finding ways to increase density. Then, the requirement for the 3D printer needs a 4ft spacing allowing for more cross ventilation to occur. Next, would be creating a front porch that reconnects with the street front and allows for more public access to streets. Finally, the last step was to create a public gathering space to give back to the community and also provide a space that reconnects with the existing buildings.

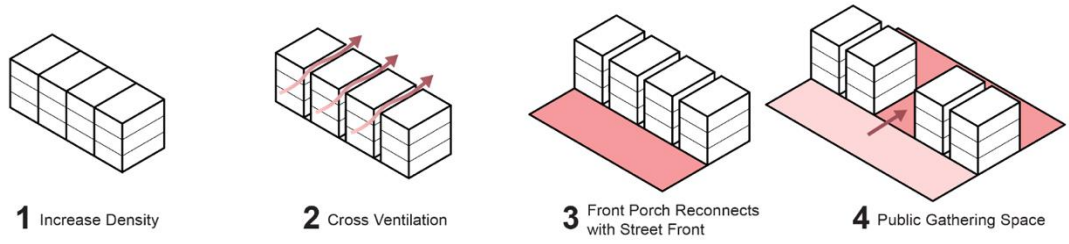



*Figure 58: Parti, drawn by author.*


*Figure 59: Proposed Site Plan, drawn by author.*

In figure 59 the proposed redesign of the site is illustrated. The development attempts to reconnect with the existing context, generates more green spaces for the community, and creates flexible community spaces at each unit block. A new ring road around the park attempts to reconnect all the divided sub-communities to create a similar design as the historic district by utilizing the park as an anchor and also having space to generate a recreational community center. The proposed design would be created by breaking the development into two phases. The first phase would develop the northwest part of the site and would include 16 cohousing units and 50 stacked duplexes. The second phase would be developed on the southeast side of the site and would consist of 14 cohousing units and 24 stacked duplexes. Views of the development can be seen further in Figure 60.

*Figure 60: Views of Proposed Development, drawn by author.*

The types of units found in the development range from one bedroom to three bedrooms and also have the option of a cohousing unit. All units include a VRF system for cooling and radiant floors for heating.


*Figure 61: Unit Listings, drawn by author.*

For the stacked duplexes, the owner of the unit would be able to rent one of the two units, helping decrease the cost burden on the owner. The stacked duplexes range from one

bedroom to three bedrooms. Another feature of all these units is that they all run mostly on solar power energy. Since the costs of construction are relatively lower than typical, there is the ability to generate larger home units compared to the units found in the historic district. The cohousing unit consists of four bedrooms, a large kitchen, workspaces, and gathering spaces. The fireplace is utilized on each floor to encourage interaction at the heart of the home.

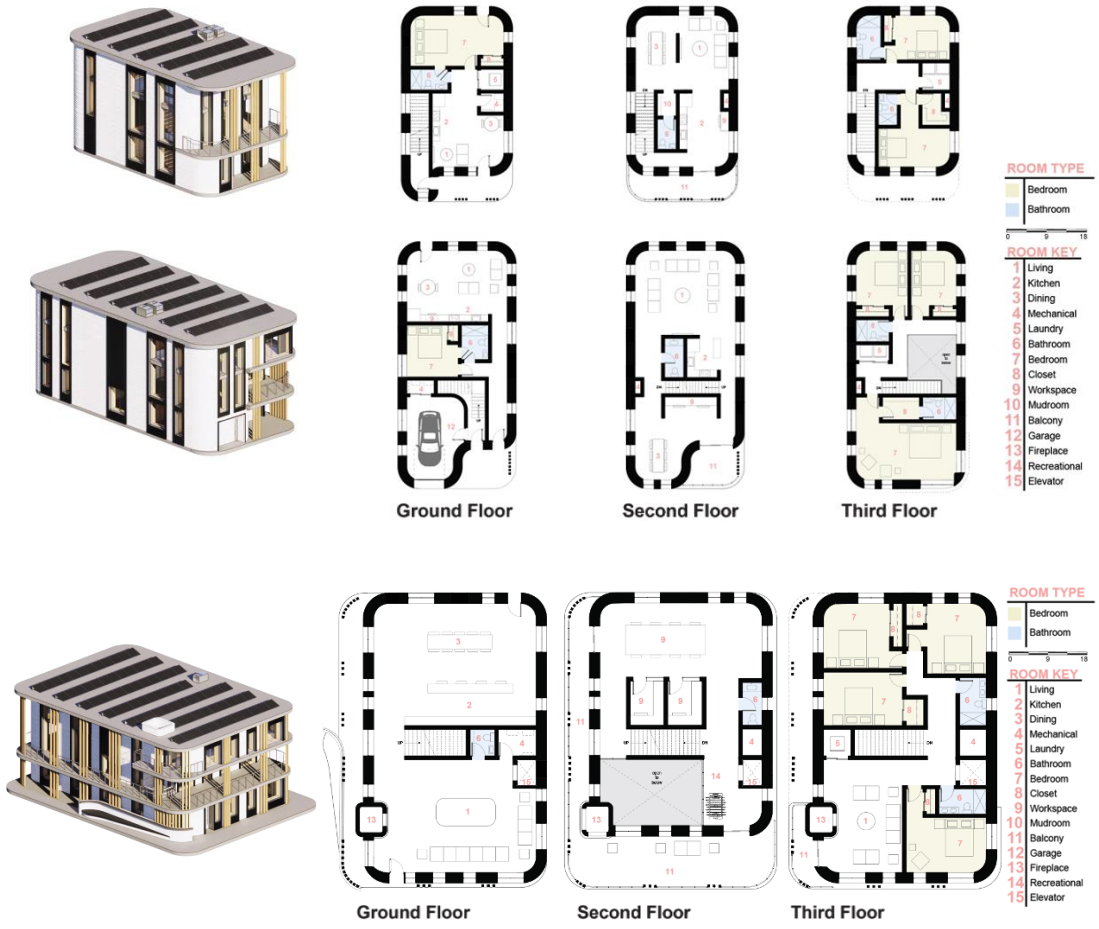



*Figure 62: Unit Designs, drawn by author.*

Finally, as seen in Figure 63, some sustainability features illustrated are the use of solar energy, more natural light, reduction in sound transmission from the spacing created between the units, and increased natural air ventilation.

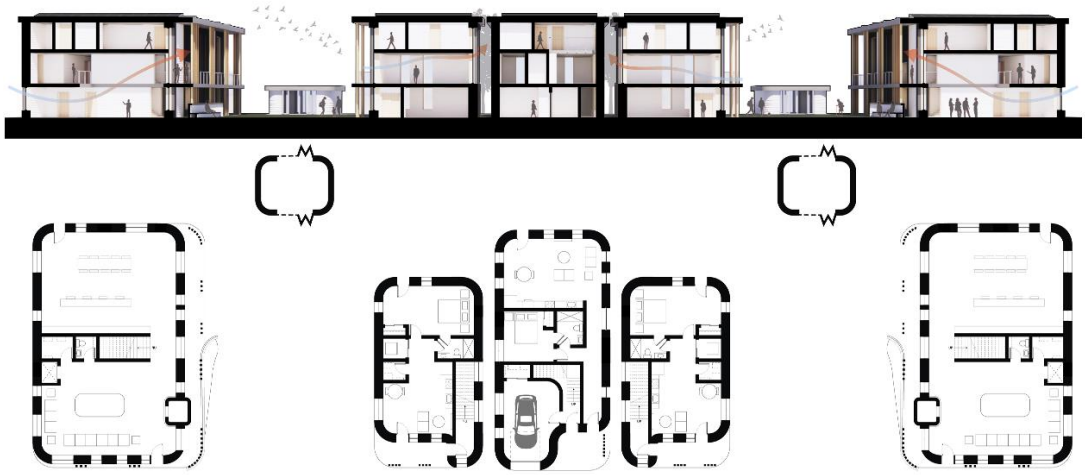


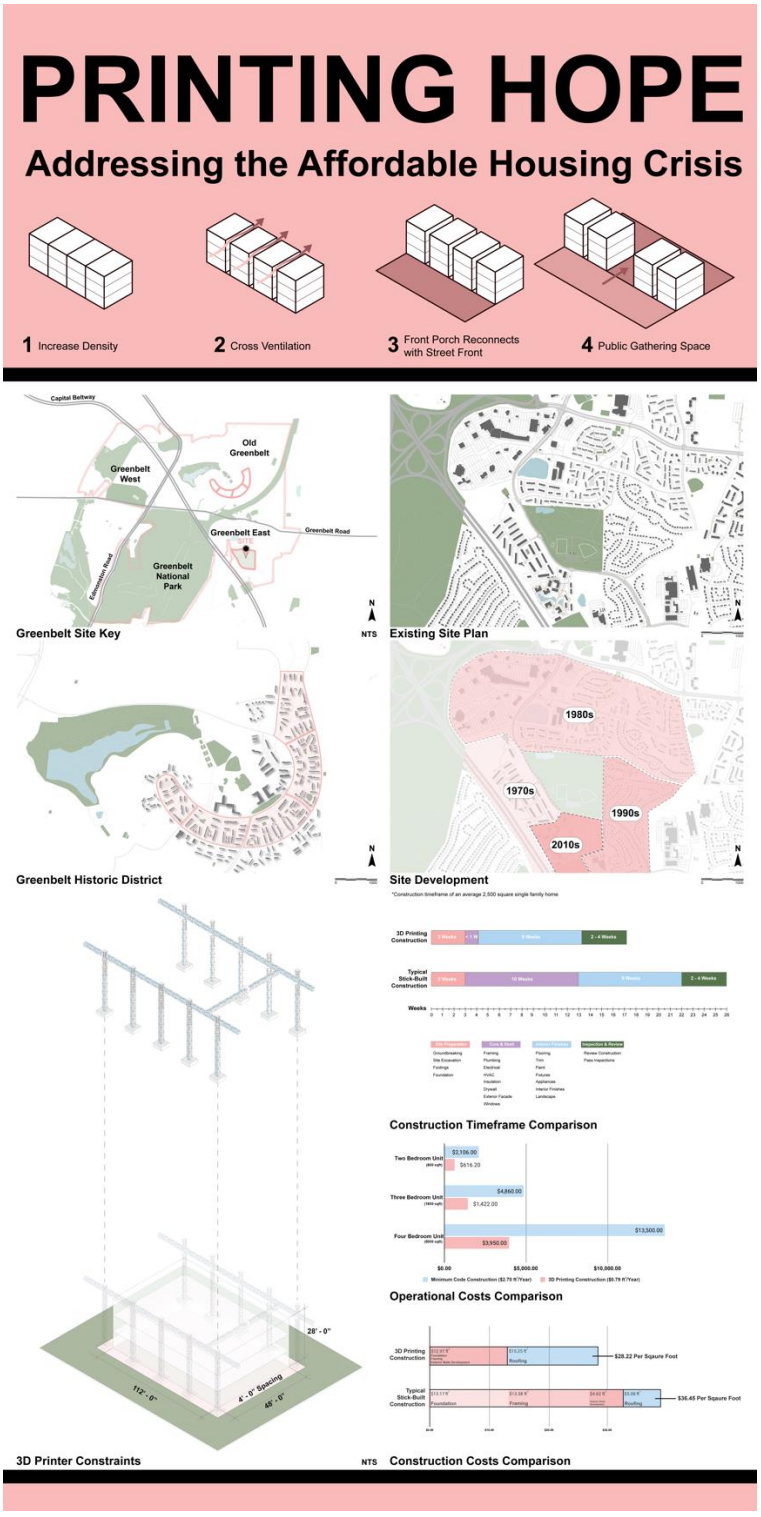
*Figure 63: Unit Block Design, drawn by author.*

*Conclusion*

In conclusion, this thesis aims to prove that 3D printing construction is a more affordable construction method and looks toward generating standard units that could be implemented in other suburban developments; while reconnecting with the existing context and increasing community engagement. The current technology cannot currently print connected units, but could be very powerful when the technology approaches this milestone by increasing density and building units similar to rowhomes. Something that was not explored much in this thesis, but could be added to 3D printing construction is the ability for customization of the units by creating a more diverse range of options. Overall, 3D printing technology is a new method of construction that is already being utilized in the construction field and it allows for more quality built construction with a more friendly budget that could help address the affordable housing crisis. To conclude, let's print hope to help create more possibilities for the American dream; while creating a more resilient and sustainable future.

# Appendices

## Appendix A: Final Thesis Defense – Board 1

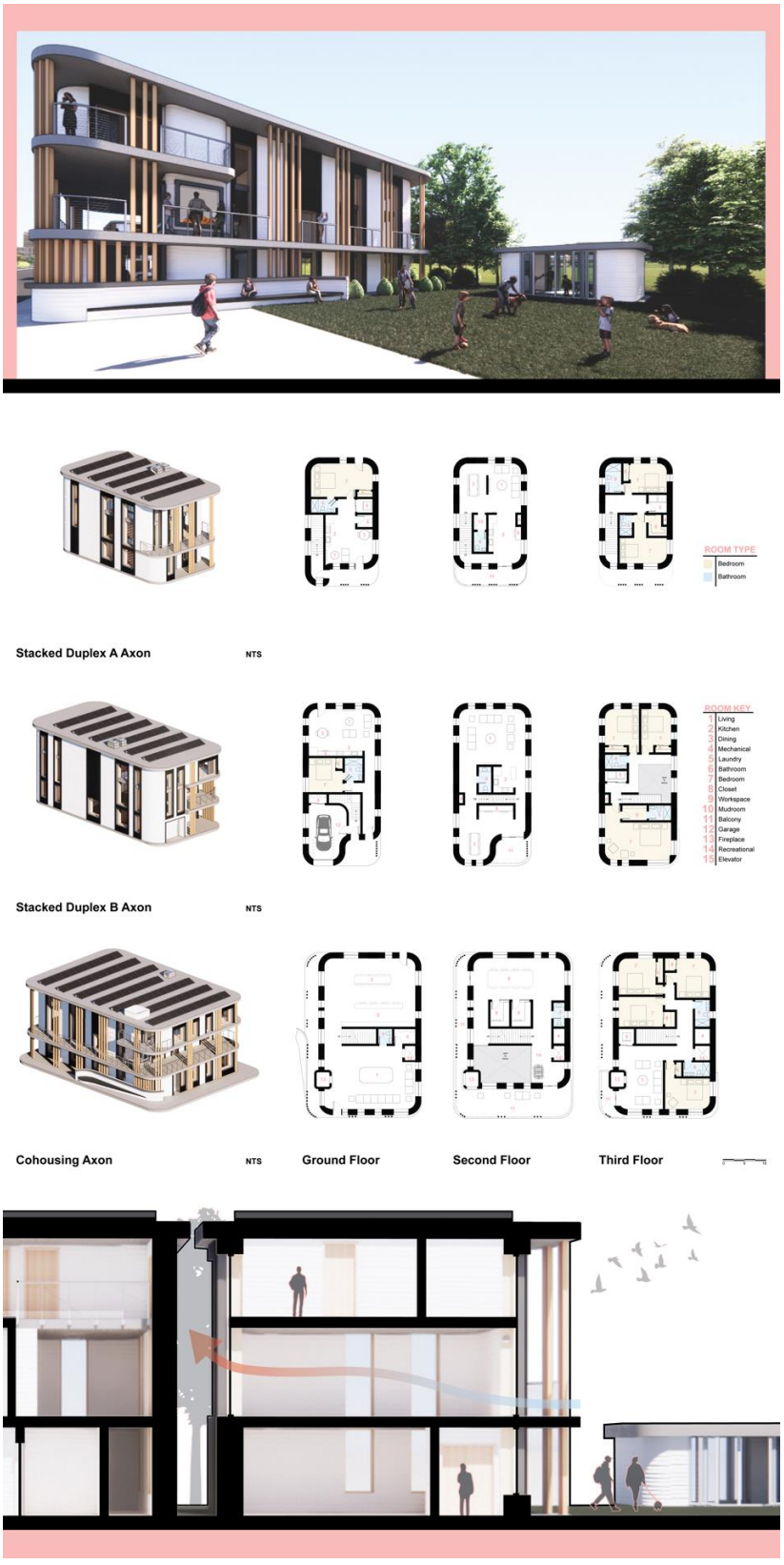


Appendix B: Final Thesis Defense - Board 2

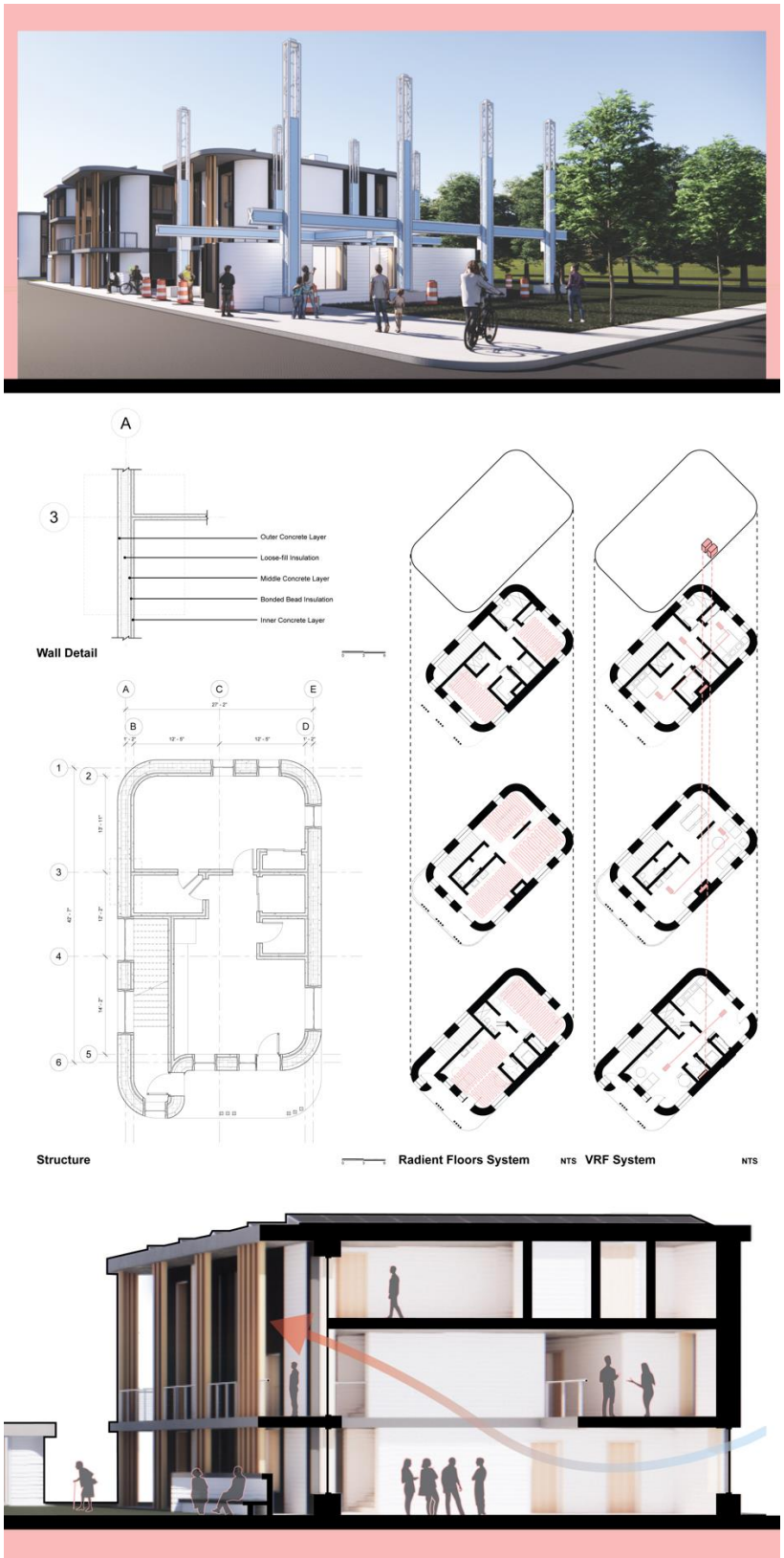



Appendix C: Final Thesis Defense - Board 3

Appendix D: Final Thesis Defense - Board 4



Appendix E: Final Thesis Defense - Board 5



# Glossary

# Bibliography

A Brief Historical Overview of Affordable Rental Housing. Accessed October 22, 2023. https://nlihc.org/sites/default/files/Sec1.03_Historical-Overview_2015.pdf.

A history of discrimination, redlining, and affordable housing work in Washington, D.C. (n.d.). https://www.povertyusa.org/stories/affordable-housing-dc.

*A Shortage of Affordable Homes - National Low Income Housing Coalition*. Accessed September 6, 2023. https://nlihc.org/sites/default/files/gap/Gap-Report_2023.pdf.

Anih, E K, C Sam-Amobi, C E Okere, P E Odoh, N N Andy, I P Onubeze, and C C Ugwu. "Design Adaptability as a Tool for Achieving Affordable Housing in Developing Economies." *IOP Conference Series: Materials Science and Engineering* 640, no. 1 (2019): 012008. doi:10.1088/1757-899x/640/1/012008.

Association, Steel Framing Industry. "Steel Framing Saves 9 Months on Construction, Beats Monsoon Season." BuildSteel.Org, Last modified September 22, 2022. https://buildsteel.org/projects/multi-family-residential/steel-framing-saves-9-months-construction-time/#:~:text=%E2%80%9CTo%20build%20a%20conventional%20concrete,founder%20of%20the%20ODF%20Group.

B., Carol. "Maryland Section 8 Housing." Affordable Housing Hub. Last modified May 6, 2023. https://affordablehousinghub.org/state-section-8-guides/maryland-section-8-housing#.

Bateman, Bruce W. "Light gauge steel verses conventional wood framing in residential construction." *Journal of construction education* 2, no. 2 (1997): 99-108.

Beaups. “Can a 3D Printer Solve the World’s Housing Crisis?” *Technology and Operations Management*. Last modified November 20, 2016. Accessed August 30, 2023. https://d3.harvard.edu/platform-rctom/submission/can-a-3d-printer-solve-the-worlds-housing-crisis/.

“Benefits of Be You Connected Communities for Early Learning.” Be You. Accessed October 12, 2023. https://beyou.edu.au/resources/sessions-and-events/be-you-connected-communities-for-early-learning/benefits.

Bertog, Kelly. “Why 3D Printed Homes Might Actually Work.” Medium. Last modified March 5, 2020. https://kellybertog.medium.com/why-3d-printed-homes-might-actually-work-d71fef286080.

“Biophilic Design as a Holistic Approach to Healthier Buildings.” BlueGreen Alliance Foundation. Accessed October 12, 2023. https://www.bgafoundation.org/news/biophilic-design-as-a-holistic-approach-to-healthier-buildings0/.

Chini, S. Abdol, and Kavita Gupta. "A comparison between steel and wood residential framing systems." *Nation* 700, no. 12,208 (1997): 4-880.

Chiu, Stephen Tse-Lun. “An Analysis on : The Potential of Prefabricated Construction Industry.” G. Undergraduate Research. Last modified April 9, 2012. Accessed October 19, 2023.

https://open.library.ubc.ca/collections/undergraduateresearch/52966/items/1.0103132.

Danko, Micaela R.. “Designing Affordable Housing for Adaptability: Principles, Practices, & Application.” (2013).

Debertin, Anne. Biophilic Design, Regenerative Design, and Equity: An Intersection. Accessed October 12, 2023. https://pubs.lib.umn.edu/index.php/muraj/article/download/3618/2783/18518.

Dita Hořínková 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* 1203 032002.

*East Lake Meadows: A Public Housing Story*. Directed by Sarah Burns and David McMahon, PBS, 2020.

Emrath, Paul. “Since Pandemic Onset, Lumber Products Have Added $14K to House Price, $51 to Rent: Eye On Housing.” Eye On Housing | National Association of Home Builders Discusses Economics and Housing Policy, Last modified July 15, 2022. https://eyeonhousing.org/2022/07/since-pandemic-onset-lumber-products-have-added-14k-to-house-price-51-to-rent/.

Environmental and Energy Study Institute (EESI). “Building Green: How Affordable Housing Can Tackle Justice and Sustainability.” EESI. Accessed October 12, 2023. https://www.eesi.org/articles/view/building-green-how-affordable-housing-can-tackle-justice-and-sustainability.

García-Alvarado, Rodrigo, Ginnia Moroni-Orellana, and Pablo Banda-Pérez. 2021. "Architectural Evaluation of 3D-Printed Buildings" *Buildings* 11, no. 6: 254. https://doi.org/10.3390/buildings11060254.

Gong, Yu, Erzsébet Szeréna Zoltán, and Gyergyák János. 2023. "Healthy Dwelling: The Perspective of Biophilic Design in the Design of the Living Space" *Buildings* 13, no. 8: 2020. https://doi.org/10.3390/buildings13082020.

"Green Cement Products Feedstock from Pozzolanic Minerals or Fly Ash." Green Cement. Accessed December 16, 2023. https://greencement.com/sustainability/.

Guedes, Anielle. "3D Printing Ready to Reshape Home Building." *Proquest,* November 23, 2015. Accessed August 30, 2023. https://www.proquest.com/openview/994bf418377c3989263e4069ed1345de/1?pq-origsite=gscholar&cbl=5572318.

"House Zero." *ICON*. Accessed September 13, 2023. https://www.iconbuild.com/projects/house-zero.

Hlr. "Addressing Challenges to Affordable Housing in Land Use Law: Recognizing Affordable Housing as a Right." Harvard Law Review, Last modified March 24, 2023. https://harvardlawreview.org/print/vol-135/addressing-challenges-to-affordable-housing-in-land-use-law/#:~:text=Restrictive%20zoning%20rules%2C%20like%20single,cost%20of%20new%20housing%20projects.

"Homeownership Rate in the United States." FRED, Last modified April 30, 2024. Accessed May 05, 2024. https://fred.stlouisfed.org/series/RSAHORUSQ156S#.

"How Long Does It Take to Build a Single-Family Home?" NAHB. Accessed October 29, 2023. https://www.nahb.org/blog/2020/09/How-Long-Does-it-Take-to-Build-a-Single-Family-Home.

Kevin Leacock, MPH. "A Brief History of Housing Policy in the U.S." National Nurse-Led Care Consortium. Accessed November 5, 2023.

Kidwell, Jake. Best practices and applications of 3D printing in the ... - cal poly. Accessed September 6, 2023. https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1090&context=cmsp.

Kolokotsa, Denia, Gloria Pignatta, and Giulia Ulpiani. "Nearly Zero-energy and Positive-energy Buildings: Status and Trends." *Technologies for Integrated Energy Systems and Networks* (2022): 239–273.

Lubell, Jeffrey, Rosalyn Crain, and Rebecca Cohen. "Framing the issues—the positive impacts of affordable housing on health." *Center for Housing Policy* 34 (2007): 1-34.

Markstedt, Kajsa, Karl Håkansson, Guillermo Toriz, and Paul Gatenholm. "Materials from Trees Assembled by 3D Printing – Wood Tissue beyond Nature Limits." *Applied Materials Today* 15 (2019): 280–285.

"Maryland." National Low Income Housing Coalition. Accessed October 22, 2023. https://nlihc.org/housing-needs-by-state/maryland#:~:text=Across%20Maryland%2C%20there%20is%20a,of%20their%20income%20on%20housing.

"Median Sales Price of Houses Sold for the United States." FRED, Last modified May 6, 2024. Accessed May 05, 2024. https://fred.stlouisfed.org/series/MSPUS.

Monroe, Rachel. "Can 3-D Printing Help Solve the Housing Crisis?" *The New Yorker*. Last modified January 16, 2023. Accessed September 6, 2023. https://www.newyorker.com/magazine/2023/01/23/can-3-d-printing-help-solve-the-housing-crisis.

More Housing for Maryland's Working Families. Accessed November 15, 2023. https://mgaleg.maryland.gov/cmte_testimony/2020/ent/3639_03032020_10478-704.pdf.

Nandinee K. Kutty (2005) A new measure of housing affordability: Estimates and analytical results, Housing Policy Debate, 16:1, 113-142, DOI: 10.1080/10511482.2005.9521536.

Nanyam, V.P.S. Nihar, Anil Sawhney, and Prateek Arun Gupta. "Evaluating Offsite Technologies for Affordable Housing." *Procedia Engineering* 196 (2017): 135–143.

Pessoa, S., A.S. Guimarães, S.S. Lucas, and N. Simões. "3D Printing in the Construction Industry - a Systematic Review of the Thermal Performance in Buildings." *Renewable and Sustainable Energy Reviews* 141 (2021): 110794.

"President Biden Announces New Actions to Ease the Burden of Housing Costs." The White House. Last modified May 16, 2022. https://www.whitehouse.gov/briefing-room/statements-

releases/2022/05/16/president-biden-announces-new-actions-to-ease-the-burden-of-housing-costs/.

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G. and Zimmerman, J.B. (2012), Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. Journal of Industrial Ecology, 16: 243-253. https://doi.org/10.1111/j.1530-9290.2011.00424.

"R+D Concept: Hexagon House." *KTGY*. Last modified September 15, 2023. Accessed September 05, 2023. https://ktgy.com/work/hexagon-house/.

Research and Feasibility Study on 3D Printed Homes In ... Accessed May 05, 2024. https://www.ahfc.us/download_file/view/7140/464.

Rippon, Jordan A. "The Benefits and Limitations of Prefabricated Home Manufacturing in North America." G. Undergraduate Research. Last modified April 11, 2011. Accessed October 19, 2023. https://open.library.ubc.ca/collections/undergraduateresearch/52966/items/1.0103127.

Sakin, Mehmet, and Yusuf Caner Kiroglu. "3D Printing of Buildings: Construction of the Sustainable Houses of the Future by Bim." *Energy Procedia* 134 (2017): 702–711.

"Sustainable Design & Affordability." Affordable Housing + Sustainable Communities. Accessed October 12, 2023. https://outreach.design.ncsu.edu/ah+sc/resources/white-papers/sustainable-design-affordability/.

"The Benefits of Affordable Housing." Midlands Housing Trust Fund, Last modified November 10, 2022. https://midlandshousing.org/the-benefits-of-affordable-housing/.

"Top 10 Largest Economies in the World." Business Insider, Last modified October 10, 2023. https://www.businessinsider.in/top-10-largest-economies-in-the-world/articleshow/70547252.cms.

V.Lojanica, V. -M. Colic-Damjanovic and N. Jankovic, "Housing of the Future: Housing Design of the Fourth Industrial Revolution," *2018 5th International Symposium on Environment-Friendly Energies and Applications (EFEA)*, Rome, Italy, 2018, pp. 1-4, doi: 10.1109/EFEA.2018.8617094.

"We Build Affordable 3D Printed Houses." *Alquist 3D*. Accessed September 6, 2023. https://www.alquist3d.com/.

Wijk, Ad van, and Iris van Wijk. *3D Printing with Biomaterials towards a Sustainable and Circular Economy*. Amsterdam: IOS Press, 2015.