Recycled Material Selection for Affordable and Sustainable Homes Using Large Scale Additive Manufacturing

by

Erika P. Mynio

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Abstract

Worldwide estimates indicate nearly 150 million people are homeless, and 1.6 billion lack adequate shelter. One of the biggest barriers of home ownership is cost, which is often driven heavily by the cost of materials required. Plastic waste is also at an all-time high, with over 5 billion tons of plastic on the earth's surface and in its oceans. This waste will take hundreds of years to degrade if not longer and incentives and use for recycled plastic is needed now more than ever.

Making lightweight homes using 3D printed recycled polymer materials is proposed as a solution to this problem. Assuming a network of manufacturing sites, a significant number of homes could be produced, raising the issue of material selection and availability.

After creating an extensive comparison of potential materials, stressing properties, availability and cost, the best candidate appears to be polyethylene terephthalate (PET). Recycled PET (rPET), is available in volumes comparable to the projected demand for low cost housing. rPET material properties optimize the feasibility, processing, and engineering use qualities of the building material, but further testing is necessary to explore the effect of feedstock processing and additives on the performance of the material.

This thesis examines the choice of (rPET) as the best potential material for large scale 3D printing of low-cost homes and presents an experimental setup for confirming this hypothesis.

Thesis Supervisor: David Hardt
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Chapter 1: Introduction

Inadequate shelter remains a global problem. This thesis explores a solution based on the additive manufacturing of homes out of recycled polymer. This solution has the potential to mass produce desirable dwelling structures that will absorb much of the unused recyclable plastics now on the planet. This work is based on the assumptions that large scale polymer deposition processes (such as the Cincinnati Inc. BAAM or the Thermwood LSAM) could create such structures, but would need a supply of material that is best provided with recycled plastics. Accordingly, this research focuses on determining which polymers are suitable for dwelling applications, and of those which are good candidates for scaling to 40 million units. Table 1-1 below includes the chemical names and common abbreviations relied on for the remainder of this work.

Plastic	Abbreviation
Polyethylene Terephthalate	(PET)
Polypropylene	(PP)
High-Density Polyethylene	(HDPE)
Polyvinyl Chloride	(PVC)
Low-Density Polyethylene	(LDPE)
Polystyrene	(PS/Styrofoam)
Polylactic Acid	(PLA)
Polycarbonate	(PC)
Polymethyl Methacrylate	(PMMA/Acrylic)
Polyoxymethylene	(POM/Acetal)
Polyamide	(PA/Nylon)
Acrylonitrile Butadiene Styrene	(ABS)

Table 1-1:Plastics discussed in this paper and the abbreviations they will be referred to by. Generic designations are also included for context for some plastics

1.1 Scaling the Problem: Homelessness vs Inadequate Shelter

It has been estimated that 1.6 billion people are inadequately sheltered, with 150 million of those being completely homeless [1]. According to the Organization for Economic Co-operation and Development (OECD), “homelessness counts in most countries include rough sleepers, people living in accommodation for the homeless and in emergency temporary accommodation, but definitions of homelessness vary across countries” [2]. Countries with some of the highest reported rates of homelessness often have broader, more encompassing definitions of the term. Countries with some of the lowest reported rates often have narrower definitions that do not include all people who live without a permanent home. For example, New Zealand is on the higher end with 0.94% of the population classified as homeless but their definition is "living situations where people with no other options to acquire safe and secure housing: are without shelter, in temporary accommodation, sharing accommodation with a household or living in uninhabitable housing." In contrast, Japan reports a 0.004% homeless population, but their definition only includes "people who live their daily life in a park, a riverbed, at a road, a station or other institutions." [2]. Figure 1-1 further illustrates numerous similar homelessness situations in the OECD.

The term "inadequately sheltered" encompasses all definitions of homelessness, regardless of whether an individual country officially recognizes the living situation under their local standard for homelessness. This term further includes people squatting in the same building on a regular basis, those who live in "abjectly poor, often dangerous, dwellings," and individuals living temporarily with friends or family [1,2]. For purposes of this thesis, the terms "homeless" and "inadequately sheltered" will be used interchangeably to encompass all those who live without a permanent or safe living situation and unequivocally need a safe home to live in.

Overall, consistent homelessness statistics are difficult to come by especially in the developing world. The overwhelming majority of countries which have joined the OECD have strong economic growth and the government institutions necessary to consistently collect homelessness statistics. It is easier to collect statistics in urban environments than rural. The countries with urban poor can more accurately count their homeless populations than those with rural poor. It is likely that developing nations with higher percentages of people below the poverty line have larger homeless populations that will reside in different areas. Where many of the reported homeless populations for OECD countries reside in cities, it is likely that there are still large populations of rural people in developing countries with inadequate shelter that may not be accounted for due to lack of surveying. These rural homeless populations need individual homes rather than the apartment style accommodations that might be a solution for urban homeless populations. This is an assumption used for the justification of building homes that may take up too large of a footprint to be implemented for an urban homelessness solution.

Table HC 3.1.1: Estimated number of homeless people, 2019 or latest year available

	Year	Number of homeless	Homeless as % of total population[1]	Figures include *more than* persons 1) living rough, 2) living in emergency accommodation, and 3) living in accommodation for the homeless?
Australia	2016	116,427	0.48%	Yes
Austria	2017	21,567	0.25%	No
Brazil	2015	101,854	0.05%	*Not provided*
Canada (2)	2016	129,127	0.36%	No
Chile	2019	14,013	0.07%	No
Croatia	2013	462	0.01%	No
Czech Republic (3)	2019	23,900	0.22%	Yes*
Denmark	2019	6,431	0.11%	Yes
Estonia	2011	864	0.06%	Yes
Finland	2018	5,482	0.10%	Yes
France	2012	141,500	0.22%	No
Germany (4)	2018	337,000	0.41%	Yes
Greece	2009	21,216	0.19%	Yes
Hungary	2014	10,068	0.10%	No
Iceland	2017	349	0.10%	Yes
Ireland	2018	6,194	0.13%	No
Israel	2018	1,825	0.02%	No
Italy (5)	2014	50,724	0.08%	No
Japan	2019	4,555	0.00%	No
Latvia	2017	6,877	0.35%	Yes
Lithuania	2011	857	0.03%	No
Luxembourg (6)	2014	2,059	0.37%	Yes
Mexico	2010	40,911	0.04%	Yes
Netherlands	2016	30,500	0.18%	Yes
New Zealand	2013	41,207	0.94%	Yes
Norway	2016	3,909	0.07%	Yes
Poland	2019	30,330	0.08%	Yes
Portugal	2018	3,396	0.03%	No
Slovenia	2015	2,700	0.13%	No
Slovak Republic	2011	23,483	0.44%	Yes
Spain	2012	22,938	0.05%	No
Sweden	2017	33,250	0.33%	Yes
United States	2018	552,830	0.17%	Yes
United Kingdom: (7)				
England	2017	(57,890 households)	(0.26% households)	Yes, but limited to certain priority categories
Northern Ireland	2018	(9,673 households)	(1.23% households)	Yes, but limited to certain priority categories; includes households threatened with homelessness
Scotland	2018	(36,465 households)	(1.50% households)	Yes; includes households threatened with homelessness

Figure 1-1: Table HC 3.1.1 from an OECD report with estimated homeless populations for countries in the OECD. Countries that do not include those that are typically classified as "inadequately sheltered" generally have lower reported homeless populations [6].

1.2 Plastic Waste

Since the invention of the first plastic in the early 20th century, plastics continue to demonstrate their useful versatility along with numerous other engineering benefits. Plastic can be lightweight, easy to manufacture, low cost, and can be made to fit countless applications. However, plastic takes centuries to millennia to biodegrade and can cause lasting environmental damage. Even if plastic is deposited for recycling by the consumer, and often it is not [3], there are many obstacles that prevent all deposited items from making it all the way through the recycling process to a recycled good.

1.2.1 Biodegradability

Plastics do not decay like typical organic material. Most plastics are derived from byproducts of petroleum, which is the end product of millions of years of decay of organisms. When these petroleum products are heated in the presence of a catalyst, extremely strong carbon-carbon bonds form [4]. These carbon-carbon bonds are what keeps bacteria from degrading food stored in plastic containers, gives plastic a seemingly infinite shelf-life, as well as making it lightweight and strong [5]. However, the same properties that make plastic useful in many situations also prevent bacteria from naturally biodegrading the plastic. Carbon-carbon bonds require substantial energy to make. Nature tends not to form high energy carbon-carbon bonds and consequently avoids expending the energy to break these bonds [4]. This means plastics will not biodegrade in a timely fashion, with estimates being anywhere from hundreds of years to never [4,5].

1.2.2 Plastic in Landfills

Research by ImpactHub estimates that since 1950, humans have produced approximately 8.3 billion tons of plastics [6]. Of the approximately 8.3 billion tons of plastic produced, an estimated 6.3 billion tons has become waste, of which 9% has been recycled, 12% was incinerated, and 79% ended up in landfills or nature. This data implies that 5 billion tons of plastic sits on or below the surface of the earth or in its oceans. Non-recycled waste plastic continues to negatively impact the natural environment. Plastic in the environment kills wildlife through ingestion, strangulation, and even by flooding when plastic blocks drainage systems [7].

Leading researchers expect the amount of plastic waste to quadruple by 2050. Finding ways to recycle and keep plastic from landfills longer is becoming more crucial now than ever before [6].

1.3 Recycling Process

Most plastics have a preferred recycling process, but the more involved processes often are not cost effective, so only a select few specialized programs accept difficult to recycle plastics. The most common recycling process is shared by the plastics with some of the highest recycling rates (PET, HDPE, and PP) and will be most relevant for upcoming discussion in this thesis.

1.3.1 Lifecycle

After the manufacturing of products from virgin material and consumer use, the recycling lifecycle starts with collection of recyclable material. After collection, recyclable material is brought to a materials recovery facility (MRF) where it is sorted into individual plastic types and shipped to a processing facility. The processing facility then cleans, sorts, shreds, and often pelletizes the plastic to transform it into an acceptable grade for manufacturing use.

1.3.2 Collection

Collection companies require consumers to sort plastic for pickup in two different ways, single stream or multi-stream. Single stream allows consumers to put all recyclable objects in one bin, so everything including plastics, metals, glass, and paper are all collected together. This process yields a higher volume recycled by the consumer because it reduces the amount of effort required by the consumer to correctly put something in the recycling bin. However, this often leads to "wishful recycling" where consumers optimistically put non-recyclable objects in recycling bins in the hope that it can be recycled in some way when the facility cannot recycle it with the processes employed. Single stream recycling also leads to higher contamination of products, especially paper, and is more difficult to sort at the MRF. Multi-stream recycling splits recycling bins into the specific categories, often having separate bins for glass, metal, plastic, and paper. This leads to lower recycling from the consumer because of the hassle of sorting, but puts less strain on the sorting system and leads to higher net yields of actual recycling [8].

1.3.3 Materials Recovery Facility (MRF)

Once the recycled materials reach the MRF, the facility employs a multitude of sorting methods to separate all the recycled materials into their respective material groups while eliminating waste before further sorting. For sorting, MRF's first use gravity to sort paper products from the rest, letting heavier plastic, metal and glass containers fall to a lower conveyor belt while paper travels along a higher conveyor. Next, workers manually sort the materials to remove any non-recyclable materials from the resulting "heavier" conveyor. Magnetic attraction then removes any steel products from the incoming stream and places the steel into a separate stream before magnetic repulsion repels aluminum into its own stream. Gravity, forced airstreams, and a gap in the conveyor work in tandem to separate glass from the plastics. Optical scanners and jet streams remove PET from the remaining plastic, and workers then manually check for any PET missed in this process while sorting the remaining plastic. Finally, the MRF bales and ships the sorted products to their respective downstream processing facilities for further processing [9].

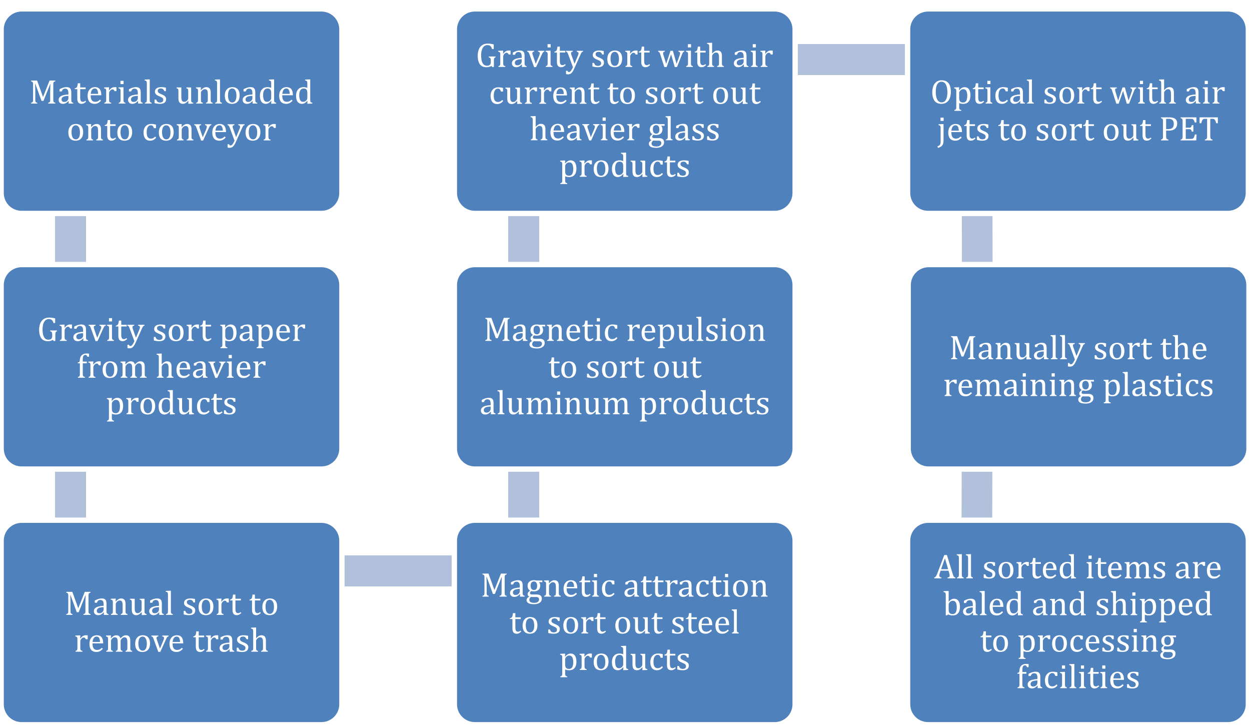


Figure 1-2: Overview of standard sorting procedure for MRF's that accept materials from single stream recycling programs. Multi-stream MRF facilities use only the steps that apply to the materials they accept [9].

1.3.4 Processing Facility

After the MRF sorts the material, it is sent to processing facilities for further refining. At the processing facility, after the bales of plastic are broken down and fed on to a conveyor, a manual sort is conducted for any contaminates the MRF missed. Next, metal detection removes any remaining metal particulates from the stream. The plastic is then sent for washing and label removal. Near infrared (NIR) sorting then detects different resin compositions and uses puffs of air to sort them accordingly. A visible light sorter then sorts, in a similar way, by container color Afterwards, operators conduct another visual inspection and manual sort in order to catch anything that the automated systems missed. Shredding then granulates the sorted plastic into flakes. Once flaked, friction washing with water jets along with high-speed rotation removes any remaining contaminants such as adhesives, dirt, or residue. After cleaning, a float-sink test is completed in order to separate out any differing plastics (e.g. caps or lids) so that only the desired plastic type remains. An oven dries the plastic and a process called elutriation removes any fines before one more metal detection pass. Finally, the flakes are screened to remove any that are too big or too small. Some processing facilities stop at this step and sell recycled plastic flakes to consumers. However, some other facilities then melt the flakes and extrude the melt through a screen filter to remove any last contaminates before extruding the plastic into pellets [10]. The process described above varies between facilities and by plastics type, but most involve the majority of these steps for recycling HDPE, PET, and PP [11,12].

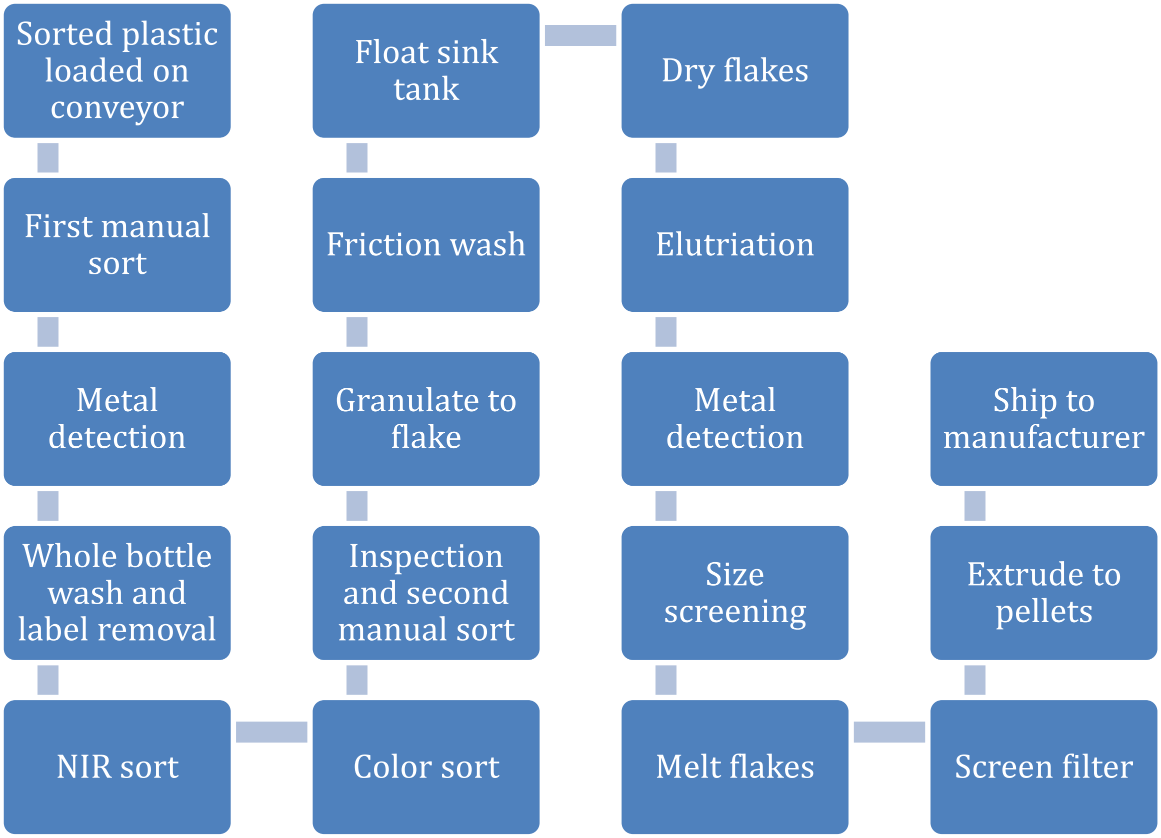


Figure 1-3: Common processing facility steps for PET, HDPE, and PP plastics. These steps vary depending on grade of plastic being produced and how much processing is completed at the MRF delivering the plastic [10].

1.3.5 Other Plastics Recycling Processes

Other plastics such as ABS and LDPE are recycled in a similar fashion, but are not accepted by curbside programs in the US so they have to be collected separately and delivered directly to processing facilities [13,14]. Plastics like PVC, PC, and PMMA are recycled with a chemical process and can release toxic chemicals during their recycling processes. This requires even more specialized facilities to recycle them [13,15,16]. Recycling technology is progressing faster now than ever before, but implementing programs and facilities to utilize new developments remains a barrier for the recycling of many plastic types.

1.4 Energy Requirements

Recycled plastic requires significantly less energy to process than virgin plastic does to manufacture. The manufacturing of virgin plastic into pellets uses energy in oil extraction, oil transportation, refining, and additive extraction [17]. Processing recycled plastic into pellets requires energy during collection, transportation, sorting, and cleaning the recycled material. According to Stanford University, this amounts to one ton of recycled plastic saving 5,774 Kwh of energy, 16.3 barrels of oil, 98 million BTU's of energy, and 30 cubic yards of landfill space [18].

1.5 Additive Manufacturing

Additive manufacturing is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer [19]. Commonly referred to as 3D printing, there are numerous different classifications of additive manufacturing technologies, including by not limited to, fused filament fabrication (FFF) (also known as fused deposition modeling (FDM)), stereolithography (SLA), and selective laser sintering (SLS) [20]. Most commonly, 3D printers use FFF technology, meaning they feed plastic filament into a heated print nozzle where it melts right before it is extruded into the designated layers needed to create the part [21]. With large scale 3D printing it would be costly and time consuming to make the appropriately sized filament, therefore, plastic pellets are fed directly into the machine where they are melted in a screw extruder before being extruded through the nozzle or die [22,23].

1.5.1 Concrete 3D Printed Homes

Concrete 3D printed homes have been proposed as a solution to the homelessness crisis by a number of companies including ICON, Winsun, and Apis Cor. The basic walls of these homes can be produced rapidly, often under a 24 hours period to provide shelter quickly and efficiently to those in need. Concrete construction provides a low cost of materials, with advertised costs ranging from $4,000-$10,000 per home [24–26]. These homes provide a viable solution to inadequate shelter for many communities across the globe. However, 3D printed concrete homes come with a series of drawbacks. The design of these systems requires the house to be built on site, which means everything needed for construction must be transported to the housing location. Concrete construction means having large amounts of their specialized concrete transported to the area, and many people in need of housing do not have roads accessible to large trailer trucks needed to efficiently transport the amount of concrete needed. The 3D printing setup must also be transported, as well as the engineers required to run it. The final construction also requires a plethora of additional pieces, such as the roof, trim, and furniture.

Figure 1-4: 500 square foot concrete home 3D printed in 27 hours by ICON built in Austin, Texas.[25]

Figure 1-5: 3D printed home by Winsun that completed 10 similar homes in 24 hours printing with a glass/concrete mix. Each home was 16,500 square feet and costs less than $5000 [26].

Figure 1-6: 3D printed concrete home constructed by Apis Cor in extreme elements. Printed in less than 24 hours costing ~$10,000 [24].

1.5.2 BAAM 3D Printer

The Big Area Additive Manufacturing (BAAM) 3D printer manufactured by Cincinnati Incorporated (CI) is marketed as one of the largest polymer extrusion 3D printers in the world. As a large-scale 3D printer, BAAM employs a pellet feed system that conveys materials directly to the extruder screw which adds thermal energy to the plastic prior to exiting the print nozzle or die. The largest print volume offered by CI is 20’ x 7.5’ x 6’ with a maximum feed rate of 80lb/hour. With these parameters and the right material selection, BAAM should be capable of printing sections for a 5000lb house in just over two days [23].

Figure 1-7: BAAM 3D printer interior (left) and exterior (right). Printing can be accomplished in a contained space and tubing conveys pellets directly into the extruder attached to the print head [23].

1.5.3 Thermwood LSAM 3D Printer

The Thermwood Large Scale Additive Manufacturing (Thermwood LSAM) 3D printer has an even larger capacity than the BAAM and conveys and extrudes plastic in a similar way. LSAM print beds are 10 feet wide, 20 feet deep and go up to 100 feet in length with possible feed rates exceeding 500lbs/hour. Although more expensive, the Thermwood LSAM should be capable of printing the same 5000lb house in just 10 hours. Projects printed on the LSAM include yacht hulls, helicopter blades, and submarine parts [22]. The technological developments in 3D printing allow for the potential of printing and transporting lighter sections of a 3D printing house. This would give all the cost and assembly advantages of a 3D printed house with significantly less transportation restrictions. 3D printing technology will only continue to improve for larger capacity and faster printing, allowing 3D printing houses to be more feasible than ever before.

LSAM 1040

Figure 1-8: Thermwood LSAM 1040 3D printer. The conveying and extrusion system is similar to the BAAM but the possible print area is much larger and has higher feed rates [22].

1.5.4 Feasibility of Polymer 3D Printed Homes

The feasibility of a 3D printed home has been demonstrated by Oak Ridge National Laboratory using the BAAM [27] with a fiber reinforced polymer. With a focus on energy conservation, they created a 38x12x13-foot building, printed in sections and later assembled to complete the finished product. To examine the feasibility of a smaller scale home using 100% polymer material, our group investigated the basic structural integrity of a 8x16 foot building (foundation, floor, wall and roof) using 100% PET. Preliminary finite element analysis under typical loading conditions (live loads, weight, wind, rain, snow) confirmed that deflections within normal limits could be achieved with overall material weight of less than 5000lb. Details on this analysis can be found in internal UROP reports by John Malloy and Tamilore Fashae [28,29].

Figure 1-9: 3D printed home designed by Oak Ridge National Laboratory printed on the BAAM with fiber reinforced polymer [30].

1.6 Thesis Outline

The HAUS project at MIT, led by Dr. Hardt, aims to find a solution in both the space of homelessness and plastic pollution using additive manufacturing. By using a 3D printer such as the BAAM or Thermwood LSAM, our group aims to utilize recycled plastic as the printing material for low cost and accessible homes for those with inadequate or insufficient shelter. Our target demographic is those in developing countries living in rural areas who wish to raise their quality of living with a safe and secure home. This thesis focuses on the material selection and testing process for the type of recycled plastic which is best suited for use in this application.

Chapter 2: Material Selection

2.1 Lifecycle Steps and Outlining Criteria

Material selection persists as one of the primary factors in determining feasibility of the MIT HAUS research project. Assuming that we utilize a recycled plastic, the type of plastic must meet certain general feasibility requirements in terms of scale, recyclability, cost, and safety. Further, the plastic must perform acceptably under standard 3D printing operating conditions from the melt and flow characteristics to the performance during the extrusion process. Lastly, after 3D printing production finishes, between the structural design and the material properties the house must withstand the elements and be structurally sound enough to meet standard building code and design guidelines to safely house a family for many years. Without a recycled plastic that can meet all the requirements, the scope of the project changes drastically. Given the state of the art in large scale additive manufacturing, initial research also assumes that just one type of recycled plastic would be used without any blends or fillers that could complicate distribution and production and therefore limit the reach this research could have. If available and feasible, additional blending and filler materials offer potential research avenues to further optimize material properties in future work.

Table 2-1 below lists the plastics initially considered for the MIT HAUS project along with common use products.

Plastic	Common Uses
PET	Water bottles, soda bottles, salad dressings bottles, peanut butter jars, cooking oil containers, mouthwash bottles, shampoo bottles, liquid hand soap containers, window cleaner bottles, tennis balls
PP	Hot food containers, thermal vests, car parts, disposable diaper and sanitary pad liners
HDPE	Grocery bags, milk and juice containers, shampoo bottles, medicine bottles, pipes and plastic lumber
PVC	Toys, blister wrap, cling wrap, detergent bottles, loose-leaf binders, blood bags, shower curtains, credit cards, rain gear, tarps, medical tubing
LDPE	Bags (grocery, dry cleaning, bread, frozen food bags, newspapers, garbage), plastic wrap, coatings for paper milk cartons and hot and cold beverage cups, some squeezable bottles (honey, mustard), food storage containers, container lids, wire and cable covering, corrosion-resistant work surfaces
PS	Food containers, egg cartons, disposable cups and bowls, packing peanuts, insulation, bike helmets
PLA	Sensitive medical applications, including implants, rods and screws, 3d printing
PC	Greenhouses, riot gear, thermal insulators for electronics, street signs, bus shelters, playground equipment
PMMA	Optical devices, plexiglass, domed skylights, swimming pool enclosures, instrument panels, aircraft canopies
POM	Gears, Delrin, paintball accessories, zippers, fan wheels, yo-yos, insulin pens, aerosol cans
PA	Substitute for low strength metals, clothing, reinforcement in rubber material like car tires, rope or thread, a number of injection molded parts for vehicles and mechanical equipment
ABS	Keyboard keys, pipes, fittings, vacuum construction, power tool housing, power socket face guard

Table 2-1: Plastics being considered for criteria evaluation as well as some of their most common products. Note that most bottles are made from PET and HDPE.

2.2 Feasibility in Context Criteria

Five main criteria were considered in order to assess overall feasibility of the MIT HAUS project: recyclability, amount produced, amount recycled, cost, and toxicity. Since the aim of this research is using recycled plastic and to provide a high-volume end-use application for recycled materials, it is crucial that the plastic chosen can be recycled. Beyond the recyclability, it is also important to take note of what the recycling process is, how simple or complex it is, and how easily the process could be scaled up to provide enough material to build millions of homes. This creates the first criteria, "recyclability," in which all these factors come together to give a general sense of how easily recycled material could be produced.

After recyclability, supply is the next major concern. The MIT HAUS initiative means to take waste from an already existing supply chain. However, if the world fails to produce enough virgin plastic produced yearly to meet demand in a reasonable timeframe, there will almost certainly not exist enough plastic to meet the recycled plastic demand required making the next criteria "amount produced."

Considering the amount of plastic produced, the following step concerns how much of the plastic produced is recycled. Although initiatives can be implemented to increase recycling rates for certain plastics among users, it creates a larger barrier than if the kind of plastic is already recycled regularly. Using a plastic that is already consistently recycled creates more supply options. With a recycling supply chain already in place, the plastic could be bought from an established recycling facility reliably if need be instead of having to set up the infrastructure to recycle the material.

Material cost, or rather economic feasibility, is the fourth criteria used in the assessment of general feasibility. Lowering the barrier to purchase the house remains a paramount consideration in providing homes to those who live in inadequate shelter. The overwhelming majority of people living in these situations do so because they cannot afford a sufficient home. Meanwhile, local government entities struggle to grapple with the problem due to insufficient and sporadic funding. The economic reality of this situation necessitates that the design of these homes and the construction process must conform to a frugal budget. In other words, the net cost of the materials utilized to produce the home must remain affordable.

The final criteria in feasibility is relative toxicity of the material. Certain plastics are known to release toxic chemicals under specific conditions. If one of the plastics being considered will release chemicals that will harm workers during the printing process, or families living in the home, it is not a viable option for consideration regardless of any promising material properties. Across all criteria, the overarching concern is that these homes are engineered ethically with regard to all aspects of the scope of the research.

2.2.1 Recyclability

The first fundamental question that immediately eliminates some plastics is “is it recyclable?” and additionally, “how difficult is it to recycle?” Table 2-2 outlines all the plastics considered with notes on their recyclability. Polylactic Acid (PLA) biodegrades and therefore generally considered not recyclable, both criteria immediately eliminating PLA from consideration. Plastics such as Polystyrene (PS or Styrofoam), Polyvinyl Chloride (PVC), Polymethyl Methacrylate (PMMA or Acrylic), Polyamide (PA or Nylon), Polyoxymethylene (POM) and Polycarbonate (PC) have potential for mass recycling in the future. However, the state-of-the-art recycling technology for these plastics remains complex and infeasible for scaling to immediately satisfy the demand of home production. This makes them unlikely candidates but does not entirely count them out. Low Density Polyethylene (LDPE), Polypropylene (PP), and acrylonitrile butadiene styrene (ABS) all have straightforward recycling processes, but difficulty sorting or cleaning leads to rejection by many recycling programs. By contrast, High Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) are accepted by almost every recycling program and have the most established recycling processes.

Plastic	Recyclability Notes
PET	Nearly every municipal recycling program in North America and Europe accepts PET bottles and containers [31].
PP	Easy to recycle but difficult and expensive to rid PP of the odor and staining of the previous product. As a result many recycling programs don't accept it [32].
HDPE	Accepted by the majority of recycling programs and one of the easiest plastics to recycle [11].
PVC	Difficult to get a uniform recyclate from mechanical recycling because there are many conflicting additives in different PVC products. PVC feedstock recycling uses chemical processes but is involved and more expensive than landfilling [33].
LDPE	While the mechanical process of recycling LDPE remains simple, LDPE often comes in plastic bags or films which can damage machinery at sorting Therefore, traditional recycling programs often reject accepting LDPE [14].
PS	PS is often dirtier than other products. PS usually cannot be recycled locally and needs to be transported to a centralized plant, increasing cost to recycle and decreasing incentive for companies to recycle [34].
PLA	Degrades under compost conditions in 180 days. Generally not recycled on a large scale but is technically possible [35]
PC	PC can be recycled in some cases, but it is capable of producing harmful chemical compounds which makes it highly unlikely to be recycled [13].
PMMA	Acrylic is one of the least recycled types of plastic because of the toxins that can be released during the process. Many recycling companies do not have the facilities or expertise to recycle acrylics [16].
POM	Thermoset plastic that should only be heated once, cannot be recycled [36].
PA	PA is difficult and costly to recycle. PA is melted at lower temperatures which won't kill or melt off contaminates so it needs to be cleaned more intensely than other plastics which is not always possible [37].
ABS	ABS is easy to recycle but not accepted by curbside programs and requires plastic to be sent to specific programs or recycled in house [13].

Table 2-2: Notes on how easily each plastic can be recycled if it is possible at all. Although many plastics have the capacity to be recycled it is often not economical because their processes are too involved.

2.2.2 Amount Produced

To ensure there is sufficient recycled plastic supply for homes, enough plastic has to be manufactured each year so at minimum, if all of it was recycled, the plastic production would meet demand. For example, to provide 400 million homes to inadequately sheltered individuals (assuming 1.6 billion shelter insecure live in groups of at least 4) over a 20-year period, further assuming a gross home weight of 5000lbs[1], some 50,000,000 tons of plastic needs to be recycled each year. The more conservative estimate is that 40 million homes would need to be manufactured over a 25-year period, bringing the necessary amount of plastic needed down to 4,000,000 tons. This means that PMMA (3.7 million tons/year produced [38]) falls below this mark, and if it was selected, it likely wouldn't be able to fulfill the demand in a reasonable amount of time. Other plastics, like PET (73 million tons/year [39]), PP (73 million tons/year [40]), HDPE (55 million tons/year [41]), and PVC (61 million tons/year [42]) have no trouble meeting demand, even on the higher end. LDPE (21 million tons/year [43]), PS (14.7 million tons/year [44]), PC (5.1 million tons/year [45]), POM (18.5 million tons/year [46]), PA (10.9 million tons/year [47]), and ABS (10.8 million tons/year [48]) have sufficient supply produced per year, but it would require a minimum 20%, and a maximum 78% recycling rate to meet demand which should be regarded as highly ambitious. Table 2-3 outlines the volume of each plastic produced globally per year.

[1] Weight estimates derived in "Design and Analysis of Additively Manufactured Recycled Polyethylene Terephthalate Floor and Footing for Dwelling House Construction" by John Malloy and "Structural Analysis of Building Panels using Polyethylene Terephthalate (PET)" by Tamilore Fashae [28,29]

Plastic	Volume Produced Per Year (Globally) (Tons)
PET	73,390,000 [39]
PP	73,700,000 [49]
HDPE	55,000,000 [41]
PVC	61,000,000 [42]
LDPE	20,900,000 [43]
PS	14,700,000 [44]
PC	5,100,000 [45]
PMMA	3,700,000 [50]
POM	18,500,000 [51]
PA	10,900,000 [47]
ABS	10,800,000 [48]

Table 2-3: Volume of plastics produced globally each year in tons. PET, HDPE, PP, and PVC and produced in significantly higher volumes than the other eight plastics.

2.2.3 Amount Recycled

Another factor that plays heavily into feasibility is how much plastic is currently being recycled. Measuring and quantifying the amount of plastic recycled indicates the level and sophistication of existing recycling infrastructure. Furthermore, the amount of plastic recycled alludes to how well people recognize it as a material to recycle and how reliably people do so. HDPE and PET both have high recycling rates in the US (18.5% and 4.7% respectively) compared to the other candidate polymers. Most of what is consistently recycled in the United States is bottles, and most bottles are made out of PET or HDPE, which contributes heavily to these statistics [3]. The remaining options have low or negligible recycling rates, due in part to the reluctance of most curbside recycling programs to accept or receive much beyond highly recognizable and easily sorted bottles. Although not impossible to implement recycling programs for plastics which are not currently recycled in large quantities, it presents a large obstacle for the selection of plastics not currently recycled at or near the desired rate. Consistent data on recycling rates doesn't exist worldwide. However, of data we have, USA recycling rates lie in the middle. If current US recycling rates were to project to average global recycling rates and assuming the goal would still be to produce 1.6 million homes a year (40 million homes over a 25-year period), the only plastics that could reasonably reach anywhere close this goal are PET and HDPE as verified in Table 2-4. Note these assumptions account for all the recycled plastic being used for the manufacturing of recycled homes which is unlikely to hold true in practice. On the other hand, the rate of manufacturing (1.6 million homes a year) will likely take years to scale up to and during this time the increased demand for recycled plastic will incentivize programs to increase recycling rates. Beyond these assumptions, this exercise serves as a sanity check of whether or not enough recycled plastic exists to meet demand.

Plastic	US Recycling Rate (%)	Volume Produced Per Year (Globally) (Tons)	Projected Amount Recycled (Globally) (Tons)	Maximum Houses/Year
PET	18.5 [3,52]	73,390,000	13,543,764	5,417,505
PP	0.2 [3,12]	73,700,000	145,007	58,003
HDPE	4.7 [3,52]	55,000,000	2,586,036	1,034,414
PVC	2.6 [15]	61,000,000	1,607,020	642,808
LDPE	N/A	20,900,000	N/A	N/A
PS	0.9 [53]	14,700,000	137,200	54,880
PC	N/A	5,100,000	N/A	N/A
PMMA	N/A	3,700,000	N/A	N/A
POM	N/A	18,500,000	N/A	N/A
PA	N/A	10,900,000	N/A	N/A
ABS	N/A	10,800,000	N/A	N/A

Table 2-4: The estimated amount of plastic recycled globally projected from US recycling rates and the resulting houses per year that could be produced assuming a 5000lb house. Many recycling rates are not available due to negligible quantities.

2.2.4 Cost

Cost drives the economic feasibility analysis of producing homes. Research indicates that recycled plastic is as or less expensive than the virgin plastic counterpart. From our initial structural analysis [28,29], it has been shown that a 200ft^2 home able to withstand typical weight, wind, snow, rain and live loading conditions, can be built using less than 5000lb of PET. If we plan to build homes which use between 5,000-10,000lbs of recycled plastic, and want to keep material cost under $2,500 (compared to the cost of $10,000 for just the materials of a traditionally built, 200 square foot house [54]) recycled plastic per pound must cost less than

$0.50 per pound, or $1.10/ kg. Consistent pricing data does not exist for all of the plastics under consideration. Therefore, for purposes of this analysis, virgin material prices will be used if the recycled material cost is unavailable. All plastics except PET, PP, HDPE, and LDPE exceeded the intended price both with its virgin and recycled prices. Table 2-5 lists the virgin and recycled cost of each plastic, as well as the materials cost for the house.

Plastic	Virgin Cost (per kg)	Recycled Cost (per kg)	Cost to Build House
PET	$0.33 [55]	$0.33 [56]	$750.00
PP	$0.26 [55]	$0.26 [56]	$590.91
HDPE	$1.15 [57]	$0.46 [56]	$1,045.45
PVC	$1.30 [58]	N/A	$2,954.55
LDPE	$0.86 [59]	N/A	$1,954.55
PS	$2.43 [60]	N/A	$5,522.73
PLA	$2.19 [61]	N/A	$4,977.27
PC	$3.97 [62]	N/A	$9,022.73
PMMA	$4.41 [50]	N/A	$10,022.73
POM	$2.48 [51]	N/A	$5,636.36
PA	$3.58 [63]	N/A	$8,136.36
ABS	$1.43 [63]	N/A	$3,250.00

Table 2-5: The cost of virgin and recycled plastic per kg and the resulting cost to build a 5000lb home. If available, the price was calculated with the recycled plastic cost but if not, the virgin cost was used.

2.2.5 Toxicity

Toxicity prevails as the most important ethical consideration of this material selection research. Specifically, toxicity concerns relate to thermal response to the sun, chemical reactions with the environment, general leaching of toxic chemicals from the plastic to people or the environment, and thermal response during 3D printing. Research by Harvard Health indicates that nearly all plastics leech trace amounts of endocrine disrupting chemicals over time into food and beverages kept in plastics containers. However, this leeching is unlikely to pose a high risk for use in a home as the released chemicals are not airborne. [64]. Additionally, it can be toxic to directly inhale fumes of any heated plastics, but the same precautions taken in manufacturing virgin plastic can be utilized for this application to the same degree of safety [64]. Overall, the plastics used consistently in food grade containers (e.g. PET, PP, HDPE, and LDPE) had little to no risk of toxicity in this context, as well as PMMA, POM, PA, and ABS [35,36,65,66]. However other plastics including PVC, PS, and PC produce the toxic chemicals DEHP, styrene, and BPA respectively, making them ethically dubious for use as a building material [65,67].

2.2.6 Narrowing Down

Table 2-6 provides an overview of how all the plastics performed among the five feasibility criteria previously defined in the form of a Pugh chart with PP as the baseline for comparison. Double negative and positives indicate extreme cases with plastics performing exceedingly well or poorly in certain categories. HDPE and PET performed extremely well under this evaluation. Based on the poor performance of the rest of the plastic types during this initial stage, the evaluation for the next two stages compares only HDPE and PET. If neither HDPE nor PET prove viable in the long run, future researchers should re-evaluate this analysis of feasibility criteria and down selection until a reasonable conclusion is met.

Plastic	Recyclability	Amount Produced	Amount Recycled	Cost	Toxicity	Score
PET	+	0	+ +	0	0	3
PP	0	0	0	0	0	0
HDPE	+	0	+ +	0	0	3
PVC	-	0	+	-	-	-2
LDPE	-	-	-	0	0	-3
PS	-	-	0	- -	-	-5
PLA	-	- -	-	- -	0	-6
PC	-	- -	-	- -	-	-7
PMMA	-	- -	-	- -	0	-6
POM	-	-	-	- -	0	-5
PA	-	-	-	- -	0	-5
ABS	0	-	-	-	0	-3

Table 2-6: Pugh chart comparing plastics on the feasibility criteria with PP as the baseline. PET and HDPE performed significantly better than rest of the plastics under consideration.

2.3 Chemical Structure

Prior to delving into the remaining comparative assessment of HDPE and PET, we must first examine their molecular structure and how this dictates the material properties they exhibit. Plastics generally contain long molecular chains and possess high molecular weight. The molecular weight of polymers ranges from tens of thousands up to several million atomic mass units. By contrast, water has a molecular weight of 18 atomic mass units [68]. The large molecular size contributes to large electrostatic forces between molecules, enabling plastics to withstand typical manufacturing forces from molding, drawing, and extrusion without falling apart [68]. Both PET and HDPE are thermoplastics, allows them to endure being heated, molded, reheated, and remolded repeatedly, though subject to thermal degradation over time caused by cyclical thermal effects. This process is made possible by the fact that the individual molecules within the plastic are separate from one another, meaning they can flow past each other when heated to allow this property [69].

2.3.1 PET Molecular Structure

The polymerization of ethylene glycol and terephthalic acid is a process which yields PET and produces water as a byproduct [70]. Therefore, PET classifies as a heterochain polymer, or a polymer that contains oxygen, nitrogen, or sulfur in their backbone chains, in addition to carbon [69]. The benzene (C6H6) ring present gives PET notable strength and stiffness. Drawing, a process by which the polymer chains align with one another in an orderly arrangement, further improves the strength and stiffness performance of PET [70].

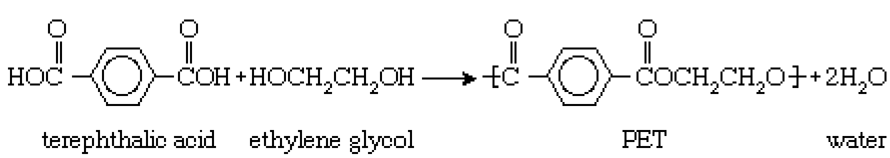


Figure 2-1: Creation of the molecular structure of PET, resulting in the benzene ring that defines key material properties of the plastic [69].

2.3.2 HDPE Molecular Structure

Cracking of ethane, which through polymerization, forms polyethylene by breaking the carbon double bond to link to another ethylene molecule. Ethylene (C2H4) forms successively, typically thousands of times, forming a chain resulting in a single polyethylene molecule. HDPE, the linear version of polyethylene, allows for denser molecule packing. LDPE, the branched version, results in less packing and a lower density material [71]. This linear structure makes HDPE a homochain polymer, having only aliphatic (linear) carbon atoms in the backbone chain. As a result of the linear chains, HDPE classifies as generally more crystalline than PET, meaning more of the HDPE molecules are arranged closely and in a discernible order and less are amorphous, or arranged randomly and intertwined. The amorphous portions of a polymer enter a rubbery and more elastic state above the glass transition temperature, where it takes reaching the melting point to introduce mobility to the crystalline portions of the plastic [69].

$$-\!\!\left[\, CH_2 - CH_2 \,\right]\!\!-$$

Figure 2-2: Section of an HDPE chain. The homogeny and repetition of the chain allows the highly crystalline structure [71].

2.4 Engineering Use Criteria

Building a structurally safe home from plastic which can withstand the wear and fatigue of daily use and environmental exposure requires predictable and consistent material properties. Especially with plastic, the form and strength of the home must withstand change in intense heat, cold, or minor natural disasters in order to keep its residents safe and to make it a desirable place to live. The material properties used to evaluate the engineering use of the home include overall strength, coefficient of thermal expansion (CTE), water absorption, glass transition temperature, and shore hardness. Overall material strength must ensure the home does not buckle or deflect substantially when subjected to internal or typical external loads (wind, water, snow, etc.). The CTE must remain low enough to avoid noticeable change in critical dimensions caused by varying thermal conditions such as those caused by the arc of the sun. The ideal plastic has no or low water absorption to avoid changes in material performance due to rain or floods. Furthermore, the glass transition temperature should far exceed the expected solar and thermal exposure in order to inhibit the onset of thermally induced premature creep. Lastly, the house has to have a high enough shore hardness that it doesn’t take noticeable damage from anything that hits its structure, whether it be rain, hail, or just moving furniture around.

2.4.1 Strength

An assessment of strength comes from a variety of different measures. These measures include tensile strength, compressive strength, yield strength, and flexural strength among other secondary measures. The compressive strength of the structural build material used in home construction proves crucial because most of the dead weight of the home puts the material in compression rather than tension. However, other strength measures remain crucial for niche areas of the structure. Table 2-7 outlines multiple strength values for HDPE and PET. Overall, PET possesses the highest strength values across the board. PET has higher compressive strength and tensile yield strength which indicates it will take more stress to yield the material in both compression and tension. The higher compressive, Young's, and flexural modulus means that PET remains stiffer and more rigid than HDPE when withstanding outside forces, which provides a sense of security to the family living inside.

	PET [72,73]	HDPE [74,75]
Compressive Yield Strength (MPa)	80	20
Compressive Modulus (GPa)	1	0.7
Tensile Strength, Yield (MPa)	60-85.5	23-29.5
Young's Modulus (MPa)	2800 - 3170	900 - 1550
Flexural Modulus (MPa)	3380	970- 1380

Table 2-7: Strength values of PET and HDPE at 23 degrees Celsius. PET exhibits strengths and stiffness properties considerably higher than HDPE.

2.4.2 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) determines how much the plastic expands when heated, and similarly how much it shrinks when cooled. Dwelling homes require building materials with low CTE to withstand large changes in daily or seasonal temperature exposure. Repeated thermal cycling causes material fatigue that leads to brittleness and premature degradation of material properties which drastically shorten the expected lifetime of the house [76]. Additionally, visually noticeable expansion or shrinkage of the home may alarm residents and make the home feel unstable, unsafe, and less desirable to live in. Table 2-8 includes a comparison of CTE values of the two contenders, and PET performs noticeably better than HDPE.

2.4.3 Water Absorption

A safe home must not substantially absorb water, especially during times of rain, flood, or snow. Absorption of water by the home typically causes noticeable and uncontrolled anisotropic expansion of the structural material exposed to water. This swelling consequently reduces the strength of the structural material in areas exposed to water. Both plastics considered have relatively low water absorption values (Table 2-8) when compared to a traditional building material such as wood (2%-8% [77]), or other plastics such as PS (up to 9% [78]) or PA (up to 13.5% [79]). Although not a determining factor between these plastics, water absorption characteristics must be examined further if the structural material ultimately differs from PET or HDPE.

2.4.4 Glass Transition Temperature

The glass transition temperature of the chosen material represents the approximate elastic behavior of the plastic under normal operating temperatures. Additionally, materials exposed to temperatures exceeding their glass transition temperature generally exhibit more creep than when operating below glass transition temperature [69]. Creep occurs when prolonged stress on the material causes the material to elongate or compress greater than initial results would indicate. For dwelling home construction, creep presents the largest concern to the compression of the walls of the house under its own weight, and sagging (elongation) of the roof over time [69]. HDPE has a glass transition temperature of -110C. Therefore, under expected home operating conditions, HDPE exists in a glass state indicating that the amorphous portion of the molecules persist in a rubbery state. [74]. PET has a glass transition temperature between 70C-80C. Therefore, PET tends to exhibit stiffer mechanical behavior over time when compared to HDPE while operating below PET glass transition temperature [72]. However, if the operating temperature exceeds the glass transition temperature of PET, then PET would perform more poorly compared to HDPE due to the higher percentage of amorphous molecules. Therefore, it remains of utmost importance to ensure that the structural build material remains at an acceptable temperature during use. [69].

2.4.5 Shore Hardness

The last point of comparison for engineering use criteria is shore hardness. Structurally, it remains one of the least important characteristics because shore hardness doesn't contribute heavily to the safety of the house. However, shore hardness plays a large part in the wear and tear of the home overtime, and how desirable the home seems to outside investors and potential residents, which remains an important aspect of this research. If a plastic with low shore hardness is chosen as the construction material, every time a harder material, such as furniture, hail, tree branches, or even an elbow, bumps against the inside or outside of the home it will leave a dent. After years of abuse from the elements and general use, the house could start to look unsafe and cause the residents and onlookers to question its integrity, even if the home is still structurally sound. The shore hardness of PET is higher than that of HDPE, ranging from 79-87 shore D hardness compared to the 50-76 range of HDPE [72,74].

	PET [72,73]	HDPE [74,75]
CTE x 10^(-5) (cm / (cm °C))	6.0-7.0	12.5 - 18.0
Water Absorption, 24 Hours Immersion (%)	0.07 - 0.1	0.01 - 0.03
Glass Transition Temperature (°C)	73-78	110
Shore Hardness D	79-87	50-76

Table 2-8: Structural material properties of PET and HDPE. PET performs favorably in everything except water absorption.

2.5 Processing Criteria

This research aims to create homes rapidly through additive manufacturing, using large scale pellet extrusion 3D printers such as the BAAM, as previously mentioned in the introduction. To accomplish this, the material selected must withstand and perform well under typical processing conditions during extrusion 3D printing. Material properties critical to processing include melting point, thermal expansion, shrinkage, post-extrusion crystallization rate, and inter-layer adhesion. A number of studies have 3D printed both virgin and recycled HDPE and PET. These studies serve as a baseline for what challenges may arise when 3D printing these materials on a larger scale. [80–85].

2.5.1 Melting Point

The melting point of a plastic indicates the temperature at which the material flows uniformly and extrudes consistently through the nozzle. The main concern surrounding melting point for 3D printing of plastics remains the energy consumption. A lower melting point plastic consumes less energy over time, especially for the large-scale use over the extended period of time this application demands. HDPE (126C-135C) possesses a melting point substantially lower than that of PET (255C) [73,75]. However, as previously noted, the lower glass transition temperature and melting point contribute to larger problems related to overall structure and longevity of homes in warmer climates. The range of temperatures at which the material melts and flows is also an important consideration. Although both PET and HDPE have about a 10C range of ideal operating temperature (245C-255C and 180C-190C respectively), studies cited report more difficulty controlling PET's range of optimal temperatures than HDPE's range [81,86]. However, these studies fail to demonstrate the root cause of the stated difference. Researchers theorize that PET's higher thermal requirement causes the difference, concluding that additional insulation may close the gap. Further investigations are warranted to justify any further conclusions.

2.5.2 Coefficient of Thermal Expansion

Exconde, Co, Manapat, and Magdaluyo's research argues that materials with low CTE have less challenges during 3D printing processing [83]. Materials with a high CTE move along the extruder before it has fully melted, which causes compressive stresses on the extruder, affecting the internal friction of the system and efficiency of extrusion [83]. Additionally, materials with high CTE expand considerably upon extrusion and shrink considerably during cooling. When not precisely controlled, the shrinkage caused by rapid cooling causes uncontrolled warpage and distortion of the 3D printed materials. Even when adhesion overcomes warpage tendencies, internal stresses remain in the solidified bulk material. As previously described in section 2.4.2 HDPE possesses a higher CTE than PET and the tendency towards high warpage and low adhesion after 3D printing [81]. On the other hand, PET possesses high self-adhesion and low warpage, making it favorable under these criteria. The lower relative CTE of PET compared to HDPE indicates PET yields higher quality parts. [86].

2.5.3 Crystallization Rate

Crystallization rate describes the rate at which a non-solid material solidifies. The degree to which a material crystalizes depends on the rate of cooling [87]. Precise control of the rate of cooling remains an area of key concern, especially when 3D printing rapidly and continuously. If the previously printed layer fails to crystalize prior to the deposition of the subsequent layer, the resulting interface typically distorts yielding part imperfections. PET possesses a lower crystallization rate than HDPE, due in part to the extrusion temperature difference [86]. Despite the challenge low crystallization rate presents, these issues are solvable. Reducing the print speed or adding talc greatly reduces crystallization problems for minimal added cost [86].

2.5.4 Extrudate Uniformity

Numerous factors directly and indirectly affect the uniformity of the extrudate as it exits the nozzle. The uniformity of the extrudate represents a strong indication of how well the material performs during the extrusion process and serves as an indicator of process variation, calculated by measuring the output diameter after extrusion through the nozzle [83]. Other issues which cause non-uniform extrudate include contaminants in the material source, incorrect extruder screw speed, and uncontrolled variation in nozzle temperature [83]. Non-uniform extrudate leads to issues with self-adhesion and overall finish of 3D printed parts. In conclusion, filament diameter is not a critical processing criteria for material selection; however, it remains a key consideration worth further attention and investigation to evaluate performance during setup and blend testing in future research [81].

2.6 Selection of PET

Based on all three categories of evaluation, feasibility, engineering use, and processing, PET prevails as the material for further investigation. PET performed favorably in every category except for crystallization rate and melting point. The largest contributing factors to PET’s selection are the recycling rate, glass transition temperature, and overall strength assessment, which were the categories with the largest difference in values that simultaneously posed the most risk in regard to success or failure of the project. Table 2-9 outlines all the criteria previously discussed and used in making this conclusion.

	Property	PET	HDPE
Feasibility	Recyclability	0	0
	Amount Produced	+	0
	Amount Recycled	+	0
	Cost	+	0
	Toxicity	0	0
Engineering Use	Strength	+	0
	Coefficient of Thermal Expansion	+	0
	Water Absorption	0	0
	Glass Transition Temperature	+	0
	Shore Hardness	+	0
Processing	Melting Point	-	0
	Coefficient of Thermal Expansion	+	0
	Crystallization Rate	-	0
	Uniform Extrudate	0	0
	Score	6	0

Table 2-9: Comparison of PET and HDPE on feasibility, engineering use, and processing criteria. HDPE serves as the baseline and PET performs favorably in almost all categories.

Chapter 3: Design of Extrusion Test System[2]

To confirm the material selection conclusion and the suitability of recycled PET instead of PET, the MIT HAUS group developed an experimental setup to extrude rPET into filament for further extrusion characterization and material property testing.. Figure 3-1 depicts a setup diagram, Table 3-1 contains the setup inventory, and Figures 3-2 and 3-3 present prototype wiring diagrams. This testing setup leverages a small-scale extruder to create extrudate samples from the recycled plastic for further characterization and testing. This setup does not perfectly represent the operating conditions of a BAAM or LSAM; however, the small-scale pellet extruder represents a better physical analog than typical FDM filament extruders.

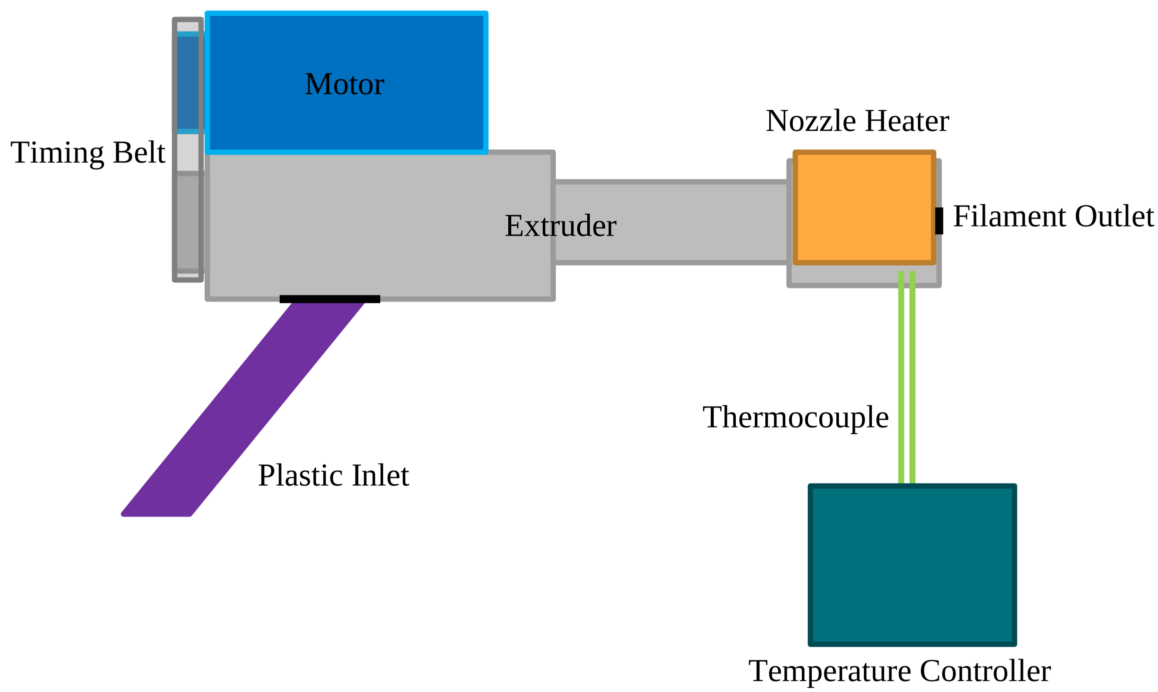


Figure 3-1: The planned extruder setup. The plastic pellets feed through the inlet and some melting takes place through mechanical shear at the screw-pellet-barrel interface. The extrudate is then brought up to a controlled temperature as it approaches the temperature-controlled nozzle heater prior to formation of the extrudate.

[2] Due to COVID-19 restrictions, setup and wiring diagrams were not completed or tested within the scope of this work. Therefore, all figures and tables in this section remain incomplete and only serve as a starting point recommendation for future experimentation.

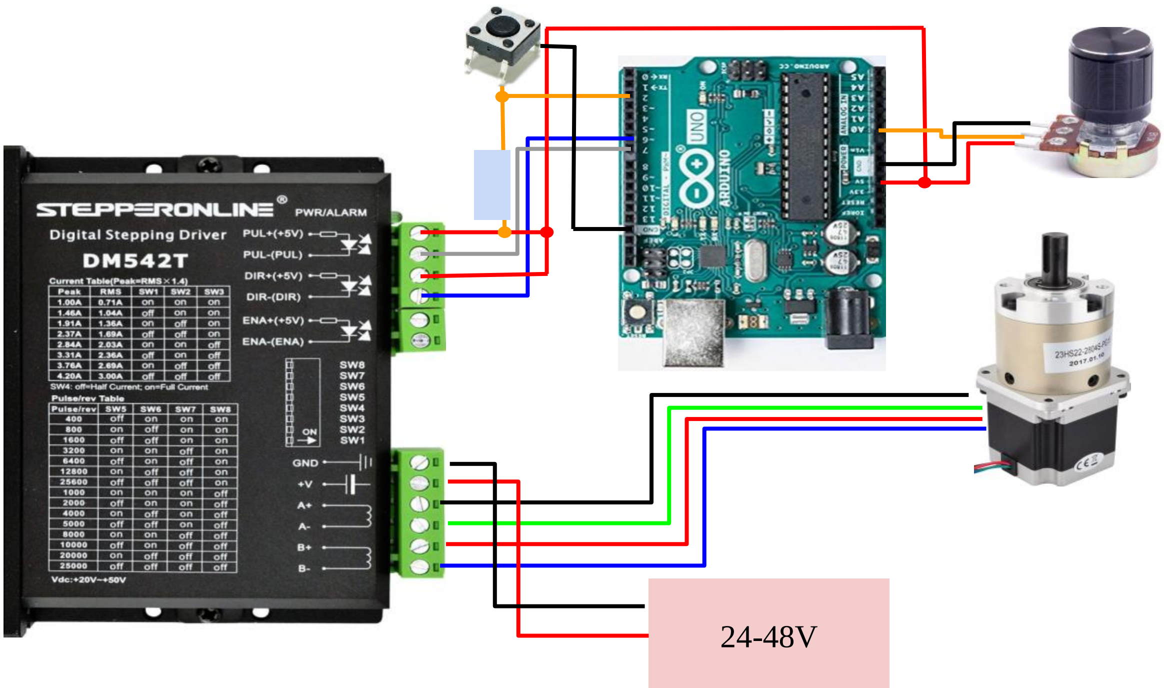


Figure 3-2: Partial wiring diagram for the motor control system. Due to COVID-19, most grounding is not included and the wiring could not be completed or tested. Unlabeled are pictured and labeled in Table 3-1.

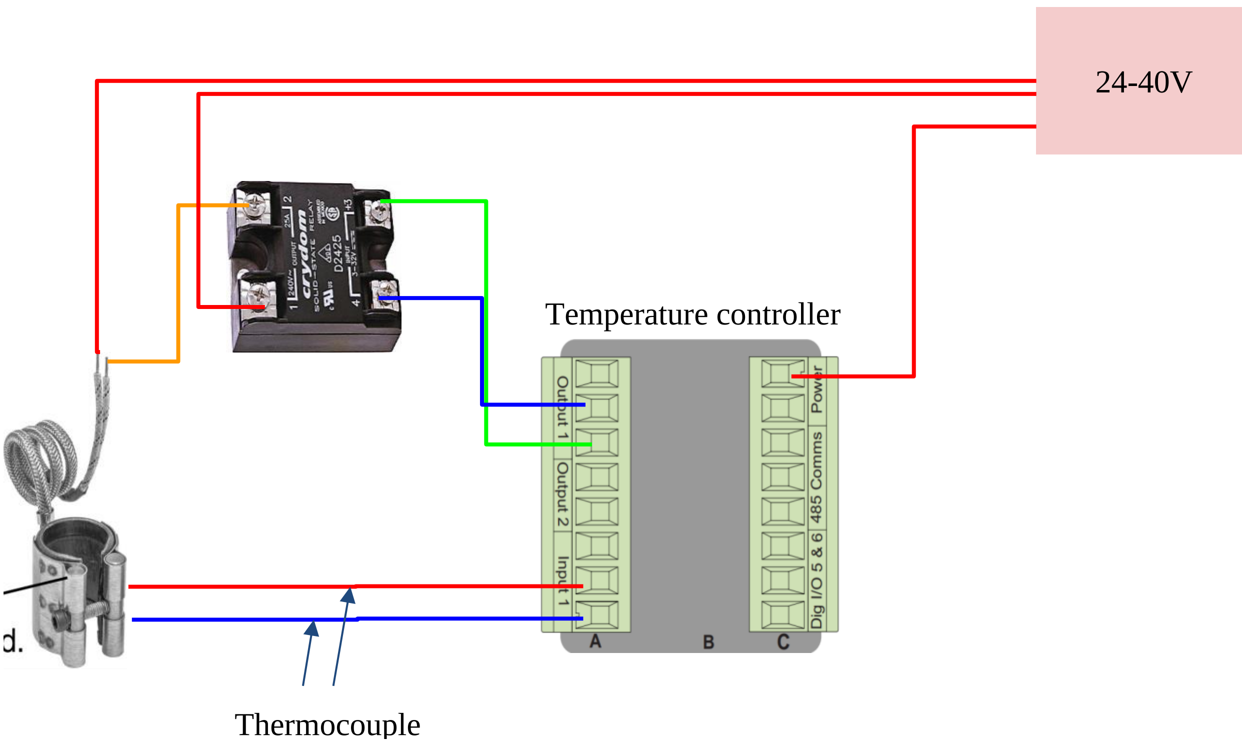


Figure 3-3: Partial wiring diagram for nozzle heater control. This setup also remains incomplete and untested as of the publication of this work due to COVID-19.

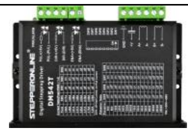
Picture	Equipment	Product Name
	Microcontroller Board	Arduino Uno [88]
	Motor Driver	Stepperonline Stepper Motor Driver DM542T [89]
N/A	Extruder	Beta prototype from Cincinnati Incorporated
	Stepper Motor	Stepperonline 15:1 Planetary Gearbox Nema 23 Stepper Motor 2.8A [90]
	Temperature Controller	PM6C1CC-1AAAAAA Watlow EZ-ZONE PID Controller, 45 mm x 45 mm, 240 V, menu type A [91]
	Nozzle Heater	McMaster Nozzle Heater with Mineral Insulation, 240V AC, 1.5" OD [92]
	Timing Belt	Gates 100XL037 PowerGrip Timing Belt, Extra Light, 1/5" Pitch, 3/8" Width, 50 Teeth, 10" Pitch Length [93]
	Timing Belt Pulley	Uxcell Aluminum XL 20 Teeth 12mm Bore Timing Belt Pulley Flange Synchronous Wheel 10mm Belt [94]
N/A	Power Supply	N/A
N/A	Switch	N/A
N/A	Potentiometer	N/A
N/A	Solid State Relay	N/A
N/A	Thermocouple	N/A

Table 3-1: Setup inventory for the proposed experimental setup. Items without a specific product name are not yet decided on. The specific kind is insignificant as long as it meets power and range specifications.

3.1 Testing Criteria

The planned testing and measurements included filament diameter, water absorption, tensile testing, and creep testing. The combination of these tests serves as an indication of both the quality of the setup and the performance of the extruded material.

3.1.1 Filament Diameter

As previously discussed, uniformity of filament diameter provides insight into any errors in the extruder setup, indicating issues involving temperature control, contaminants in the material source, incorrect extruder screw speed, and reduced nozzle temperature. The author recommends testing filament diameter by running the extruder for a predetermined period of time, allowing the extruder to reach steady state. Once the extruder reaches steady state, begin sampling the extruder output with a designated amount of time in between each sample. Once the samples cool to room temperature, measure the diameter multiple times along the length of each sample using a well calibrated contact micrometer or contactless micrometer. Analysis of the data yields insights into the uniformity of the samples and the quality of the experimental setup [81].

3.1.2 Water Absorption

Water absorption testing evaluates how the water absorption of the extruded plastic differs from the virgin PET values. Results from this testing indicate whether or not water absorption values remain in an acceptable range for dwelling home applications. The author recommends that water absorption experiments adhere to ASTM D570 which involves preparing test specimens to have a length of 50 ± 2 mm, drying them in an oven for 1 hour at 110 C for conditioning, and immersing them in a container of distilled water and maintained at 25 ± 1 C for 24 hours. Once fully submerged, withdraw the specimens from the container and wipe off all surface moisture with a dry cloth. Next, weigh the specimen to the nearest 0.001g and place back in the water. Repeat this drying and weighing process every 24 hours for 7 days to determine the total water absorbed when substantially saturated [81]. To determine compliance as a building material, we must estimate the amount of water the house absorbs based on home dimensions and the water absorption percentage obtained from testing.

3.1.3 Tensile Testing

Tensile testing on the extruded filament determines how strength values compare to those in other research on rPET filament, as well as the strength values of virgin PET. Through tensile testing with ASTM D3379-75 standards, we calculate the yield strength and Young's modulus for the filament specimens. Conduct initial tensile testing on filament samples. If testing yields promising results, conduct a 3D printing tensile testing experiment on 3D printed type V tensile bars in accordance to ASTM D638 as well as DMA bars (35 mm × 12.5 mm × 2 mm) [95]. The experimental procedure should include tensile specimens 3D printed in various directions and orientations. Typical extrusion 3D printing parts exhibit anisotropic mechanical behavior, specifically possessing lower tensile strength in the direction of the layers. Therefore, determining the reduction in strength with 3D printed recycled PET in all directions is necessary for moving forward with the project [96]. The results of this testing yield material performance data necessary to accurately model and simulate structural performance. The results further inform design decisions related to 3D printing orientation and design for assembly.

3.1.4 Creep Testing

As mentioned previously, creep indicates long term structural performance of the home, especially in warmer climates where plastic likely exhibits varying degrees of creep. 3D printed creep specimens must adhere to ASTM D2990-17 specimen standards. These should then be sent to a testing facility to go through ASTM D2990 testing, which will test tensile, flexural, and compressive creep and creep rupture for plastics [97]. The author recommends partnering with third parties specializing in creep testing because creep testing equipment is highly specialized to meet the needs of long duration testing, sometimes exceeding 1000 hours [98].

3.1.5 Other Tests

The author also recommends testing several other material properties with time and resources permitting. Other material properties relevant for this project include compressive strength, compressive modulus, flexural strength, flexural modulus, glass transition temperature, melting point, coefficient of thermal expansion, crystallization rate, and shore hardness. These are all material properties used to make the initial decision to further investigate PET as the primary structural material for the MIT HAUS project. The author recommends completing this analysis in order to evaluate the 3D printed rPET performance as compared to the performance of virgin PET. Should the results from this additional testing yield values which vary significantly from virgin material values, the author recommends reevaluating the initial material choice.

Chapter 4: Future Testing

After validating the hypothesis that recycled PET coming from a materials processing facility performs to an acceptable level when 3D printed, conduct further experiments to test both the recyclate processing conditions and possible fillers. Recyclate processing conditions should include cleaning method treatments and granule uniformity treatments. Additive and filler testing should include treatments of fiberglass, carbon fiber, talc, cellulose fiber, and any other materials found in abundance in target geographies.

4.1 Recyclate Processing Conditions

Testing different recyclate processing conditions and the effect they have on the performance of the plastic provides insight into the feasibility of low-cost low-tech micro-factories which produce recycled PET. If demonstrated as feasible, PET can be dropped off or collected for the same facility that 3D prints the homes. Locally sourcing and producing rPET possesses the potential to reduce both purchasing and transportation costs when compared to purchasing rPET from third party vendors outside of the target geography. The amount of cleaning and processing plastic requires before printing to produce an acceptable material gauges how much industrial equipment is necessary to set up a possible processing facility. The best-case scenario is that plastic just needs to be sorted and fed into the 3D printer without removing labels or washing, reducing costs associated with the traditional cleaning and refinement processes of recycling facilities.

4.1.1 Cleaning Method

As discussed in the introduction, the normal cleaning process for recycled PET is extensive. Common industry practice demonstrates that PET is often washed first to remove labels and adhesives, sorted, inspected, shredded, and friction washed again [10]. For testing the cleaning methods, one of these steps is taken away at a time (except shredding) and material performance tested to see their effect. Then, combinations of these steps would be removed until eventually unwashed bottles are shredded and extruded. These tests indicate how contaminants, mixing colors, and container labels affect the performance of the material when 3D printed. A test monitoring bacteria and mold growth is also required in assessing viability outside the ones previously discussed. Without cleaning the PET fully, there remains a high possibility that organic matter residing in the bottles will grow on the walls of the house if they survive the heat of extrusion which proves detrimental to the health of those living in the house.

4.1.2 Granule Uniformity

The size, shape, and uniformity of the granules put into the 3D printing process directly contributes to material performance. Figure 4-1 exemplifies the difference in uniformity between what most material processors call a "flake" and a "pellet." Flakes are shredded PET, with the same thickness of the original container, so each flake has a different thickness, and they also display a variety of size based on how the material was shredded. Flakes can also exhibit slightly different material compositions depending on what additives contribute to their original product. Pellets are processed from flakes, and exists as a more refined and uniform product. Flakes are melted down, mixed, and extruded through a die to make pellets. Uniform extrusion makes pellets easier to work with for manufacturing plants because they all melt and process at a similar rate with a more similar material composition. If adequate structural properties are obtained by 3D printing flakes as opposed to pellets, significantly less processing is necessary, further reducing cost and barriers to local material recovery. To test this, PET should be shredded with different methods that result in varying sizes, and the extruded material tested against the results from PET pellets. Some of the most important differences beyond overall strength characteristics may come from filament uniformity as any unmelted portions or differences in additive distribution results in non-uniform extrusion issues.

Figure 4-1: Flake size and shape (left) vs. pellet size and shape (right). Pellets are manufactured resulting in uniformity while flakes have greater variation [99,100].

4.2 Additives and Fillers

Fillers have the potential to improve material strength, reduce weight, or reduce cost of the home among other advantages. Each target geographic region has different levels of access to filler materials, so it remains important that the homes are manufacturable without any fillers. However, in areas where fillers are available locally and provide benefits to the construction process, their effects require thorough testing on lab scale before implementing them in the field. Buying fillers locally also helps stimulate local economies while reducing transportation costs.

4.2.1 Talc as an Additive

One of the biggest drawbacks to using PET remains the recorded issues it has with crystallization rate as discussed in section 2.5.3. Having a lower crystallization rate necessitates a slower print speed, which slows production and increase operating costs in the long term. Previous research found this issue remedied by using talc as an additive in a ratio of 5% [86]. The cost of talc ($0.10-$0.36/kg), is comparable to the cost of recycled PET ($0.33/kg), so the largest costs for adding talc exists in sourcing, transportation, and the cost of the additive feeder required to add talc at the appropriate feed rate [101]. The issues with crystallization rate may worsen with a larger extrudate due to the increase in cooling time, but the increase in time it will take the nozzle to travel back to the same spot could offset this issue. If crystallization rate becomes a limiting factor, perform testing on adding talc in different ratios to confirm positive crystallization rate results. Additionally, material properties testing must confirm compliance with necessary values.

4.2.2 Glass Fiber as an Additive

Glass fibers have historically increased stiffness and strength in plastics. Research further indicates adding glass fiber to PET filament for 3D printing results in a significant increase in tensile strength [95]. This is potentially beneficial for material property improvement of PET, however the cost of glass fibers is ~$2/kg, making it significantly higher than the cost of PET ($0.33/kg) and therefore increasing the cost of the house dramatically if added to the entire structure [39,102]. The application of glass fibers in areas that require more reinforcement, such as corners, edges, and doorways could prove beneficial in terms of overall structural integrity.

However, addition of glass fibers will require the same rigorous material property testing as previously listed before confidence for building use can be instilled.

4.2.3 Other Additives and Fillers

There are countless other additives that offer promise for use in this application. The incorporation of other plastics could test how much acceptable variation can occur in the sorting process [103]. Mixing recycled cardboard with plastic feedstock could explore the effect on weight and serve as another way to incorporate recycled material into the homes [104]. Biochar, a byproduct created from packing peanuts, shows potential for increasing desirable properties in PET during 3D printing and could be incorporated to improve house longevity [105]. These additives and more all show promise, but ultimately it will depend on the results of initial testing to determine what, if anything, will ensure the best possibility of success for these homes.

Chapter 5: Summary and Conclusion

Homelessness and plastic waste remain pervasive issues in today's global climate, with an estimated 1.6 billion individuals living with inadequate shelter and an estimated 6.3 billion tons of plastic waste in our environment. Homes manufactured rapidly with large scale additive manufacturing exist as a promising solution to the homelessness crisis, but this solution currently focuses mainly on concrete mixtures as a construction material. By combining large scale additive manufacturing of low-cost homes with the material choice of recycled plastic, this research proposes a solution at the intersection of the problem spaces of homelessness and plastic waste.

This thesis defines the criteria necessary for the selection of a recycled plastic type for the use of producing low cost homes using additive manufacturing. This thesis further refines these criteria into three categories: feasibility, engineering use, and processing. Through comparison of materials against these criteria, PET is identified as the best choice for further testing and experimentation to confirm its viability as a structural material choice for dwelling home construction. Overall, global production and recycling occur in substantial quantities to provide enough material to meet the housing need. Furthermore, PET possesses strength and durability characteristics capable of serving as a structural build material. Lastly, PET performs favorably under additive manufacturing processing conditions.

This thesis proposes, outlines, and details a preferred experimental framework for testing extrusion and large-scale additive manufacturing of rPET. Should initial test results confirm that rPET performs similarly to the material properties of virgin PET used to make the material selection, future testing should include different methods of creating the recycled feedstock and additives to improve the material performance, including fiberglass, carbon fiber, talc, and cellulose fiber.

Once testing is complete, the next milestone for this research is to create a lightweight, affordable, home printed in rPET with large scale additive manufacturing, along with the necessary plans to scale up manufacturing and reach the areas most in need of these homes. Both the BAAM and the Thermwood LSAM provide a large enough build volume and high enough feed rates to accomplish economically 3D printed homes. Furthermore, further technological innovation will only serve to improve 3D printer performance, and provide even more promising estimates for feasibility of future research.

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