Third Progress Report: PET Wheelchair Design
Team Sustainability

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1. Executive Summary

Roughly 20 million people who require wheelchairs for mobility do not have access to them. Many of those who do have access do not have an appropriate wheelchair. This is especially an issue for disabled people in developing and rural areas where medical services are not readily available. Existing high quality, lightweight wheelchairs are commonly priced around $5,000, and more affordable wheelchair designs often do not meet basic desired qualities such as durability, comfort, and weight requirements. Even affordable wheelchairs are not modular and cannot be taken apart easily, making shipping to remote locations very costly. To address this issue, a team of mechanical engineers is developing a wheelchair design that incorporates PET material for a sustainable, affordable product. If the wheelchair is modular and can be broken down to be packed more efficiently, the shipping cost will be reduced. Another option is to design the chair so that it can be made locally in developing countries, almost entirely eliminating the need for long-distance shipping. The developed wheelchair design must account for the important functions of the chair including weight capacity, mobility, transportability, and user comfort. The goal is to identify a design that can incorporate PET but still achieve the durability and strength that would be expected from typical steel or aluminum frames.

In order to compare various design concepts, the team is using Autodesk Fusion 360 which has structural analysis capabilities. To begin, chair components were correctly dimensioned according to anthropometric data. Before using generative design, wheelchair sub-components were analyzed using FEA. Then the team input various specification inputs such as materials, manufacturing methods, and geometric constraints, loads and the software generated iterations of possible design solutions. This method has been used to select a design that best achieves the requirements outlined by the project sponsor. To verify that the final design is acceptable it must be prototyped and analyzed so that the performance metrics can be checked. The final wheelchair must have a minimum lifetime between three to five years, and it must be capable of carrying a person of 160 pounds. In order to be considered a lightweight device, the chair itself must weigh less than 25 pounds to ensure ease of movement for the user. If the PET wheelchair design generated by the software can successfully meet all of these requirements, the next steps would be prototyping a model. Because there are multiple risks associated with the selected design, the team will likely have to continue making edits to the generated design to achieve the desired results. After prototyping, the final steps would be to finalize manufacturing methods as well as to improve upon possible problem areas in the current features.

2. Nomenclature

a. ADA (Americans with Disabilities Act)
b. ANSI (American National Standards Institute)
c. Caster: A single or set of small wheels that help the wheelchair swivel and maneuver
d. FEA (finite element analysis)
e. ISO (International Organization for Standardization)
f. PET (polyethylene terephthalate)

3. Main Body

3.1 Introduction and Background

The design problem is to create a proof of concept for a sustainable, affordable wheelchair with the material properties in consideration. If 3D printing is chosen as a manufacturing method, the design should be able to be downloaded in any location with a 3D printer available and printed locally. This would solve the logistical issues that arise with shipping fully assembled product made from mass production. There is currently no effective way to efficiently pack many wheelchairs for transport and these additional costs quickly make mass production and preassembly a cost-ineffective production method. Concepts to consider for this project include the size limitations of standard manufacturing methods including 3D printers and extrusion machines; a whole chair cannot be printed in one run, rather it should be broken into parts that can be assembled with minimal or, ideally, no tooling. This also is beneficial in certain unforeseeable situations such as power loss in areas with unreliable electrical grids; only certain parts need to be reprinted rather than the whole chair being restarted if power is to go out. This modularity would compromise some structural integrity, but FEA and other simulation analysis will be conducted to find a frame shape that balances these different aspects.

The intended user is a person averaging 160 lbs., a weight specified by the client, who lives in a country where wheelchairs are not easy to obtain. The wheelchair is to be used manually — no motors or any electrical products will be involved. Instead of creating new plastic wheels, bicycle wheels are to be repurposed to have an attached handle; this handle would be the only part of the wheel that is manufactured. Other functions that will be included in the design are: a footrest, a seat (not including the seat cushion), back support, the frame itself, casters and potentially a small storage space under the seat. This project will produce a small-scale prototype showing that PET plastic or other sustainable material can be viable for creating a wheelchair along with simulations and the associated analysis showing whether this is possible and how. The details of the thought process in creating the design will be discussed in more detail.

This report will outline the design process to create the wheelchair specified by the sponsor. It is important to first explore existing products and applicable patents, as well as codes and standards that apply to wheelchairs in order to ensure that legal action cannot be taken against the finalized product. It is then necessary to evaluate the customer requirements and engineering specifications that should be prioritized in order to facilitate the function to form design process. Market research will then be conducted to observe existing solutions to the problem being addressed. The design process will then be described with the development of a morphological chart to address the needs developed in a function tree in order to facilitate design concept ideation. From this ideation stage a singular design is selected which is recreated with CAD and then analyzed using FEA in order to ensure the design is feasible. In addition, Generative Design is utilized to finalize the design and optimize the structure of the product as much as possible.

3.2 Existing Products, Prior Art and Applicable Patents

There are hundreds of existing wheelchairs on the market. The frame of the wheelchair is categorized primarily as dual tube or monotube. Figure 1 shows a popular monotube wheelchair with a single foot platform and casters to the side of the platform [1]. This wheelchair base cost is $2,400 without any customizations and weighs 17 lbs. Figure 2 shows a sports wheelchair that has a sturdier frame and angled wheels [2]. It has wider aluminum tubes and also features the dual tube design. The price of this wheelchair is not disclosed online. Figure 3 displays a Steel Transport Wheelchair [3]. This wheelchair requires someone else to push them around; the wheels do not have to be at arm's length. It has a steel frame and has adjusted armrests. This wheelchair costs $93 online. Figure 4 is a 3D, generative design wheelchair from Disrupt Disability [4]. This wheelchair is in its prototype phase and does not have a listed price. This wheelchair is intended to be modular and have the seat switched out depending on the user. Figure 5 showcases a new wheelchair on the market that is propelled by a hand pushing motion [5]. It has rear-wheel steering compared to most wheelchairs that are front wheeled. It is estimated that about 90% of wheelchairs are push-rim propelled which is physically straining to the shoulders, wrists and hands. The scooter is considered more ergonomic for the users than traditional wheelchairs because of its efficient biomechanical design. The total marketspace is not limited to these wheelchairs, but these include common aspects for wheelchair design as a whole which the team can draw upon for ideas.

Figure 1: Colours Razer Blade Wheelchair [1]

Figure 2: Hammer Sports Wheelchair [2]

Figure 3: Steel Transport Wheelchair [3]

Figure 4: 3D, Generative Design Wheelchair [4]

Figure 5: ROTA RoChair Mobility Scooter [5]

While collecting information about other existing wheelchairs, it was also important to perform a patent search to prevent patent infringement as well as find ideas from old patents that could be used to create future designs. Because wheelchairs are a relatively old technology, most patents related to their design are either expired or outside of the goal of this project (power chairs, etc.). With all of this considered, a few patents were identified that could be of use for both the conceptual and final design stages. The first one is shown in Figure 6, which details a multi-part seat comprising a softer, foam insert into a harder plastic base [6]. In the likely case the seat is manufactured using 3D printed plastic, this multi-part seat design may be useful in increasing the comfort of the user.

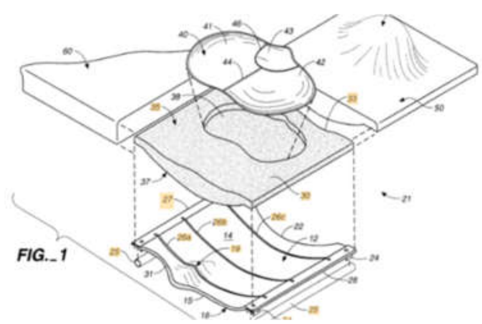


Figure 6: Wheelchair seat assembly with contoured seat pan US5857749A - 1996[6]

A second patent, shown in Figure 7, describes how a standard wheelchair can be broken down into multiple nearly planar pieces [7]. This type of design could be ideal for the team's purposes as it would break down, making both shipping and assembly significantly better. Unfortunately, this is one of the few wheelchair patents that is still active, so the team cannot use these ideas directly. However, it could still be used for the basic ideas to implement a unique locking mechanism instead.

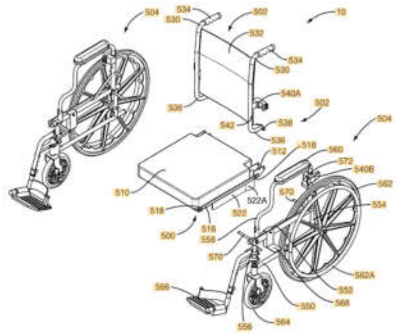


Figure 7: Convertible wheelchair having removable side frames US8196950B2 - 2006[7]

One last patent, shown in Figure 8, shows a wheelchair adjustable in both height and width using slide-and-lock rails and pins [8]. Although the initial design is specified to a weight group, it would be useful to have mechanisms that can adjust for overall size as this would significantly improve user comfort and posture.

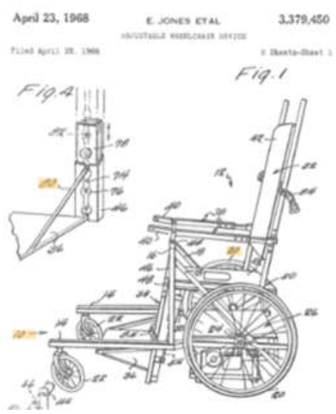


Figure 8: Adjustable wheelchair device US8196950B2 -1966[8]

3.3 Codes and Standards

Codes that are relevant to the wheelchair testing and usage are listed in Table 1. Indices 1:16 list the ISO standards which have ANSI equivalents [9]. These codes are voluntary for wheelchair manufacturers and are utilized to set standards for testing processes associated with wheelchair function, durability, and set up. Indices 17:22 refer to ADA standards associated with the infrastructure requirements for wheelchair accessible areas [10]. While there are not codes developed that directly deal with the design and manufacture of wheelchairs, the standards listed in Table 1 may be extrapolated to develop engineering requirements for the finalized design.

Table 1: Relevant Codes for Wheelchair Design[9][10]

	Code
1	ISO / TC 173 Assistive Products for Persons with Disability / SC 1 Wheelchairs
2	ISO/TC 173/SC 1/WG 1 Test Methods – Work Program
3	ISO 7176-1 Wheelchairs – Part 1: Determination of static stability
4	ISO 7176-3 Wheelchairs – Part 3: Determination of effectiveness of brakes
5	ISO 7176-5 Wheelchairs – Part 5: Determination of dimensions, mass and maneuvering space
6	ISO 7176-7 Wheelchairs – Part 7: Measurement of seating and wheel dimensions
7	ISO 7176-8 Wheelchairs – Part 8: Requirements and test methods for static, impact and fatigue strengths
8	ISO 7176-11 Wheelchairs – Part 11: Test dummies
9	ISO 7176-13 Wheelchairs – Part 13: Determination of coefficient of friction of test surfaces
10	ISO 7176-15 Wheelchairs – Part 15: Requirements for information disclosure, documentation and labeling
11	ISO 7176-20 Wheelchairs – Part 20: Determination of the performance of stand-up wheelchairs
12	ISO 7176-22 Wheelchairs – Part 22: Set-up procedures
13	ISO 7176-26 Wheelchairs – Part 26: Vocabulary
14	ISO 7193 Wheelchairs – Maximum overall dimensions
15	ISO 13570-1 Technical Report: Guidelines for the application of the ISO 7176 series on wheelchairs
16	ISO 13570-2 Technical Report: Wheelchairs – Typical values and recommended limits or dimensions, mass and maneuvering space as determined in ISO 7176-5
17	ADA Ramp Specifications Require a 1:12 ramp slope ratio which equals 4.8 degrees slope or one foot of wheelchair ramp for each inch of rise. For instance, a 30 inch rise requires a 30 foot handicap wheelchair ramp.
18	ADA Guidelines Require a Minimum 5' x 5' Flat, unobstructed area at the top and bottom of the ramp.
19	ADA Standards Require wheelchair ramps to have a Minimum width of 36 inches of clear space across the wheelchair ramp. Massachusetts and California ADA code now require 48 inches ramp width to be an ADA compliant ramp.
20	ADA Code Compliance Require a Minimum Turn Platform size of 5' x 5'. California ADA ramp code now requires a minimum 6 foot (in the direction of travel) platform size.
21	ADA Guidelines for Wheelchair Ramps allow a Maximum run of 30 feet of wheelchair ramp before a rest or turn platform.
22	ADA Ramp Guidelines Require ADA Ramp handrails that are between 34" and 38" in height on both sides of the wheelchair ramps.

3.4 Customer Requirements and Engineering Design Specifications

As shown in Figure 9, Coca Cola ultimately has the greatest ability to provide resources to enable possible production of the team's designs. As a company with an interest in sustainable efforts, it promotes the use of PET recycled products.

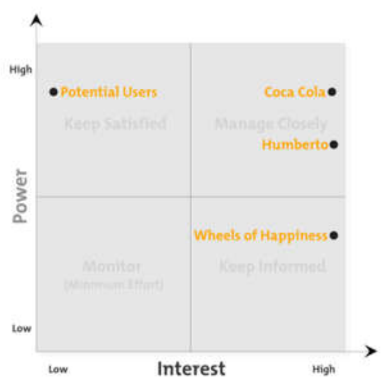


Figure 9: Stakeholder Analysis for Sustainable Wheelchair

The disabled persons that the design is catering to would be more concerned with the affordability of the wheelchair than whether it is made sustainably. In addition to a low cost, user function priorities include chair comfort, strength, mobility, and transportability. To ensure that comfort needs are being met, the wheelchair must be designed to account for user pressure points as well as the ergonomic data for both the 95th percentile man and 5th percentile woman.

Making a comfortable chair requires careful selection of the footrest, bike wheel grip, brake grip, and backrest. The user would interact with these components by either resting on them or handling them. Seat width is important because a width too small would restrict the user, and a width too large would enable slouching and possibly lead to asymmetrical posture. The angle between the seat and backrest should be around 100 degrees to allow the user to comfortably rest against the back. The backrest should be 17 to 18 inches tall to support the upper back. The depth of the seat should allow the user a couple inches of space behind the knees to avoid pressure on the body. A slight seat slope would allow the user to comfortably sink into the seat.

Additionally, the chair must be strong and durable enough to hold the weight of the user for extended periods of time. The design sponsors have requested that this particular wheelchair can hold a 160 lbs. person for a lifetime minimum between three and five years. In order to achieve a high mobility in the wheelchair, it must be steerable and lightweight. Caster wheels and brakes allow the user greater control over movement. For this design the sponsors have requested a maximum total chair weight of 25 pounds to ensure that users would have the strength to steer. Finally, the wheelchair must be transportable. Great transportability and modularity would enable users to take the wheelchair wherever necessary, but it would also reduce shipping costs which in effect would reduce the chair cost. Toolless assembly is another target feature for the wheelchair, as many of the target customers in developing countries may not have access to tools that would be necessary to build a traditional wheelchair.

The sponsors have not given any constraints in terms of the manufacturing method or design software. 3D printing is a possibility if the proper tools are provided. Because this is meant to be a low-cost machine, materials are restricted mostly to cheaper materials such as plastic and wood. Higher quality metals may be used for the components of the chair that bear the most weight such as the wheel axle. The team has access to Autodesk 360 generative design software which requires particular inputs such as manufacturing methods and material. It outputs many iterations of possible design solutions and will allow the team to analyze both strengths and issues with the designs.

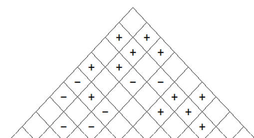
The full list of specifications for the design are listed in Table 2. Listing the requirements for the project itself, it can be seen that the forces associated with the design consist of the ability to support a user weighing up to 160 lbs. and the maximum chair weight of 25 lbs., both of which are demands of the sponsor. While the use of PET plastic and toolless assembly are focuses of the design, neither are considered requirements and are therefore labeled as wishes. The product is required to be safe in its final stage and should be comfortable to the user. While the design will ideally be adjustable in height and width to accommodate as many users as possible, for this iteration of the product it is not a demand. The product is required to last a minimum of three to five years, however utilizing 3D printing/additive manufacturing is not a necessary aspect. The product must be easily broken down to increase ease of transportation for the user and reduce shipping costs. Ideally the overall cost of the chair would be less than $1500 and the shipping costs would either be minimized or nonexistent, however this is not a requirement for this stage of development.

Table 2: Specification Sheet for Wheelchair Requirements

Changes	D/W	Requirement	Target Value (if applicable)	Responsibility	Source
9/1/2019		**Kinematics**			
	D	Vertically Mobile			
		Forces			
	D	Support Weight	<160 lbs		Sponsor
	D	Design Weight	<25 lbs		Sponsor
		Materials			
	W	PET plastic			Sponsor
		Safety			
	D	User safe from moving parts			
		Ergonomics			
	D	Comfortable to User			
	W	Adjust Height	0"-6"		
	W	Range of Width	12"-18"		
		Production			
	D	Lifespan	3-5 years		Sponsor
	W	3D Printable			Sponsor
		Assembly			
	W	Tooless Assembly			Sponsor
		Transport			
	D	Easily Broken Down			Sponsor
		Cost			
	W	Minimize Cost	<$1500		Sponsor
	W	Reduce Shipping Costs			Sponsor

Using the recommendations from the sponsor as well as predicted needs of potential users, a set of customer requirements was entered into a House of Quality (Table 3) and weighted based on their relative importance. The most important criteria was that the wheelchair be lightweight; this came at the recommendation of the sponsor as wheelchair users often have difficulty both moving around with a heavy wheelchair and transporting it when not in use. Other highly important requirements included comfort, durability, and ease of mobility. Engineering requirements were input from factors that the design team could change through various concepts. Using the relations throughout the House of Quality, it was determined that the choice and use of sustainable materials in the wheelchair frame was the most important specification. This is likely driven by the weight constraint, as the density and required thickness of the frame sections will determine the total mass of the chair. Other important design criteria included shipping cost, rigidity, and total number of parts. These three requirements have interrelationships driving their importance; the more separable parts in the wheelchair design allows for more parts to be shipped at once but increases the number of necessary interfaces potentially decreasing rigidity. Additionally, the least important engineering requirement is the manufacturing time. This is beneficial, as the most likely candidate for manufacturing is some form of additive manufacturing, which is generally a slow process. The project sponsor has also communicated that total product release time is not a concern for the design team at this stage of the project. For the final design, many of the engineering specifications remain the same, with the only major difference being that adjustable height will no longer be considered and instead a design will be created with an appropriate height for the majority of people.

Table 3: House of Quality Listing Customer and Engineering Requirements



Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

Weight	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Tooless Assembly	Weight Capacity	Manufactured from Sustainable Material	Shipping Cost	Rigid	Manufacturing Time	Product Lifetime	Number of Parts	Manufacturing Cost
	Column #	1	2	3	4	5	6	7	8	9
	Direction of Improvement	▼	◇	◇	▼	▲	▼	▲	▼	▼
6	Transportable	●	▽	○	●				●	
10	Lightweight	▽	●	●	●	●	▽	○	○	●
8	Comfortable			○		○			▽	
8	Durable	○	●	●	○	●	▽	●	●	○
8	Ease of Mobility			▽		▽		○		
4	Ease of Assembly	●	○	○	●		○	▽	●	●
	Technical Importance Rating	124	180	224	204	194	30	130	200	150
	Relative Weight	9%	13%	16%	14%	14%	2%	9%	14%	10%
	Weight Chart									

3.5 Market Research

According to the World Health Organization, about 10% of the population has disabilities and 20 million of those who require a wheelchair do not have one[11]. Current commercial high quality lightweight typically cost $3,000-$5,000 for wheelchairs that are about 10-15 lbs. There are foundations that currently send wheelchairs over to developing countries. The Wheelchair Foundation supplies a single wheelchair for a donation of $80. However, this does not include shipping container or land shipping costs. The Foundation does not disclose how donations affect the pricing of the wheelchair. The Wheelchair Foundation has multiple generations as shown in Figure 10 A & B. The downsides to these frames is that they are heavy and foldable. When chairs are foldable, they are more prone to wear. The Free Wheelchair Mission also provides wheelchairs that are $150 each and can ship 100-280 wheelchairs in a shipping container. The sponsor would like to be able to fit more wheelchairs within the shipping container, where the overall costs will be reduced as shown in Table 4.

Figure 10 A & B: Iterations of Wheelchair Foundation Low Cost Wheelchair

Table 4: Shipping Container Costs

Shipping Container Costs	
Units	**$ / Unit**
50	**$200**
300	**$33**
800	**$13**
1550	**$6**

3.6 Design Concept Ideation

In order to aid in the process of design with a focus on function to form, a function tree shown in Figure 11 is utilized to break down the different design elements which are important to the development of the initial concepts. The main elements of design are comfort of user, ability to hold a user up to 160 lbs., mobility of the wheelchair, and transportability of the wheelchair. Further evaluating these concepts, in order to maximize the comfort of the user the design must hold the feet of the user and be adjustable to their height, allow the user to easily grip the wheels of the chair, have a comfortable grip for the brake, have a splashboard that is adjustable to the user's width, and have a backrest that supports the user. In order to provide support within the chair up to 160 lbs., different materials should be considered, potentially extending beyond the limits of PET to other sustainable materials, and the Frame to Chair and Frame to Caster connections should be analyzed to maximize the support in relevant areas. To increase to mobility of the chair itself, different methods of steering, braking, and wheel/caster distribution should be considered, as well as ensuring that the chair itself is lightweight. Finally, in order to ensure that the user is the ability to transport and store the chair, the design should be simple to break down, have interchangeable parts, and ideally require minimal tools for assembly.

Sustainable, Low Cost Wheelchair

- Comfortable for User
  - Holds Feet
    - Adjustable Leg Height
  - Grip the Bike Wheels
  - Wheel Splashboard
    - Adjustable Width
  - Backrest
- Holds 160 lbs
  - Materials
  - Frame to Chair Connection
    - Monotube
    - Two Tubes
  - Frame to Castors
    - Monotube
    - Two Tubes
- Mobile
  - Steerable
  - Brake System
  - Light Weight
  - Wheel Distribution
- Transportable
  - Broken Down
  - Interchangable
  - Tooless Assembly

Figure 11: Function Tree for Sustainable, Low Cost Wheelchair

Several of the concepts listed in the function tree are utilized in the Morphological Chart (Table 5) to facilitate design. In order to hold the user's feet, the chair may feature a fabric hammock (Table 5: A1), dual hard footrests (Table 5: B1), a single platform (Table 5: C1), or a set of bars (Table 5: D1). To grip the wheels and propel the wheelchair forward, the design may utilize propulsion levers (Table 5: A2), a nail on an extension (Table 5: B2), or a scotch yoke mechanism (Table 5: C2). The bike grip options include a pull to lock system (Table 5: A3), a swinging motion (Table 5: B3), or a lock that flips horizontally to prevent motion (Table 5: C3). Different concepts to adjust the width of the chair include loose clip hooks (Table 5: A4), pegs (Table 5: B4), and sliders (Table 5: C4). The feature that serves as a backrest may be a 3D printed mesh (Table 5: A5), a set of posts and fabric (Table 5: B5), or rigid bars (Table 5: C5). In order to support the frame to chair connection, the concepts may utilize a single post (Table 5: A6), monotube (Table 5: B6), dual tube (Table 5: C6), truss (Table 5: D6), or four peg (Table 5: E6) support system. Another focus of support is located at the frame to caster connection, which may be solved utilizing on offset from the frame by arms (Table 5: A7), a monotube (Table 5: B7) or dual tube design (Table 5: C7), or placing the casters directly underneath the frame (Table 5: D7). Focusing on the mobility of the design, the caster system heavily influences the steerability of the chair, and may be accomplished using a single ball design (A8), two front casters (Table 5: B8), two rear casters (Table 5: C8), or a single caster (Table 5: D8). The braking system is integral to the function of the design as well, and may feature a manual pin (Table 5: A9), a latching mechanism (Table 5: B9), or a grip that is either parallel to the wheel (Table 5: C9), perpendicular to the wheel (Table 5: D9), or functions as a hook (Table 5: E9). Finally, the wheel distribution is important to the user's ability to propel the chair forward and may either have the wheels in front (Table 5: A10), under (Table 5: B10), or behind (Table 5: A11) the user.

Table 5: Morphological Chart Highlighting Main Components of Design

Functions		Options				
		A	B	C	D	E
Holds Feet	1	Fabric Hammock	Dual Hard Foot Rests	Single Platform	Bars	
Grip Bike Wheels	2	Propulsion Levers	Nail on an extension	Scotch Yoke Mechanism		
Brake Grip	3	Pull to Lock	Swing Down	Flips Horizontally		
Adjustable Width	4	Loose Clip Hook	Pegs	Slider		
Backrest	5	3D Print Mesh	Posts and Fabric	Hard Bars		
Frame to Chair Connection	6	Single Post	Monotube	Dual Tube	Truss	4 Pegs
Frame to Castors Connection	7	Offset from Frame by Arms			Directly Underneath Frame	
Steerable	8	Dyson Ball	Two Front Casters	Two Back Castors	1 Castor	
Brake System	9			Parallel to the Wheel	Perpendicular to the Wheel	Hook
Wheel Distribution	10	Wheels in Front of Person	Wheels Under Person	Wheels Behind Person		

The first concept features the functions shown in Figure 12 and has a dual tube frame to chair connection (Table 5: C6) with rear wheels (Table 5: C10) and two front casters (Table 5: B8). It is also comprised of multiple parts, allowing it to be easily broken down to be manufactured and transported. If the parts need to be replaced into sturdier parts, this is an option. The frame that holds the seat consists of one curved piece (Table 5: B5), and allows a fabric to slip over the tubing or to be tied. It allows the design to find different ways to incorporate PET bottles if the frame may need to be sturdier in its design after the FEA analysis are done in the next phase. A downside to this design is that it is not adjustable to width. Because it has the ability to be broken down by multiple parts, this may also be its weak point. It may not be structurally sound in a design that is easiest for manufacturing and transportability.

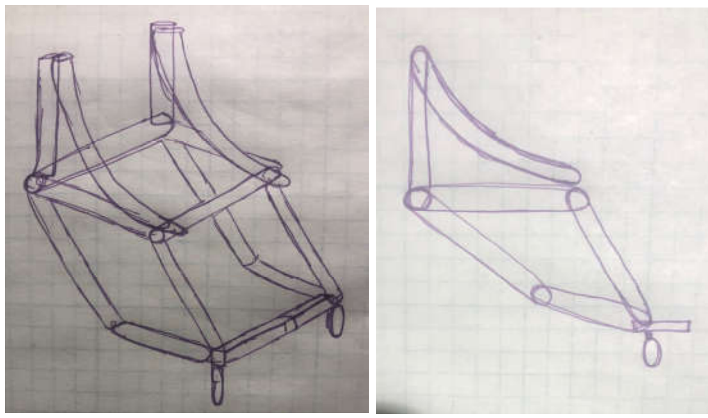


Figure 12 A & B: Concept 1

The second concept features the functions shown in Figure 13. The main focus of this design was the propulsion levers (Table 5: A2), an innovative approach to the traditional method of generating motion in a wheelchair. This is a more efficient way to increase the power per push using a more ergonomic motion- both helpful for the prevention of troubles such as carpel tunnel and for maneuvering over more uneven terrain which could be the case for some of the environments this chair eventually reaches. The main wheels will sit further forward (Table 5: A10) for a more powerful reaction from the propulsion levers. Since this uses more plastic, only one caster (Table 5: D8) in the front will be used along with a single footrest panel (Table 5: C1) to conserve weight. The back panel being two posts with fabric also save material (Table 5: B5). The seat sits on a single post (Table 5: A6) that connects to the front caster, these two parts would be disassemblable from each other to further pack it down if it needs to be shipped.

Figure 13: Concept 2

The third design concept in Figure 14 features a bulkier frame design utilizing a truss support system (Table 5: D6) with the wheels placed in front of the user (Table 5: A10) and two casters places behind (Table 5: C8). The motion control would comprise conventional nail on handles to the wheels (Table 5: B2) with in-line, under-frame casters (Table 5: D7). The seat back rest would be a 3D printed mesh (Table 5: A5), the chair width would be adjustable using hooked in splashboards (Table 5: A4), and the footrests would consist of two separate, solid footrests (Table 5: B1). The advantage of this design is that it would be exceptionally rigid and durable due to the well supported frame, as well as comfortable for the user. However, the main downside is that the frame would likely be very heavy as well as difficult to assemble/disassemble, making transport and movement more difficult.

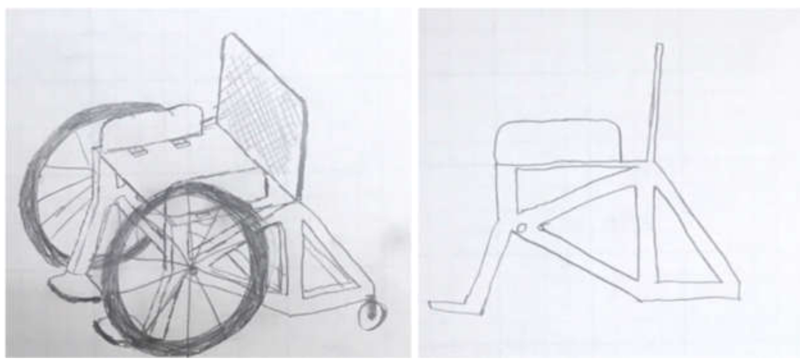


Figure 14 A & B: Concept 3

The fourth concept shown in Figure 15 has a dual tube frame-to-chair (Table 5: C6) connection with two caster wheels (Table 5: B7). Having two caster wheels would facilitate steering and balance for the user. If the casters are placed in the front, the wheels would have to be offset to the back to ensure that the wheelchair will not tip over. The issue with having two casters is that it requires more manufacturing than using just a single caster. Minimizing part count would reduce material and manufacturing needs and this is important because low cost is a priority. Additionally, the steering handles are nailed onto the wheels (Table 5: B2) which means the user must be able to comfortably reach and roll the wheels with their hands. This would be difficult to do if the wheels were offset to the back end of the seat.

Figure 15: Concept 4

The fifth concept shown in Figure 16 is a minimalist monotube design (Table 5: B6) with a single ball-style caster (Table 5: A8) at the front. The design also contains a two-bar construction for holding the user's feet (Table 5: D1). Back support for the user is through fabric attached to 2 posts (Table 5: B5) and the wheels are positioned slightly behind the user (Table 5: DC10). The monotube design prioritizes weight saving as its main focus, making it one of the most lightweight designs. This concept also allows for easy transport of the wheelchair for shipping, as it would be easily possible to tightly pack the wheelchairs together in order to preserve space and fit more frames in a single shipping container. This concept would also be very easy to assemble, as there would not be many additional parts separate from the main frame. A disadvantage to this design is that because of its simplicity, use comfort is sacrificed. The design makes use of simple fabric or cushions with little support for the backrest and seating which would not make it the most comfortable for users. The single caster design also does not provide as much stability and steerability as a more traditional dual-caster system.

Figure 16: Concept 5

The sixth concept shown in Figure 17 utilizes a truss system (Table 5: D6) in order to increase the support of the design. In addition, a single caster in the rear of the wheelchair is included to increase the maneuverability of the chair (Table 5: D8). Due to this positioning, and the inclusion of the nail on an extension method of gripping the wheels (Table 5: B2) the positioning of the main wheel must be located under the user (Table 5: B10). Finally, the design features a fabric seat backing (Table 5: B5) and a peg system to adjust the width of the chair (Table 5: B5). While the concept highlights support of the user and maneuverability, because of the intricate design of the truss system and rear single caster, the interchangeability of parts is severely limited. This support will also increase the overall weight of the design.

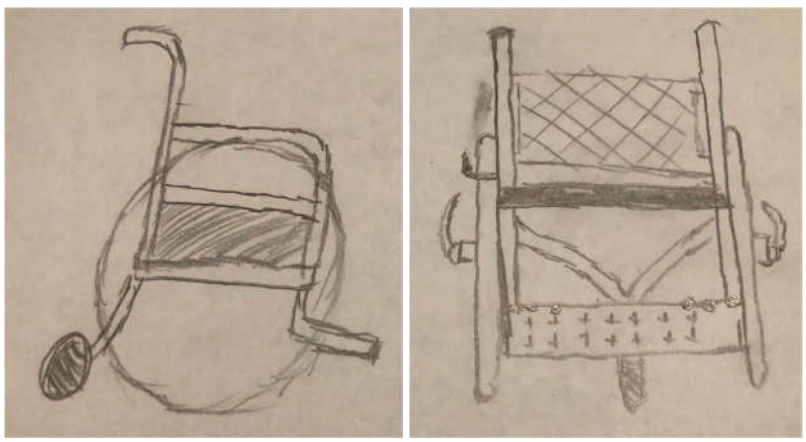
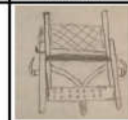


Figure 17 A & B: Concept 6

3.7 Concept Selection and Justification

In order to evaluate and select a concept to develop for the remainder of the project, an evaluation matrix (Table 6) was developed comparing the six concepts that were generated. Utilizing the weights of customer requirements developed in the House of Quality (Table 3), the concepts were evaluated, revealing Concept 6 to have the highest resulting total and optimizing the relevant customer requirements. The design itself highlights the weight capacity of the chair, toolless assembly, rigidity, and product lifetime. While the intricacy of the design may increase both the number of parts and the manufacturing time, the design itself should ensure that the product's structure and mobility are optimized while using sustainable materials.

Table 6: Evaluation Matrix Comparing Initial Concepts

		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5		Concept 6	
													
Criteria	**Importance**												
Transportable	6	2	12	1	6	1	6	1	6	3	18	2	12
Lightweight	10	4	40	3	30	2	20	2	20	3	30	3	30
Comfortable	8	1	8	2	16	3	24	2	16	1	8	2	16
Durable	8	3	24	1	8	4	32	2	16	2	16	4	32
Easy of Mobility	8	3	24	4	32	2	16	3	24	2	16	4	32
Ease of Assembly	4	2	8	1	4	2	8	3	12	3	12	2	8
Total			116		96		106		94		100		130
Relative Total			0.18		0.15		0.17		0.15		0.16		0.20
4 = Very Good, 3 = Good, 2 = Satisfactory, 1 = Tolerable, 0 = Unacceptable													

Major concerns with the design primarily center around ensuring that utilizing PET plastic for the design provides significant support for the user. The FEA that was performed on the generated design solution does not indicate failure or bending in components where failure would be expected for PET material. This means that the FEA is not entirely reliable and further testing must be performed on prototyped parts to observe the effects of stress and strain. It is also uncertain whether or not considered manufacturing methods are viable for the wheelchair components. Everything in the current design hinges on the PET material performing ideally and it is likely that adjustments will have to be made depending on the PET performance. Because of the intricacy of the chosen design, it will be important to focus on the ability of the final project to be broken down, both to lower shipping costs and increase the transportability of the product. It will also be important to manage tolerances around the wheel axles and braking system, as it is currently designed with the assumption that those systems will be purchased from other sources. There are a few other aspects of the selected design that must be considered to meet the customer and safety requirements. For instance, when riding over road bumps wheelchair users frequently lift the front caster off the ground by putting weight on the back end of the seat. This is done so that the chair can be rolled over the bump without the caster scraping the ground. In order to overcome this, the rear caster will have to have more of a spring to it compared to other casters in order to handle the front wheels going over the bumps first. One potential issue with placing the caster in the back is that the chair might not roll over bumps smoothly. Additionally, the wheels have been offset to the front as opposed to the back. A possible consequence of this is that the wheel placement could interfere with the user's ability to transfer in and out of the chair. Another possibility is that the user might topple over if the center of body mass is shifted forward too much when moving out of the wheelchair. If the team moves forward with 3D printing, there are a few concerns that the intricate spindle-like members may be prone to breaking when actually used in rugged environments. All of these concerns will be considered when prototyping to see if the design is viable.

In Figure 18, the CAD model of the selected design has been created, utilizing entirely PET plastic for the frame. The wheels and casters are imported designs with standardized dimensions for components which would be purchased separately. This model also utilizes hollow cylinders as a simple solution to interconnect parts. The design includes two side trusses which support the weight of the user, two rear trusses to connect the rear caster to the frame, a set of wheels with a PET axle, and a backrest and footrest to make the chair more comfortable.

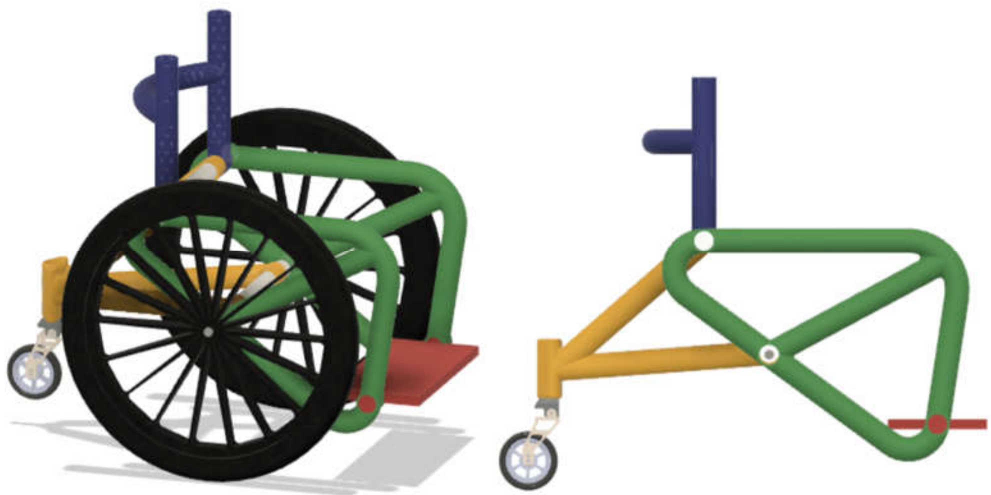


Figure 18: CAD of Selected Design

3.8 Industrial Design

To maximize comfort and ease of use for the customers, the selected design must incorporate factors of anthropology, sociology, and cognitive psychology. The persona that the chair is being designed for has been defined as a person of limited mobility with limited resources that is roughly 160 pounds or less. Therefore, anthropometric measurements for a 160 lbs. person are being used to dimension and to size the chair. Components such as the footrest have been arranged intentionally to function for a person of this size. Talking to wheelchair users provides necessary context and stories with regard to understanding which design features are important. For instance, wheelchair users have noted the importance of a low center of mass for the wheelchair. Chairs are typically set to a low height in order to prevent the chair from tipping over. A low center of gravity also facilitates the process of transferring in and out of the chair because the user does not have to use excessive strength to lift himself or herself very high. Additionally, users have noted the importance of the caster placement for balancing purposes. The selected design has a single caster at the rear end of the chair because this would be more stable than a design with a single caster in the front while also minimizing the amount of plastic used. The bike wheels in the selected design are located near the front so that the user does not have to exert excessive force to roll the wheels. To address the human factors of cognitive psychology, the design has been made fairly intuitive as it emulates widely familiar concepts from existing wheelchairs.

The designed wheelchairs may be either donated to people who cannot afford them or highly subsidized. If the target demographic is to be given the product, the design focus is on practicality and usability as opposed to aesthetics. In the chance that Coca Cola or another company would sponsor the donations, the wheelchairs would be branded as a sustainable, cost-effective alternative to existing designs. If the users need to pay the full cost for the wheelchair their priority would still likely be affordability over aesthetics. The chair colors and patterns would be largely determined by the 3D printing filament or manufacturing method. There could be standard colors that would be used for customers of all genders and ages. If the sponsors wish, filament color can be based off the standardized company branding.

3.9 Detailed Technical Analyses, Experimentation, and Design Performance Prediction

The primary form of structural physical analysis will be Autodesk Fusion 360's FEA analysis software focusing on stress, displacement, and safety of factor. The FEA displays a color map and exaggerates the changes on the model. The FEA outputs its results based on standard new PET filament. There are concerns that 3D printed PET will have different structural components than what the FEA outputs. There are also concerns that the orientation of the printer will affect the material properties because of the different grain directions. An experiment is underway where horizontally 3D printed dog bones and vertically 3D printed dog bones will be tested for its stress and strain. These results will then be inputted into Autodesk Fusion 360 manually and the generative design models will have to change to meet the new material properties.

For the FEA on the footrest, two forces were used to simulate the weights of the users' legs on the surface. The two pegs on the side of the footrest where it would be attached to the side trusses were fixed for the analysis. The maximum deformation for the part as seen in Figure 19 was shown to be 0.6512 mm, which is well within an acceptable range of deformation for this part. The maximum stress as shown in Figure 20 is 4.958 MPa which is relatively small and occurred around the connection between the pegs and the flat part of the footrest which is the weakest part of the initial design. The minimum factor of safety as seen in Figure 21 is 10.97 which is more than acceptable for the desired use case.

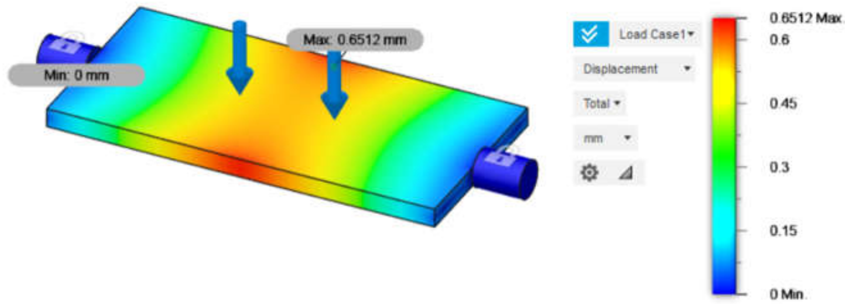


Figure 19: Displacement FEA of Footrest

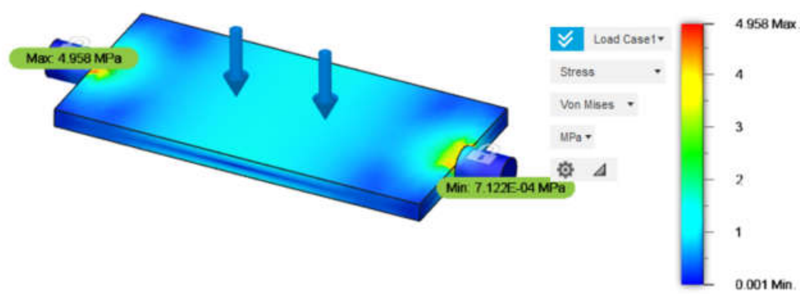


Figure 20: Stress FEA of Footrest

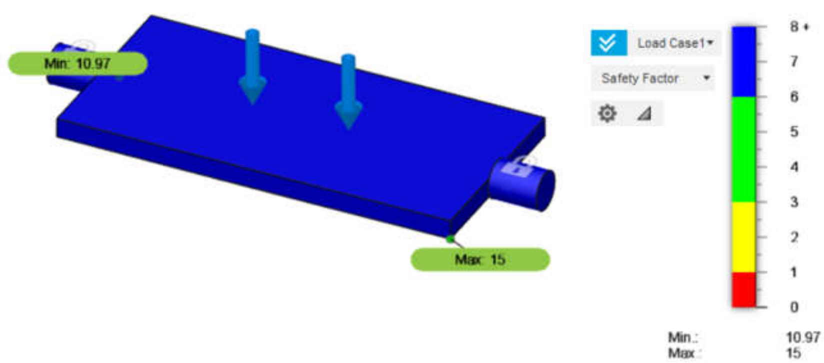


Figure 21: Safety Factor FEA of Footrest

For the back truss, there is almost no displacement or stress at the axle holes due to the fixed nature of these axles, therefore the primary section under stress is the end caster attachment point. Loads here were simulated as the load applied from the caster as a result of the ground reaction from a portion of the 160lb persons weight. The displacement at this point was found to be 2.6 mm with a stress of 9.1 MPa and a safety factor of 6. This is acceptable, but it is likely that through generative design that a lighter design with even higher factors of safety could be achieved.

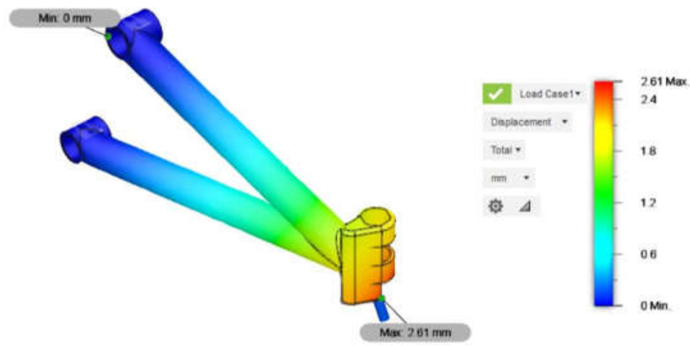


Figure 22: Displacement FEA of Back Truss

Figure 23: Stress FEA of Back Truss

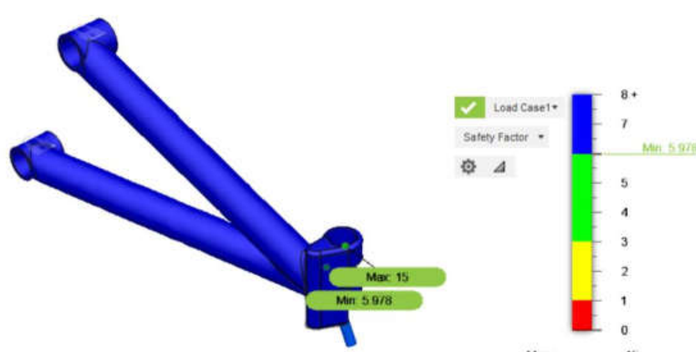


Figure 24: Safety Factor FEA of Back Truss

The static FEA analysis on the Side truss should it to be mostly sufficient for handling loads associated from the seated person, but not for the weight of the legs on the footrest. Loads were placed at the bar where the seat would be tied on, the wheel axle location, and the connection location for the footrest based on a 160 lbs. person. The results show a large displacement of about 7.9 mm at the footrest connection, but the rest of the displacements across the frame are acceptable. The maximum stress was found to be 6.5 MPa, which is acceptable considering the minimum 8.4 safety factor at the same location. These values were approved upon using generative design with the key design parameters and the same load case.

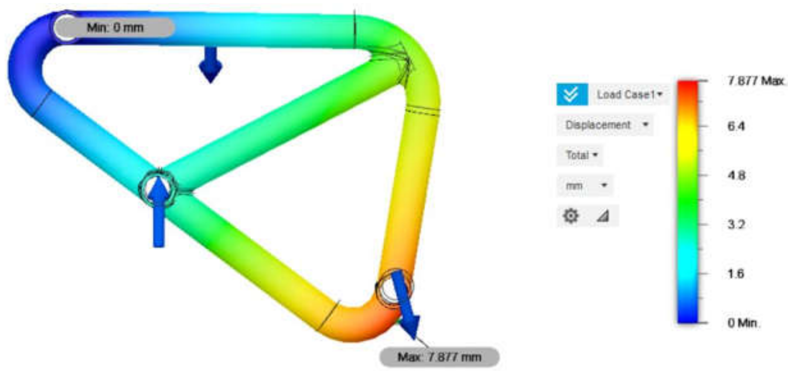


Figure 25: Displacement FEA of Side Truss

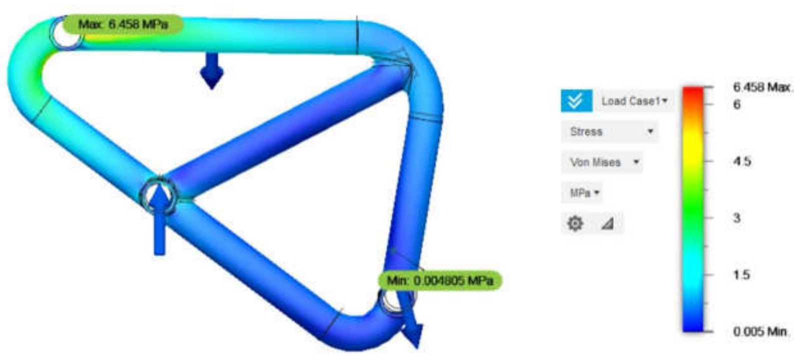


Figure 26: Stress FEA of Side Truss

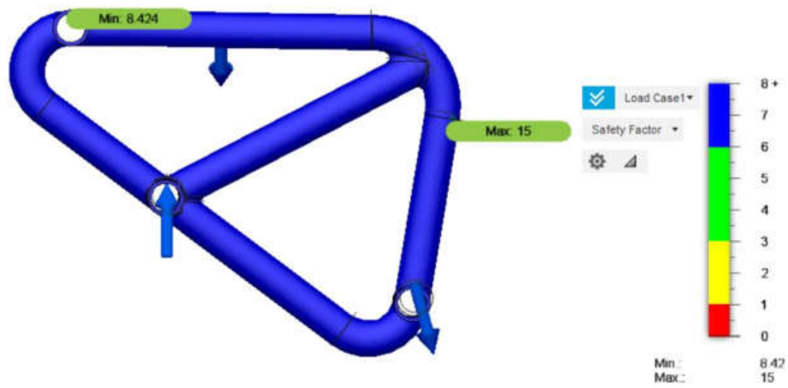


Figure 27: Safety Factor FEA of Side Truss

The printed axle used to connect the wheels supports a load of up to 375 N on each side where it connects with the side truss. Constraining the bar at both ends, an FEA is utilized to verify the strength of the component when made with PET. In Figure 25, it can be shown that with a total force of 750 N acting upon it, the maximum displacement of the bar is 0.7618 mm which can be considered negligible. In addition, the location of maximum von Mises stress occurs at the point of force application, with a magnitude of 4.595 MPa as shown in Figure 26. Finally, Figure 27 reveals that the bar itself has a minimum safety factor of 11.84 which is more than sufficient for the operating conditions of the wheelchair.

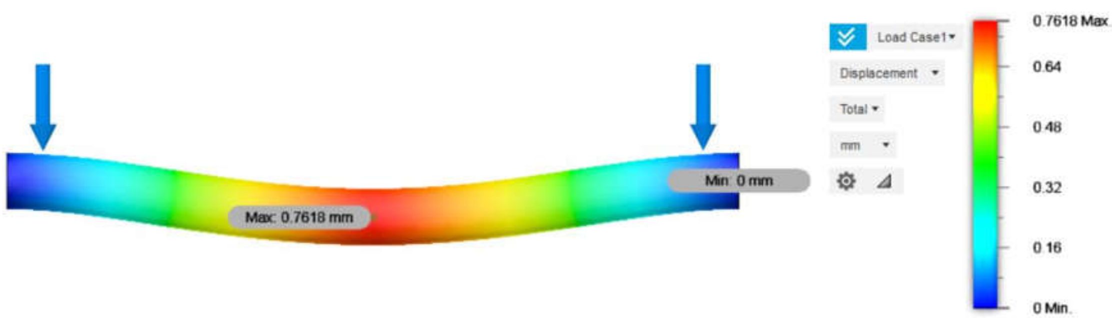


Figure 28: Displacement FEA of Axle

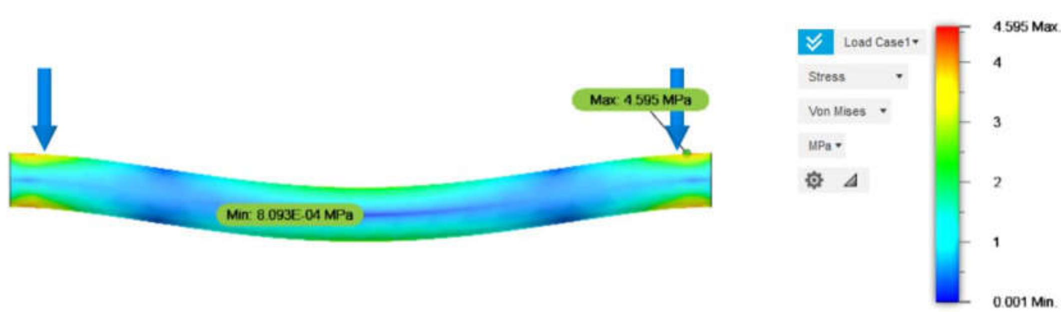


Figure 29: Stress FEA of Axle

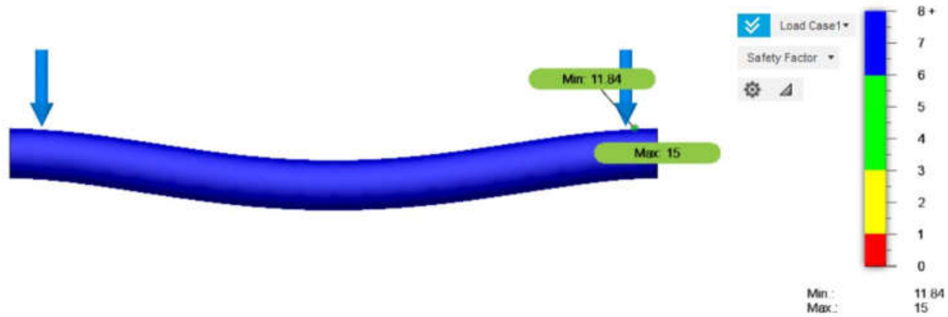


Figure 30: Safety Factor FEA of Axle

An FEA was performed on the backrest fixture as well, as shown in Figures 28 - 30. In order to estimate the pressure placed on the backrest by the user, 25% of the force applied by the weight of the individual was used, in this case a load of 190 N. With this force applied the maximum displacement on the feature is 0.8009 mm, which is within an acceptable range of deflection as shown in Figure 28. In addition, the maximum Von Mises stress is 2.07 MPa applied at the base of the backrest itself shown in Figure 29. With these applied forces applied however, the component has a minimum of safety factor of 15, revealed in Figure 30.

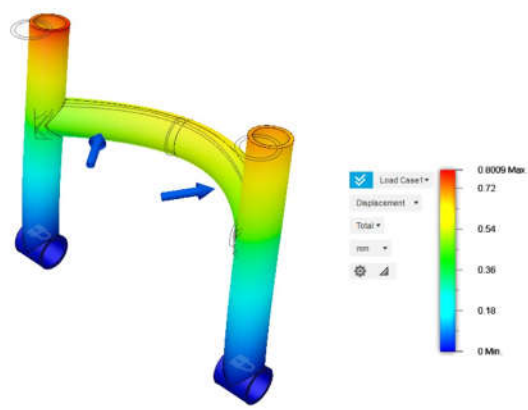


Figure 31: Displacement FEA of Back Rest

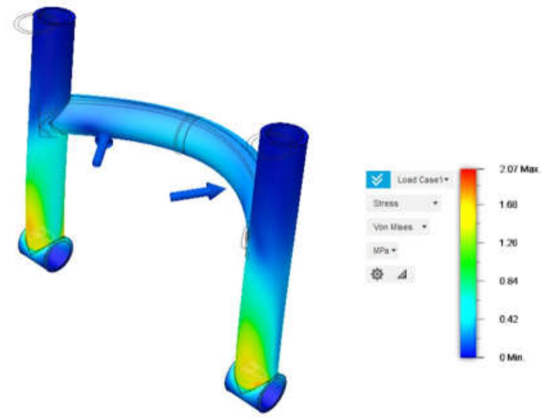


Figure 32: Stress FEA of Back Rest

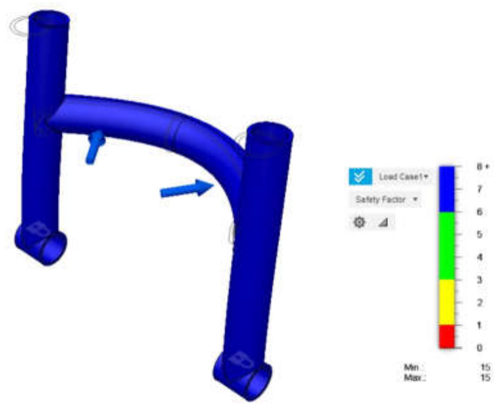


Figure 33: Safety Factor FEA of Back Rest

The handle or wheel grip that the user would roll would be attached to the bike wheels on the chair. There would be six extrusions from the handle that can be screwed onto the bike wheel. As the wheel rolls the handle would spin with it and vice versa. Therefore, the main force on the handle would be a tangential force on each of the bike wheel grip extrusions. The FEA performed on this part can be seen in Figures 31 - 33 where the stress and displacement appear exaggerated for visual purposes. The displacement of each extrusion is shown to be 0.0015 mm at a maximum. The calculated maximum stress on the part is 0.08 MPa and the factory of safety is 15 which means that there is low risk of part failure. Because the user would be directly interacting with this component to push the wheels, the design would be kept as it is. Designs for this part that are generated by Fusion 360 make the handle far more complex and as a result, less intuitive for the user.

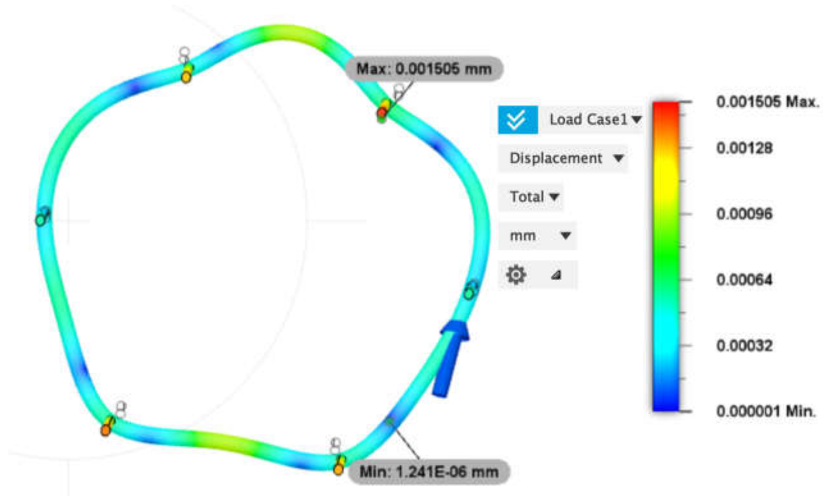


Figure 34: Displacement FEA of Bike Grip

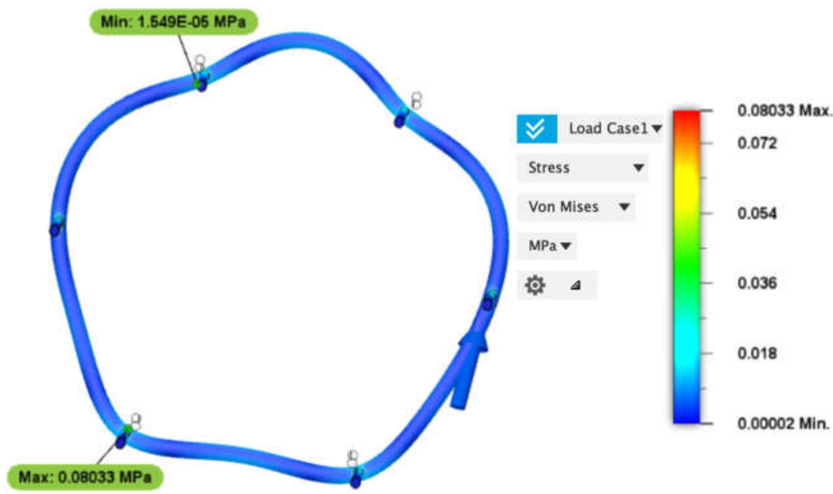


Figure 35: Stress FEA of Bike Grip

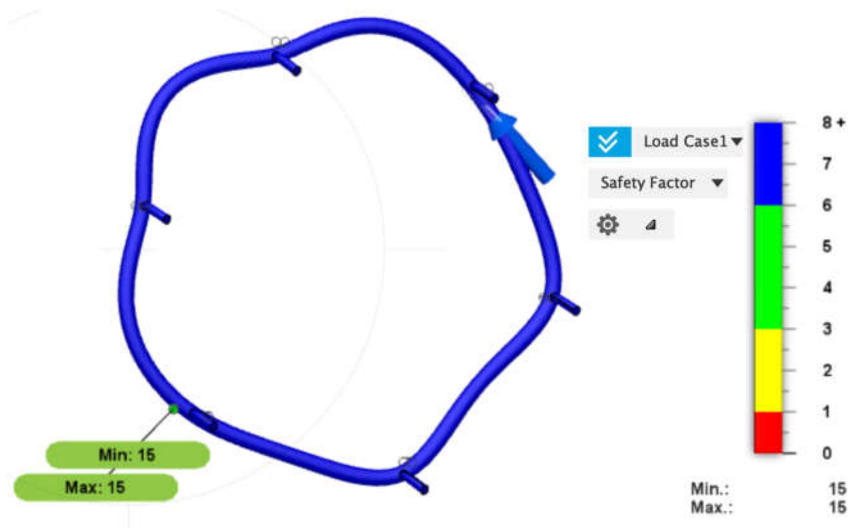


Figure 36: Safety Factor FEA of Bike Grip

The majority of this design will be created using Autodesk Fusion 360's generative design feature. The inputs are the expected forces in the appropriate directions as well as the specific features to preserve and remove in the design, and the outputs are dependent on these forces; therefore, the created designs are ideally able to sustain such forces. This will also serve to reduce the mass of the design as well as highlight the faults analyzed in the FEA. The material properties of the PET are different when 3D printed vs other manufacturing methods, so in order to accurately replicate this in generative design these properties will be found using stress-strain testing using a 3D printed PET dogbone. A quote has been acquired for the printed part and will be tested using the Systems Lab stress-strain lab setup.

Generative design was performed on the footrest to decrease weight while maintaining structural stability. Some resulting generative design options are shown in Table 7. The study was set to maximize stiffness with a mass target of 1.5 kg which would be significantly less than the original design. The final design option was chosen mostly based off of how functional the results would be in actually supporting the user's feet. This disqualified many of the options in Table 7 because even though they would technically support the forces produced by the user's leg, the surface profile would not be practical for supporting the user's feet. Outcome 3 was chosen as the most practical design and is shown in Figure 37. The weight of the chosen generated design was 1.38 kg which is significantly lower than the 2.78 kg weight of the original design, while retaining similar stiffness properties.

Table 7: Generative Design options for footrest

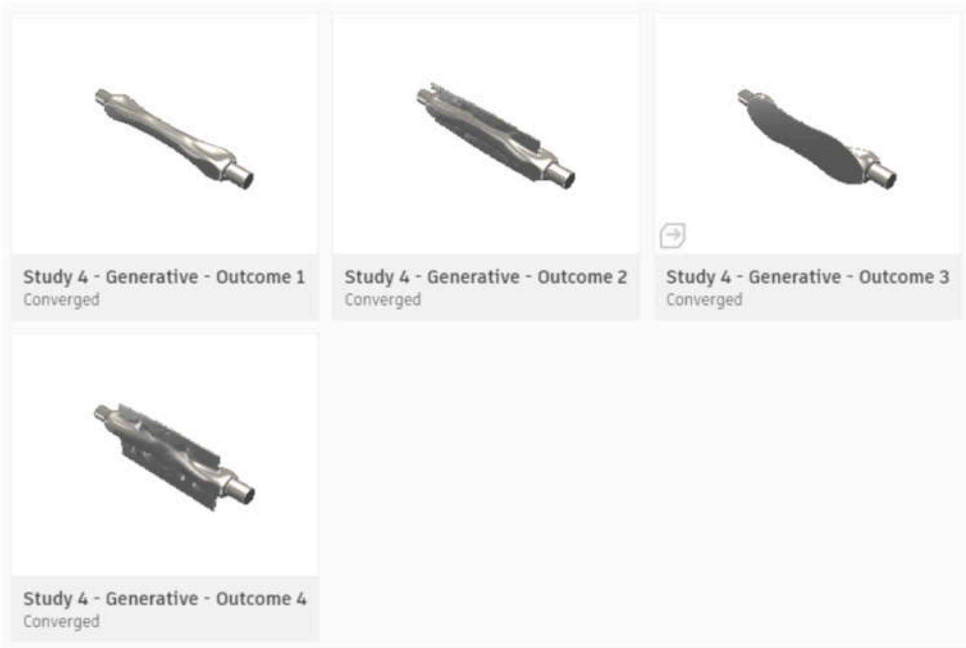


Figure 37: Generative Designed Footrest

The back truss was generated using the same methods as the previous generated parts, with the design parameters of the conventional back truss and the load case from its FEA. The goal parameters for the study were both minimize mass and maximize stiffness with the results for each case shown in Table 8 with their respective properties. The clear choice from these results was Study 3 Outcome 1 as it had both the lowest weight and the highest factor of safety across all designs. This design is shown in Figure 38 and was used in the final assembly. The final weight reduction from the conventional design was about 1.2 kg and the final safety factor was 20.67.

Table 8: Generative Design Options for Side Truss


Study 3 - Generative - Outcome 1
Converged


Study 3 - Generative - Outcome 2
Converged


Study 3 - Generative - Outcome 3
Completed


Study 3 - Generative - Outcome 4
Converged

Properties	Study 3 - Generative - Outcome 1	Study 3 - Generative - Outcome 2	Study 3 - Generative - Outcome 3	Study 3 - Generative - Outcome 4
Status	Converged	Converged	Completed	Converged
Material	PET Plastic	PET Plastic	PET Plastic	PET Plastic
Orientation	-	X+	Y+	Z+
Manufacturing method	Unrestricted	Additive	Additive	Additive
Visual similarity	Ungrouped	Ungrouped	Ungrouped	Ungrouped
Volume (mm^3)	7.603e+5	1.642e+6	7.661e+5	7.858e+5
Mass (kg)	1.172	2.531	1.181	1.211
Max von Mises stress (MPa)	2.6	2.7	2.7	2.7
Factor of safety limit	20	20	20	20
Min factor of safety	20.67	20.01	20	20
Max displacement global (mm)	1.41	4.92	2.39	2.34


Study 4 - Generative - Outcome 1
Converged


Study 4 - Generative - Outcome 2
Converged


Study 4 - Generative - Outcome 3
Completed

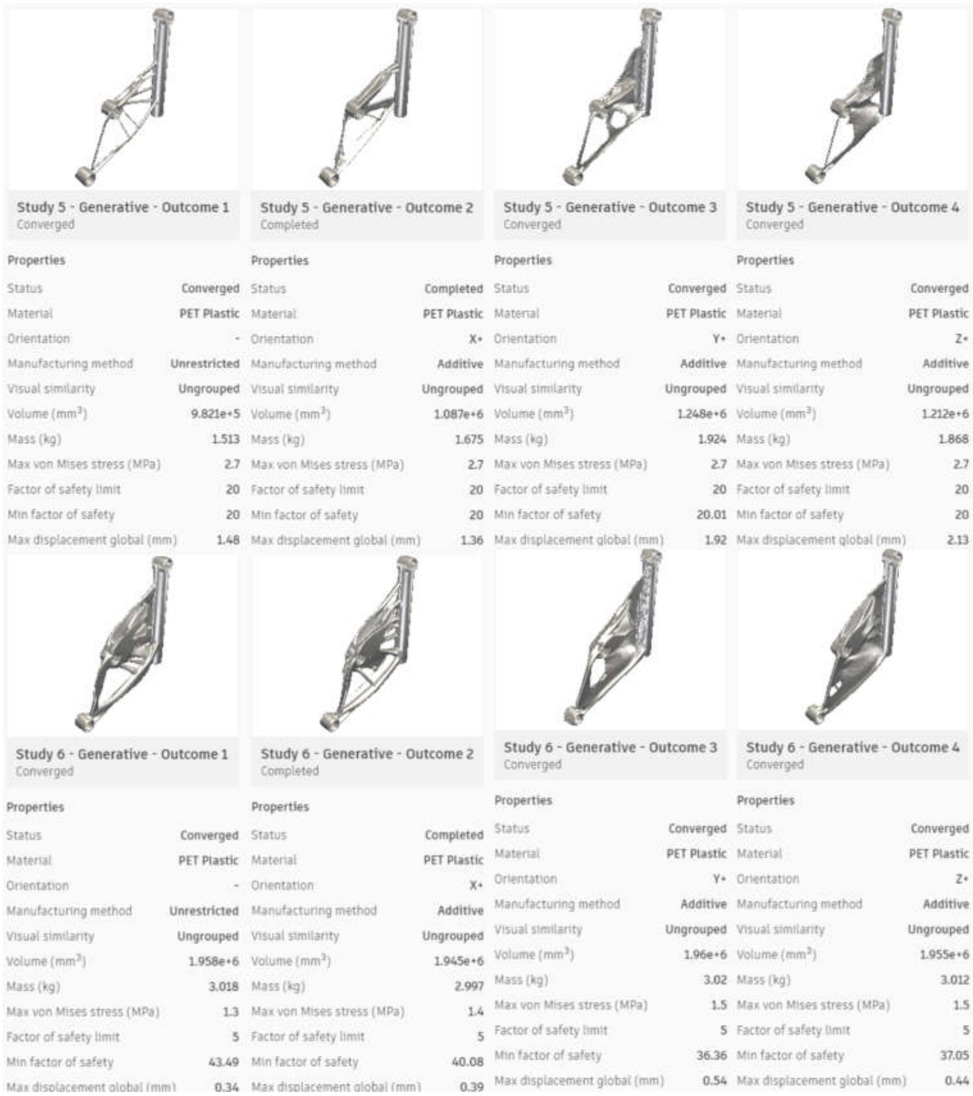

Study 4 - Generative - Outcome 4
Completed

Properties	Study 4 - Generative - Outcome 1	Study 4 - Generative - Outcome 2	Study 4 - Generative - Outcome 3	Study 4 - Generative - Outcome 4
Status	Converged	Converged	Completed	Completed
Material	PET Plastic	PET Plastic	PET Plastic	PET Plastic
Orientation	-	X+	Y+	Z+
Manufacturing method	Unrestricted	Additive	Additive	Additive
Visual similarity	Ungrouped	Ungrouped	Ungrouped	Ungrouped
Volume (mm^3)	9.746e+5	9.801e+5	9.868e+5	9.856e+5
Mass (kg)	1.502	1.51	1.521	1.519
Max von Mises stress (MPa)	2.7	5.4	3.2	4
Factor of safety limit	10	10	10	10
Min factor of safety	20.33	10	17.22	13.75
Max displacement global (mm)	1.04	13.83	1.39	1.25

Figure 38: Generative Designed Back Truss

The optimized side truss was created using generative design with the focus being on maintaining structural integrity as this part is the most critical to the rigidity of the frame. The generative design study imported the hole locations of the conventional tube designed side truss and the long tube that will be used to string the fabric across. The study was run with both minimize mass and maximize stiffness objectives with the results shown in Table 9. The Study 6 Outcome 1 result, shown in Figure 39 was chosen because it had the highest factor of safety of all designs while still maintaining relatively low weight. The total weight for this design came out to 3.01 kg compared to 3.80 kg of the conventional design, a significant reduction in weight. The bigger advantage of the generative design is the increase in safety factor from 8.4 to 43.49 which is critical for its application.

Table 9: Generative Design Comparison for Back Truss



Properties	Study 5 - Generative - Outcome 1 (Converged)	Study 5 - Generative - Outcome 2 (Completed)	Study 5 - Generative - Outcome 3 (Converged)	Study 5 - Generative - Outcome 4 (Converged)
Status	Converged	Completed	Converged	Converged
Material	PET Plastic	PET Plastic	PET Plastic	PET Plastic
Orientation	-	X+	Y+	Z+
Manufacturing method	Unrestricted	Additive	Additive	Additive
Visual similarity	Ungrouped	Ungrouped	Ungrouped	Ungrouped
Volume (mm^3)	9.821e+5	1.087e+6	1.248e+6	1.212e+6
Mass (kg)	1.513	1.675	1.924	1.868
Max von Mises stress (MPa)	2.7	2.7	2.7	2.7
Factor of safety limit	20	20	20	20
Min factor of safety	20	20	20.01	20
Max displacement global (mm)	1.48	1.36	1.92	2.13

Properties	Study 6 - Generative - Outcome 1 (Converged)	Study 6 - Generative - Outcome 2 (Completed)	Study 6 - Generative - Outcome 3 (Converged)	Study 6 - Generative - Outcome 4 (Converged)
Status	Converged	Completed	Converged	Converged
Material	PET Plastic	PET Plastic	PET Plastic	PET Plastic
Orientation	-	X+	Y+	Z+
Manufacturing method	Unrestricted	Additive	Additive	Additive
Visual similarity	Ungrouped	Ungrouped	Ungrouped	Ungrouped
Volume (mm^3)	1.958e+6	1.945e+6	1.96e+6	1.955e+6
Mass (kg)	3.018	2.997	3.02	3.012
Max von Mises stress (MPa)	1.3	1.4	1.5	1.5
Factor of safety limit	5	5	5	5
Min factor of safety	43.49	40.08	36.36	37.05
Max displacement global (mm)	0.34	0.39	0.54	0.44

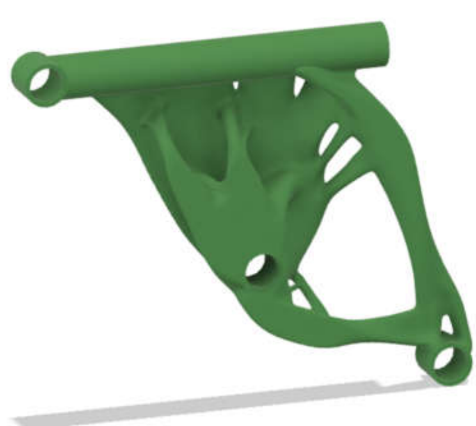


Figure 39: Generative Designed Side Truss

Generative design was performed on the backrest component in order to reduce the mass of the part. In order to analyze the viability of different manufacturing methods, five designs were generated in Table 10. Using mass as a main constraint, Outcome 5, which utilizes 3 axis milling, is unviable with a mass of 14.115 kg. Comparing the remaining designs Outcome 1, which was generated with the unrestricted option for manufacturing, has the lowest mass (0.709 kg), maximum von Mises stress (2.90 MPa), and highest minimum factor of safety (18.73). While Outcome 3, generated with additive manufacturing in the y-direction, has a lower max displacement of 0.65 mm, this is comparable with Outcome 1 (0.69 mm). Therefore, Outcome 1 was selected as the final design for the assembly, as shown in Figure 40.

Table 10: Generative Design Comparison for Backrest



Properties	Study 4 - Generative - Outcome 1 (Converged)	Study 4 - Generative - Outcome 4 (Converged)	Study 4 - Generative - Outcome 5 (Converged)
Status	Converged	Converged	Converged
Material	PET Plastic	PET Plastic	PET Plastic
Orientation	-	Z+	Z-
Manufacturing method	Unrestricted	Additive	3 axis milling
Visual similarity	Ungrouped	Ungrouped	Ungrouped
Volume (mm^3)	4.601e+5	4.688e+5	9.16e+6
Mass (kg)	0.709	0.722	14.115
Max von Mises stress (MPa)	2.9	6.7	6.2
Factor of safety limit	2	2	2
Min factor of safety	18.73	8.07	8.71
Max displacement global (mm)	0.69	1.88	2.31


Properties	Study 4 - Generative - Outcome 2 (Completed)	Study 4 - Generative - Outcome 3 (Completed)
Status	Completed	Completed
Material	PET Plastic	PET Plastic
Orientation	X+	Y+
Manufacturing method	Additive	Additive
Visual similarity	Ungrouped	Ungrouped
Volume (mm^3)	4.633e+5	4.624e+5
Mass (kg)	0.714	0.713
Max von Mises stress (MPa)	7	4.1
Factor of safety limit	2	2
Min factor of safety	7.79	13.3
Max displacement global (mm)	1.19	0.65

Figure 40: Generative Design for Backrest

The generated components were used to replace the manually designed components of the wheelchair, as shown in Figure 41 A-D. The finalized design reduced the mass of the wheelchair itself from 26.756 kg to 12.679 kg, a reduction of 52.61%. This model, while more complex, severely reduces the material used to manufacture a functional wheelchair for an individual, and hopefully can be produced and distributed more easily at a lower cost than the standard wheelchair.

Figure 41 A: Generative Design for Full Design

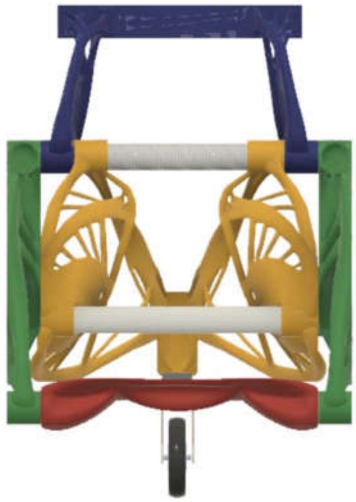


Figure 41 B: Generative Design for Full Design

Figure 41 C: Generative Design for Full Design

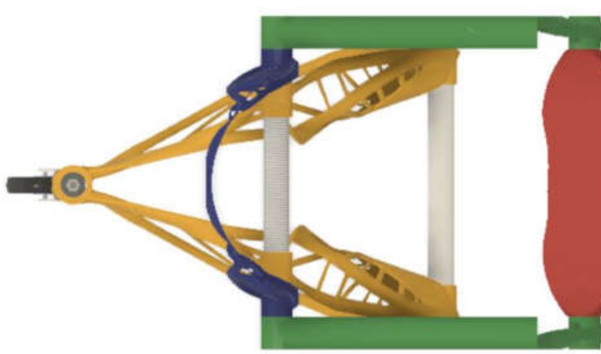


Figure 41 D: Generative Design for Full Design

While the previously generated models reflect a design developed from solid PET, the mechanical properties of 3D printed PET are much weaker depending on print orientation and infill percentage. The mechanical values listed in Table 11 are developed from 3D printed dogbones from recycled PET filament similar to the material that would be utilized for the finalized design [14]. Material properties in Fusion 360 were updated to conform to the various sets of print options listed and regenerated to develop more accurate parts for the final design.

Table 11: Mechanical Properties of 3D Printed PET

Material	Fusion 360 PET	Vertical Print 50% Infill	Vertical Print 100% Infill	Horizontal Print 50% Infill	Horizontal Print 100% Infill
Young's Modulus	2.758 GPa	1.328 GPa	2.140 GPa	1.470 GPa	2.264 GPa
Yield Strength	54.4 MPa	11.0 MPa	22.7 MPa	27.3 MPa	39.9 MPa
Tensile Strength	55.1 MPa	11.1 MPa	22.8 MPa	27.7 MPa	40.9 MPa
Density	1.54 g/cm^3	0.77 g/cm^3	1.54 g/cm^3	0.77 g/cm^3	1.54 g/cm^3

The final footrest design is shown in Figure 42. After re-running the generative design with the new material properties, there were two designs that were feasible for 3d printing. A comparison between the two designs can be seen in Table 12. Due to the factor of safety being the same between the two designs, the lighter of the two designs with 50% PET fill was selected for the final wheelchair.

Figure 42: Updated Generative Design for Footrest

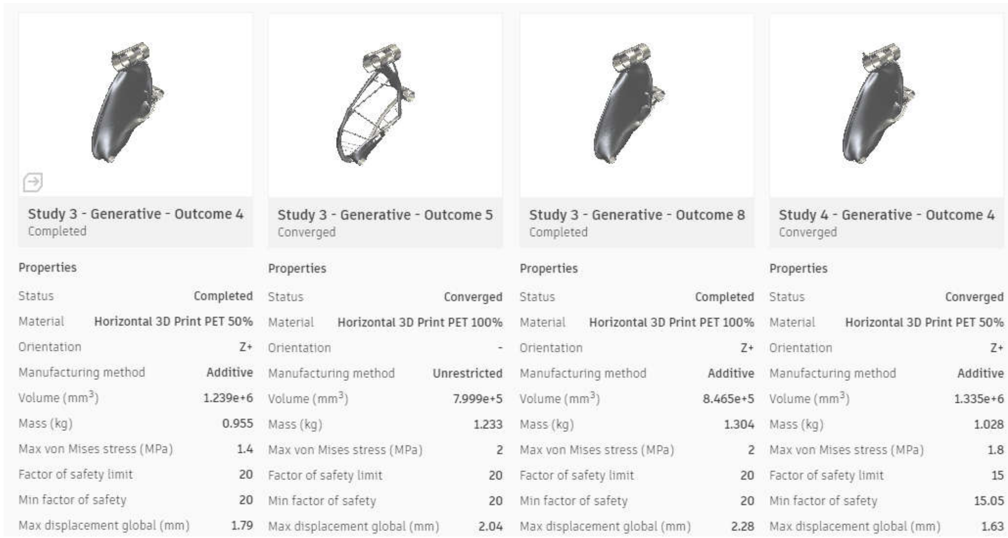
Table 12: Updated Generative Design Comparison for Backrest

	Study 8 - Generative - Outcome 7 (Converged)	Study 8 - Generative - Outcome ... (Converged)
Properties		
Status	Converged	Converged
Material	Vertical 3D Print PET 50%	Vertical 3D Print PET 100%
Orientation	Y+	Y+
Manufacturing method	Additive	Additive
Volume (mm^3)	1.589e+6	1.012e+6
Mass (kg)	1.224	1.56
Max von Mises stress (MPa)	1.9	2.1
Factor of safety limit	5	5
Min factor of safety	5.88	11.05
Max displacement global (mm)	0.06	0.04

The expansion of materials in the generative design had a large effect on the back truss, which previously was lightweight and strong, but had a large risk of damage because of the many thin members in its structure. The new back truss is shown below in Figure 43, and comparisons between four of the best generated options are shown in Table 13.

Figure 43: Updated Generative Design for Back Truss

Table 13 Updated Generative Design Comparison for Back Truss



Properties	Study 3 - Generative - Outcome 4 (Completed)	Study 3 - Generative - Outcome 5 (Converged)	Study 3 - Generative - Outcome 8 (Completed)	Study 4 - Generative - Outcome 4 (Converged)
Status	Completed	Converged	Completed	Converged
Material	Horizontal 3D Print PET 50%	Horizontal 3D Print PET 100%	Horizontal 3D Print PET 100%	Horizontal 3D Print PET 50%
Orientation	Z+	-	Z+	Z+
Manufacturing method	Additive	Unrestricted	Additive	Additive
Volume (mm^3)	1.239e+6	7.999e+5	8.465e+5	1.335e+6
Mass (kg)	0.955	1.233	1.304	1.028
Max von Mises stress (MPa)	1.4	2	2	1.8
Factor of safety limit	20	20	20	15
Min factor of safety	20	20	20	15.05
Max displacement global (mm)	1.79	2.04	2.28	1.63

Multiple generated designs would have been acceptable for the wheelchair, but ultimately using a 50% infill design was shown to be the common factor that provided an optimized design. In addition, the horizontal print type (Z Orientation) was also a key factor for creating a strong design. Ultimately, the first design in the table was chosen because it was the lightest design with the highest safety factor while also removing the thin members present in the first-generation design.

For the side truss, a similar set of commonalities appeared. Figure 44 shows the final side truss design and Table 14 shows the best four designs that were compared to choose that design. Again, most of the preferred designs utilize a 50% infill, horizontally printed PET, and the 100% infill part was ruled out because it included too many thin and fragile members. The final chosen design was the third design on the table as it was a balance of weight and safety factor that allowed the whole wheelchair to meet the weight requirement while also maintaining structural integrity.

Figure 44: Updated Generative Design for Side Truss

Table 14: Updated Generative Design Comparison for Back Truss

	 Study 5 - Generative - Outcome 1 Completed	 Study 5 - Generative - Outcome 5 Converged	 Study 6 - Generative - Outcome 1 Converged	 Study 6 - Generative - Outcome 4 Converged
Properties				
Status	Completed	Converged	Converged	Converged
Material	Horizontal 3D Print PET 50%	Horizontal 3D Print PET 100%	Horizontal 3D Print PET 50%	Horizontal 3D Print PET 50%
Orientation	-	-	-	Z+
Manufacturing method	Unrestricted	Unrestricted	Unrestricted	Additive
Volume (mm^3)	3.379e+6	1.713e+6	2.932e+6	2.91e+6
Mass (kg)	2.604	2.639	2.259	2.242
Max von Mises stress (MPa)	1.1	1.3	1.4	1.4
Factor of safety limit	30	30	5	5
Min factor of safety	24.39	30.01	19.88	19.5
Max displacement global (mm)	0.47	0.62	0.55	0.57

Because the backrest is not a component which requires a significant focus on support, the designs generated were developed using 50% infill material in order to reduce the overall mass of the component and meet the set weight requirement for the product. The models listed in Table 15 reflect the outcomes for both horizontally and vertically printed outcomes. The vertically aligned components were completed but failed to produce a geometry that would be compatible with the finalized assembly. However, the horizontally aligned designs produced several outcomes which nearly identical factors of safety, von mises stress, and maximum displacement. As a result, outcome 1, shown in Figure 45 was selected due to its low mass of 0.784 kg, as well as minimum safety factor of 15.

Table 15: Updated Generative Design Comparison for Backrest

				
	Study 2 - Generative - Outcome 1 Converged	Study 2 - Generative - Outcome 2 Converged	Study 2 - Generative - Outcome 3 Converged	Study 2 - Generative - Outcome 4 Converged
Properties				
Status	Converged	Converged	Converged	Converged
Material	Horizontal 3D Print PET 50%	Horizontal 3D Print PET 50%	Horizontal 3D Print PET 50%	Horizontal 3D Print PET 50%
Orientation	-	X+	Y+	Z+
Manufacturing method	Unrestricted	Additive	Additive	Additive
Volume (mm^3)	1.017e+6	1.359e+6	1.195e+6	1.453e+6
Mass (kg)	0.784	1.047	0.921	1.12
Max von Mises stress (MPa)	1.8	1.8	1.8	1.8
Factor of safety limit	15	15	15	15
Min factor of safety	15	15	15	15
Max displacement global (mm)	1.47	1.31	1.22	1.25

				
	Study 2 - Generative - Outcome ... Completed	Study 2 - Generative - Outcome ... Completed	Study 2 - Generative - Outcome ... Completed	Study 2 - Generative - Outcome ... Completed
Properties				
Status	Completed	Completed	Completed	Completed
Material	Vertical 3D Print PET 50%	Vertical 3D Print PET 50%	Vertical 3D Print PET 50%	Vertical 3D Print PET 50%
Orientation	-	X+	Y+	Z+
Manufacturing method	Unrestricted	Additive	Additive	Additive
Volume (mm^3)	1.021e+7	9.478e+6	1.071e+7	1.035e+7
Mass (kg)	7.866	7.303	8.255	7.977
Max von Mises stress (MPa)	1	1.1	1	1
Factor of safety limit	15	15	15	15
Min factor of safety	10.85	10.22	10.73	10.75
Max displacement global (mm)	0.39	0.39	0.39	0.39

Figure 45: Updated Generative Design for Backrest

3.10 Final Design, Mockup and Prototype

The final design is shown in Figure 46. The most notable changes include that the spindly members have been removed. This happened because the material properties of the 3D printed PET plastic were inputted into the software, while the software previously assumed the mechanical properties to be similar to injection molded PET properties. The infill settings were updated as well. This allows for the parts to be more rugged especially if forces other than the weight of the person is applied- such as a kick or an object falling onto the wheelchair.

Figure 46 A: Generative Finalized Design

Figure 46 B: Generative Finalized Design

Figure 46 C: Generative Finalized Design

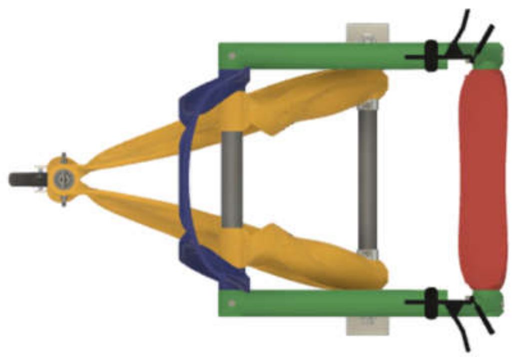


Figure 46 D: Generative Finalized Design

The prototypes that were created are small scale models printed from ABS at a 1/3 and 1/5 scale by volume. The models are scaled down to be printed in the 3D printers at the Invention Studio, where the largest bed sizes are 10" by 10", allowing for the longest possible dimension to be 14.14". A spool of PET filament was purchased, but a lab was not able to configure the printers to accommodate the new material in a timely manner; the final prototypes used ABS plastic. The prototypes showed all the parts interlocking and effectively communicated how the chair would look if produced to scale.

The original requirements are: the weight of the chair is under 25 lbs., the chair can support a 160lb person and the cost to fall under $1500 all while being 3D printed from PET plastic. The simulations show that the plastic can sustain load of a 940.8 lbs. person and the weight of the chair is around 22.4 lb. Moving forward, the full-scale model will be printed in the actual material to do stress testing. The current estimated cost is $636.60 as shown in the bill of materials in Table 16. The final design has passed all of the criteria set by the sponsor for this iteration.

Table 16: Bill of Materials

No.	Part	Material	Process	Total Cost	Vendor
1	Wheel	Pre-Assembled	Pre-Assembled	$25.00	Alibaba
2	Caster Assembly	Pre-Assembled	Pre-Assembled	$90.08	Sportaid
3	Quick Release Mechanism	Pre-Assembled	Pre-Assembled	$27.50	DME Hub
4	Brakes (2)	Composite	Premade	$130.00	Sportaid
5	Caster Connecting Tube	Aluminium	Premade	$12.31	McMaster-Carr
6	Adjustable Wheel Connection (2)	Aluminium	Sand Cast	$7.50	In-House Manufacture
7	Wheel Axle	Aluminium	Pre-Assembled	$19.38	McMaster-Carr
8	Back Crossbar	Aluminium	Pre-Assembled	$19.38	McMaster-Carr
9	Side Truss Left	PET	Additive	$53.64	3D Manufacture
10	Side Truss Right	PET	Additive	$53.64	3D Manufacture
11	Rear Truss Left	PET	Additive	$41.14	3D Manufacture
12	Rear Truss Right	PET	Additive	$41.14	3D Manufacture
13	Footrest	PET	Additive	$43.84	3D Manufacture
14	Backrest	PET	Additive	$41.79	3D Manufacture
15	Steel Wingnuts - M8	Steel	Pre-made	$6.35	McMaster-Carr
16	Steel Socket Screws - M8 x 60 mm Long	Steel	Pre-made	$13.83	McMaster-Carr
17	Steel Socket Screws - M8 x 80 mm Long	Steel	Pre-made	$7.08	McMaster-Carr

3.11 Manufacturing

Initial manufacturing plans for the product rely on large scale 3D printing. All of the parts were generated in the software with the manufacturing method set to 3D printing, so all of the parts should be easily 3D printable. The tolerances on the design is determined by the nozzle size of the 3D printer. Once a printer is selected for large-scale full-sized manufacturing, the tolerances for the design can be implemented. All of the material properties were taken from specifications for recycled PET filament, however depending on the quality of the recycled PET the material properties can degrade. To solve this glycol or similar materials can be added to bring the PET quality back up to desired levels. A cost analysis may be performed by utilizing the density of filament, job time, cost per hour of print, and filament cost. Utilizing these inputs and an estimate print rate of 0.1 kg of filament per hour, it is possible to simulate the cost per part of each piece to be printed.

3.12 Societal, Environmental, and Sustainability Considerations

As the design relies heavily on the use of recycled PET plastic, it is important to evaluate the regulations ensuring the used PET is sanitary to use after processing. PET and polyethylene naphthalate utilize similar initial processes for the preparation of recycled material to ensure the material is suitable for food-contact use [15]. Due to these processes, the FDA has no longer required the evaluation of tertiary steps to prepare the plastics for usage. For the purposes of this iteration of the design, the heating and treatment of the PET should follow these guidelines and be safe for those who are in contact with the finalized product. Because PET is used almost exclusively for food storage, structural regulations are not in place for the plastic.

In order to further analyze the social impact of the project, Table 17 is used to evaluate the goal and scope in relation to sustainability. The objective of the assessment overall is to determine the social impact of the PET used in the printed sustainable wheelchair. Ideally, the design will provide a low-cost solution to those with limited mobility in areas that have few solutions to this problem. For the functional unit of a printed wheelchair frame it is important to consider the production, manufacturing, and use stages of the lifecycle. Within the production stage, it is important to analyze the methods in which the PET is extracted and how it is processed with additive manufacturing to form the unit. The assembly of the unit should be analyzed for the manufacturing stage, while the use stage should focus on the long product life of the unit.

Table 17: Sustainability Goal and Scope

Objective of Assessment	Design Function	Functional Unit	Lifecycle Stages Considered	Associated Activities
Assess social impact of PET component of sustainable wheelchair	Provide low cost wheelchair to areas with few solution to limited mobility	Wheelchair Frame (1)	Production	Raw Material Extraction
				Material Processing (Additive)
			Manufacturing	Product Assembly
			Use	Long Product life

In order to understand those affected by each lifecycle stage, Table 18 conducts and inventory of each of the stakeholders associated with the stages. Associated with the production cycle, it is important to evaluate the methods in which the workers are affected. Workers are impacted by health and safety concerns associated with the use of PET, both with the sanitation concerns associated with used bottles and the extraction of the recyclable materials themselves both of which should be regulated under FDA standards. Manufacturing impacts both the consumer and the local community. The consumer is most affected by the length of the assembly process of the functional unit, which is reduced by the simplicity of the connection pieces of the design itself. Alternatively, the local community is most affected by how easily the unit is to distribute and the waste associated with the distribution, both of which are reduced by the ability of the design to be disassembled and stored easily. The consumer is also affected in the use stage of the lifecycle, focusing on the transportability of the unit, facilitated by the versatility of movement of the design. Within the use stage, society is also affected by the need to provide for accessibility to users of the design, which is mitigated by the structure and maneuverability of the wheelchair.

Table 18: Sustainability Inventory Analysis

Product Lifecycle Stage	Stakeholder Group	Social Impact Category	Impact Indicators
Production	Worker	Health and Safety	Sanitation associated with used bottles
			Extraction of renewable material resources
Manufacturing	Consumer	Simplicity of Assembly	Time associated with assembly
	Local Community	Distribution	Ease of distribution
			Waste associated with transportation
Use	Consumer	Ease of Use/Transportability	Versatility of movement
	Society	Accessibility	Infrastructure needed for unrestricted movement

3.13 Risk Assessment, Safety and Liability

The potential hazards of the design are shown in Table 19. Because the design was optimized by the generative design software it is already built to withstand the expected forces. Therefore, the formalized risk assessment approach shown in Table 19 shows that all the potential hazards have a low initial risk level. It is unlikely that the chair truss would break under the weight of the user because the generated design is predicted to have a mass capacity of 426.71 kg— more than five times the mass of the defined persona. That being said, even with the use of generative design certain measures must be taken to minimize risk. Material replacement for the axle part in particular could be considered because this component bears a lot of weight. Using a metal instead of PET would ensure proper support. It is possible that outside forces can damage the truss and backrest, but this can be mitigated by incorporating support material such as glycol in the fragile segments and connection points. The load wearing structures were also designed to be less exposed so that rough terrain does not damage the frame.

Table 19: Evaluation of Risk Assessment

Hazard No.	Hazard	Frequency	Severity	Initial Risk Level	Mitigation
1	Truss breaks under weight of user	Improbable	Marginal	Low	Extensive use tests performed to reinforce FEA
2	Axel cannot support load	Improbable	Marginal	Low	Consider changing material to ensure proper support
3	Outside damage breaks truss	Remote	Marginal	Low	Increase support material on fragile members of truss
4	Rough Terrain	Remote	Negligible	Low	Design frame so load bearing structures are less exposed
5	Backrest breaks	Remote	Negligible	Low	Increase material around connection points of backrest

3.14 Patent Claims and Commercialization

After further prototyping and testing of this design, or with future iterations of this design the following patent claim may be made: A medical device to aid in the mobility of disabled individuals consisting of *a) a frame constructed primarily using recycled PET plastic, b) a truss system which supports a user, c) a wheel-axle system powered by the user, and d) an ergonomically designed backrest and footrest,* whereby said device can move freely across most surfaces.

A company could possibly form around future iterations of this design and release the patent to allow production of the chair. The company could work with Wheels of Happiness or other resourceful organizations that have a large impact on people with mobility disabilities. The product would not be meant for profit-making as it is likely it would be highly subsidized or donated. Therefore, there would not be any need for regular advertisement.

3.15 Conclusions and Future Work

With this first iteration of the design completed, there is significant room for improvement with following work after a series of testing. First, the recycled PET filament obtained should be tested in ensuring its properties listed match with in-house stress/strain testing. Multiple fully scaled prototypes should be printed with the recycled PET filament. The amount of material printed as a support should be measured to understand the amount of support material that is lost to manufacturing, and how much that is costing the production of the wheelchair. Second, an assembly manual should be created as each individual part is put together as intended. One of the first tests should be to ensure it can support 160 lbs. Another test should be a drop test. There should be a test that simulates the wheelchair running off a curb with a user. There should be another test that simulates the user running into walls and rounding corners. There should also be a test that simulates different terrain. After these user tests, the wheelchair should be tested to see what its maximum load will be and if it matches the model predictions.

After ensuring that the prototype is safe to be used, the design of the model should be tested. Multiple wheelchair users should test the prototype in a safe and controlled environment. Some potential commentary could be the adjustability of the center of gravity and backrest. The most important part of this testing period will be to note if the one castor in the back is user friendly and what, if any, adjustments will need to be made. After listening to user's feedback, the wheelchair should be redesigned with any considerations to create a second iteration.

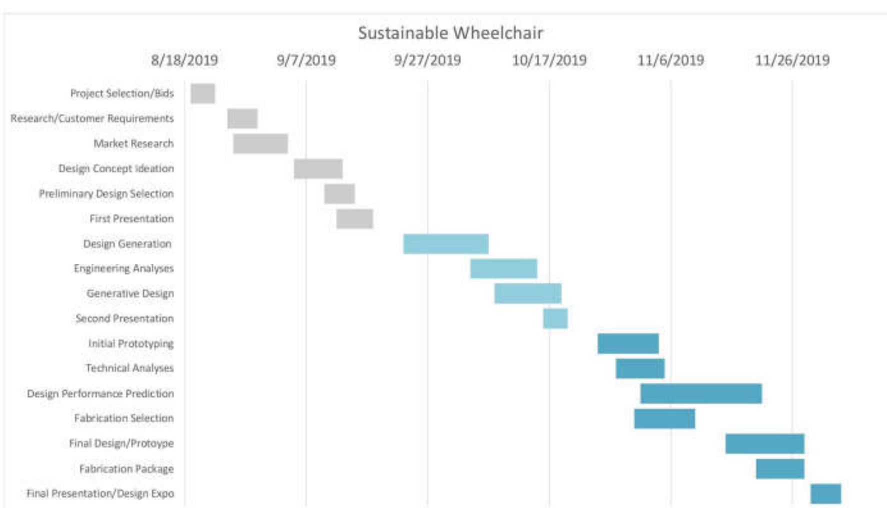
Other potential design phases that should be considered will be additive materials and different additive manufacturing methods. PET is not the most 3D printable material. The addition of glycol to PET creates PETG which creates a glossy and smooth surface finish and adheres to the bed better than PET. Depending on costs and weight, testing with carbon fiber may be laid over with PET to potentially create a stronger and more lightweight material. While 3D printing may be a viable option, it may be worth considering injection molding as a possible manufacturing method. This will be dependent on where the manufacturing will take place and the funding obtained since the initial start-up cost of injection modeling could be costlier but has larger manufacturing capabilities.

With this first iteration, the initial research and design components have been laid out to create a foundation for future iterations to be made. There are multiple venues that this wheelchair can be enhanced. There are user mobility concerns, material choice, and manufacturing methods that can be explored in the future in order to create a sustainable, transportable, and low cost wheelchair that can be distributed to underserved communities through the Wheels of Happiness Foundation's network.

Table 20 A: Gantt Chart Relaying Schedule of Project Development

TASK NAME	START DATE	DUE DATE	DURATION	SPRINT/MILESTONE
Project Selection/Bids	8/19/2019	8/23/2019	4	Initial Stages
Research/Customer Requirements	8/25/2019	8/30/2019	5	
Market Research	8/26/2019	9/4/2019	9	
Design Concept Ideation	9/5/2019	9/13/2019	8	
Preliminary Design Selection	9/10/2019	9/15/2019	5	
First Presentation	9/12/2019	9/18/2019	6	
Design Generation	9/23/2019	10/7/2019	14	Design Stages
Engineering Analyses	10/4/2019	10/15/2019	11	
Generative Design	10/8/2019	10/19/2019	11	
Second Presentation	10/16/2019	10/20/2019	4	
Initial Prototyping	10/25/2019	11/4/2019	10	Final Product
Technical Analyses	10/28/2019	11/5/2019	8	
Design Performance Prediction	11/1/2019	11/21/2019	20	
Fabrication Selection	10/31/2019	11/10/2019	10	
Final Design/Protoype	11/15/2019	11/28/2019	13	
Fabrication Package	11/20/2019	11/28/2019	8	
Final Presentation/Design Expo	11/29/2019	12/4/2019	5	

Table 20 B: Gantt Chart Relaying Schedule of Project Development



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