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Material Selection for an Electric Motor Assisted Stroller

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By: Luke Appling

Abstract

The focus of this report is the process used for material selection for components of an electric motor assisted stroller designed for a senior design project. Both Solidworks' FEA testing and CES EduPack's materials database were utilized to gather the necessary data to evaluate both material properties and component design parameters.

The initial selection process focused on gathering the necessary data and desired properties for each component system of the design. First finite element analysis was conducted on each component to find the maximum stresses encountered in operation. Then components were considered in terms of other important factors that might affect operation or the overall functionality of the system as whole. These factors include things such as corrosion resistance, environmental durability, machining cost, price, and thermal properties.

All the gathered factors and data were then used to compare potential materials found using CES EduPack's material database. A single material was then chosen for each component system and tested under FEA analysis to ensure that a satisfactory factor of safety was found.

Acknowledgments

First, I must thank my senior design group including Adrian Valvida Portilla, Darian Layberger, Okie McCart, and Mark Fox.

I must recognize the professors and staff of Kennesaw State University who have shared their knowledge with me and guided me though the many questions that I have had during my years here. Professors such as Dr. Kami Anderson, Dr. Mir Atiqullah, Dr. David Veazie, and Dr. Ayse Tekes.

I must also thank my family for allowing me to have the opportunity to receive an education and encouraging me to strive to better myself. Without their support I would never have grown into the person that I am today.

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1 Introduction

1.1 Main Project

Last semester I began my senior design track with Senior Design 1. All students in the class were tasked with creating proposals for several of the available projects offered by both the professor and several companies. The proposals were then reviewed by the companies and teams were chosen biased on how well they liked them. I was assigned to a group with four other students: Adrian Valvida Portilla, Darian Layberger, Okie McCart, and Mark Fox.

We were chosen to work on a project for the class instructor Dr. Atiqullah. He asked us to develop an idea that he had been considering for a while, an electric motor assisted collapsible stroller. This system would be able to assist a parent in transporting children over uneven terrain or over long distances by lessening the physical effort required to push them. After meeting with Dr. Atiqullah several times we were able to develop a series of design specifications that must be met to ensure the system worked as intended:

1. Stroller must be able to carry 120 lbs load
2. Must be able to handle an 8-inch bump
3. Must collapse enough to fit in a $5 * 3 * 4\ ft^3$ trunk
4. Must take less than a minute to fold and unfold
5. Motor must provide 30 lbs of force
6. Batteries must last for 4 hours of use
7. Batteries must Fully charge in 12 hours
8. Must adhere to all child safety regulations
9. Must cost less than $500

These specifications served as the hard boundaries for our project, we were free to add additional restrictions and specifications as we progressed through the project, but they were less critical. This allowed us to have a lot of freedom when we began researching and designing the system.

1.2 Specific Project

The specific purpose of this report is document the research done to assign the different types of materials that will make up each of the main components. All materials selected were rated by some of the following characteristics

- Weight
- Price
- Strength
- Environmental footprint
- Thermal Properties
- Chemical Reactivity
- Environmental Durability

Each material's properties will be weighed against the factors listed above, although only the factor relevant to the materials intended use will be considered for the purposes of material selection.

Two specific sections will be devoted to each component evaluated. The first section will focus on component design and the factors that are necessary for that component. This will include factors such as the anticipated loading on the component, price limitations for materials, manufacturing methods for each component, as well as any other factor that is necessary for that component (*i.e.* UV durability, Fatigue life, Thermal properties). The second section will focus on the desired properties of each material and the material selection process. The materials will be evaluated by their non-necessary but desirable properties and rated accordingly.

It is important to note that only components designed to be manufactured will be documented in this report. The components in our system that are purchased and already manufactured will not be considered in this report. Those parts are already selected and rated biased on the component characteristics and are outside the scope of this capstone research report.

2 Component Evaluation

All components will be defined and evaluated in this section. All necessary factors for each component will be defined and evaluated in this section to pick appropriate materials

2.1 Component Definitions

With the large number of parts in the assembly it is important to define which components and sections we are selecting materials for. The components evaluated are listed along with the corresponding names and colors on the assembly in Figure 2.1.1.1.

1. Frame: Green
2. Axles: Yellow
3. Plastics: Blue
4. Housing: Black
5. Fabric: Not shown in model

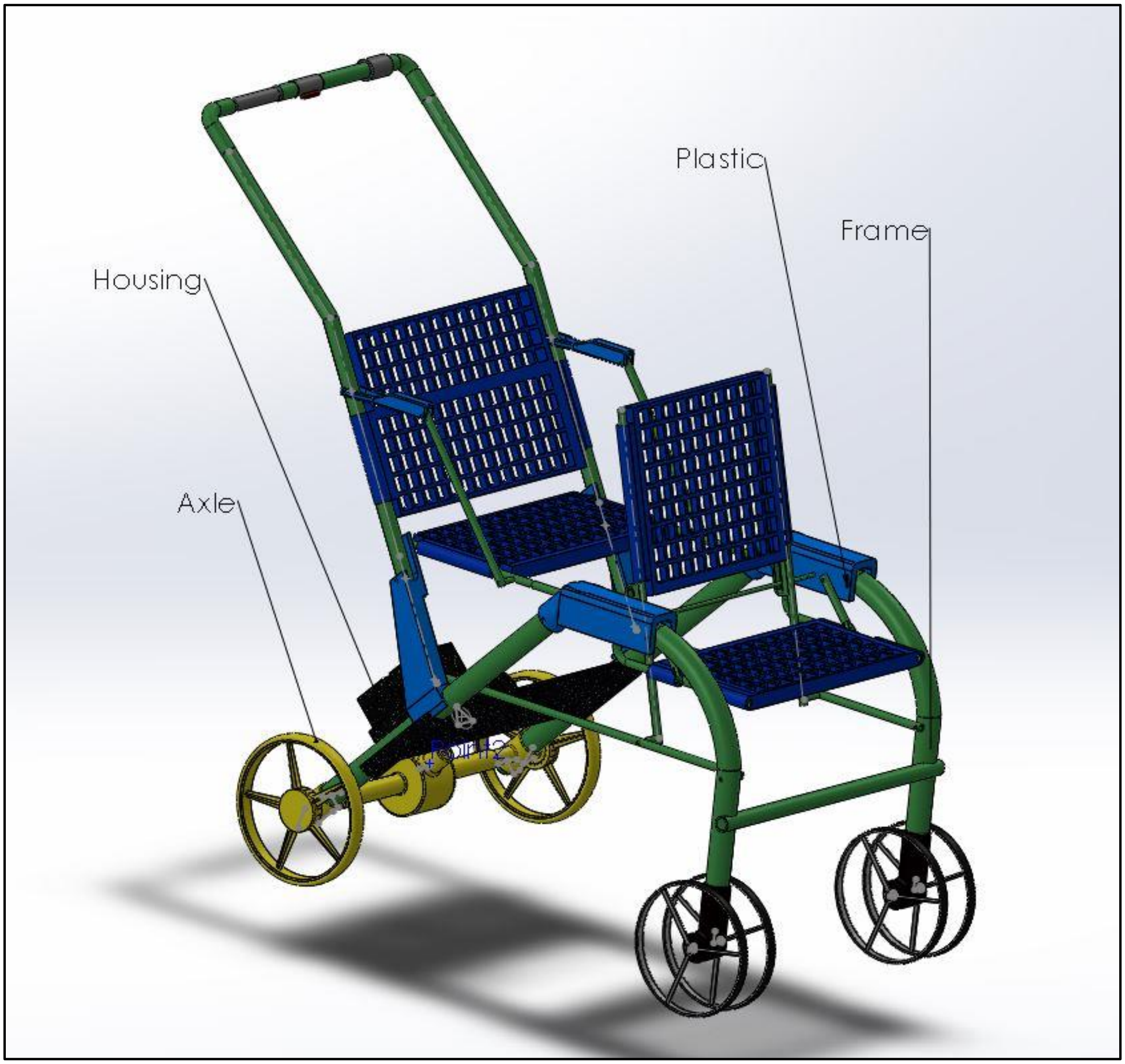


Figure 2.1.1.1: Full assembly with colored components

2.2 Frame

This component is comprised of several tubes which make up the body of the stroller system. This component must withstand all the load on the system and still be able to collapse when needed. A clear image of half of the frame can be seen in Figure 2.2.1.1.

2.2.1 Forces acting on the frame

Due to the complex geometry of the frame the component was loaded into Solidworks and placed under the expected load to generate a maximum Von Mises Stress. The analysis generated a max Von Mises Stress of 71920 kPa as seen in Figure 2.2.1.2.

Figure 2.2.1.1: Frame half view with highlighted components

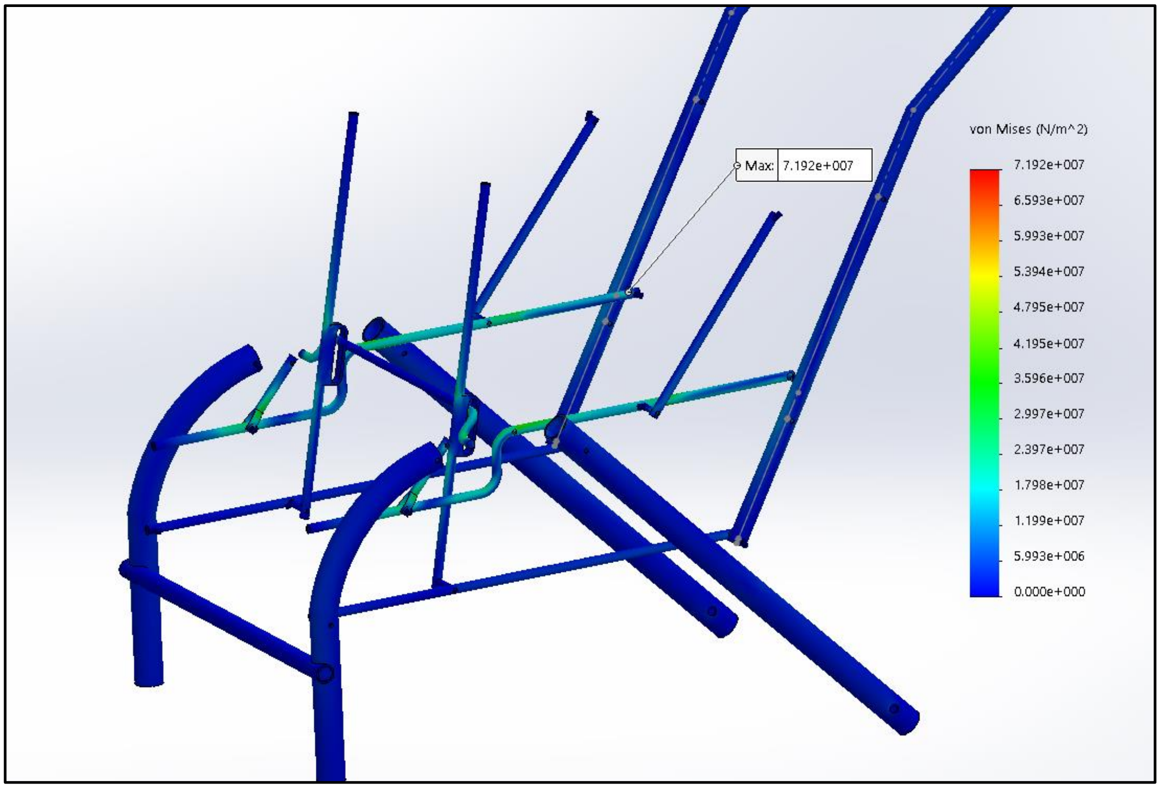


Figure 2.2.1.2: Frame stress test with all other components hidden

2.2.2 Manufacturing Method

The tubes will be ordered in the appropriate sizes and cut to size, then they must be drilled with the appropriate holes. They must be made from a weld friendly material as some tubes must be welded together to form more secure joints.

2.2.3 Price

As this system makes up most of the structure it must be reasonably low cost and widely available.

2.2.4 Environmental Durability

As this system will be exposed to a variety of outdoor environments for a number of years corrosion resistance of the main frame is extremely important. It must be resistant to corrosion due to both freshwater and salt water as well as any other liquids it might encounter in an urban environment.

2.3 Axles

This component is comprised of two main shafts the floating axle which holds all the weight of the system, and the driving axle which turns inside the floating axle and powers the wheel. A clearer image of the axles can be seen in Figure 2.3.1.1.

2.3.1 Forces Acting on the Axles

We decided to apply 80 lbs, a little over half of the max weight of the system, on the back axles two connection points to the frame. Applying the resulting loads of 40 lbs per connection in a stress analysis in Solidworks yielded a maximum Von Mises Stress of 4401 kPa. This analysis can be seen in Figure 2.3.1.2 and Figure 2.3.1.3.

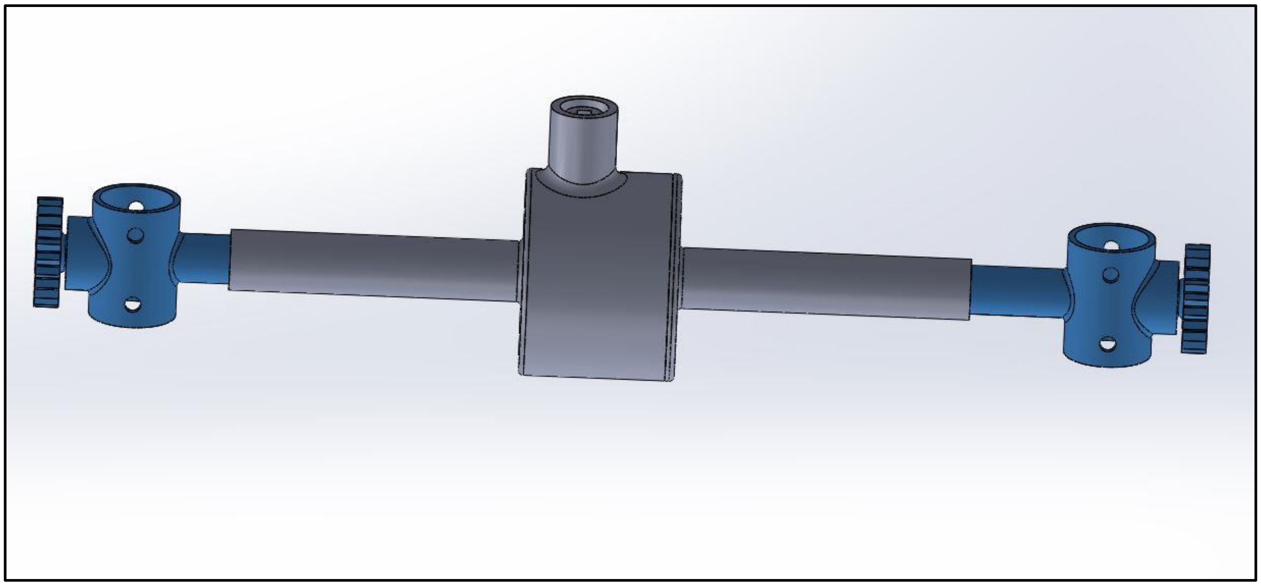


Figure 2.3.1.1: Axle Sub-assembly with colored load bearing components

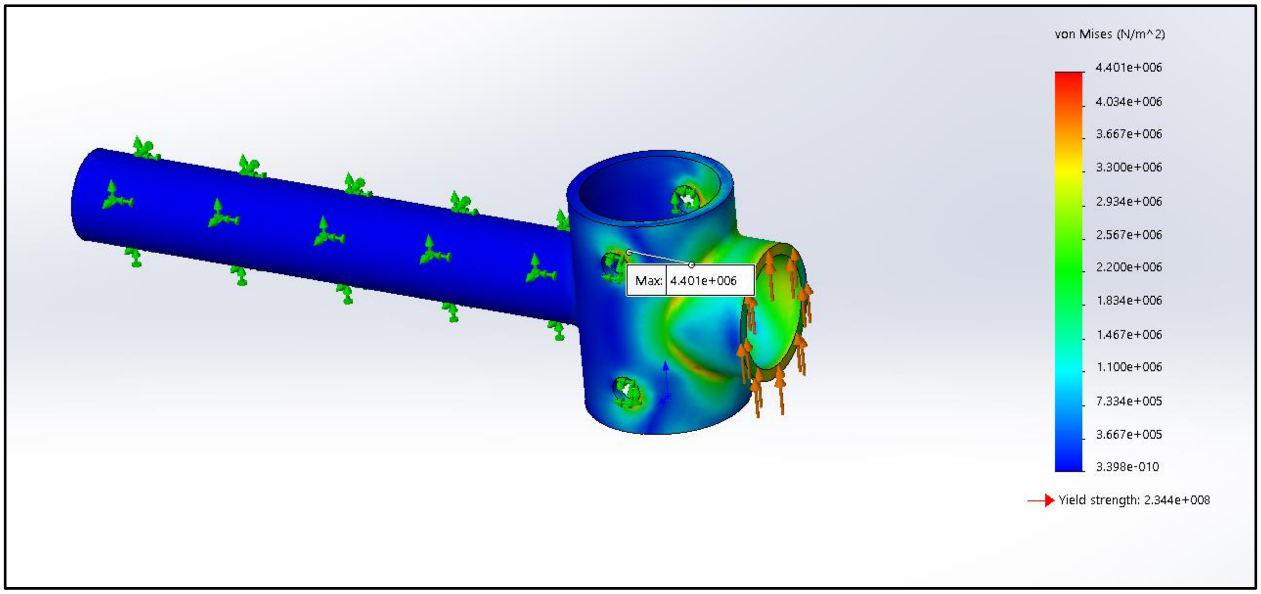


Figure 2.3.1.2: Axle Mount Stress simulation

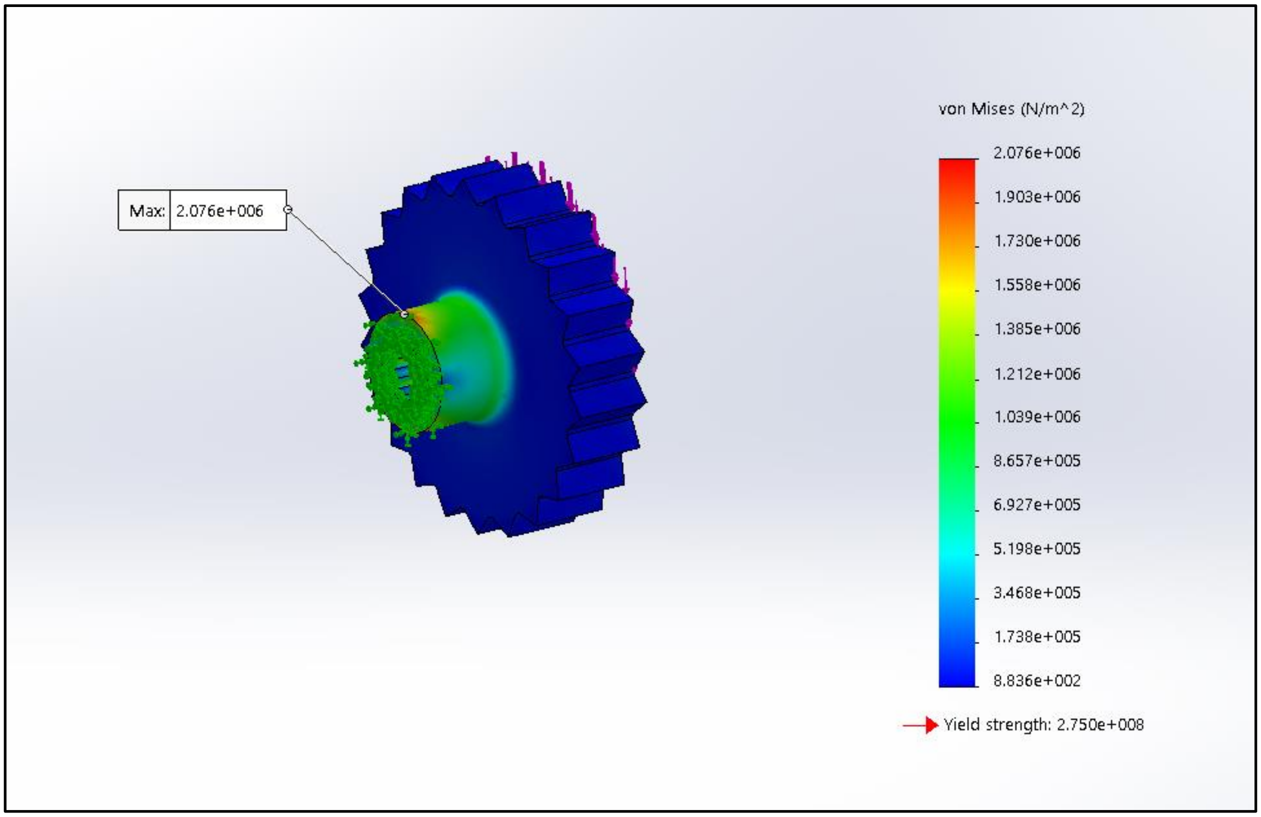


Figure 2.3.1.3: Wheel Hub Stress simulation

2.3.2 Manufacturing Method

This component will be manufactured out of pre-rolled tubes and a central shaped sphere. It is vital that the material chosen is easily weldable as it will be critical that the floating axle retains strength across its length.

2.3.3 Environmental Durability

As this component is so close to the ground, it will be the most exposed element to the environment. The material chosen must be extremely resistant to all forms of corrosion and be able to withstand any reasonable amount of wear and grime it might accumulate from outdoor use.

2.4 Plastics

There are several parts of our system that due to either their odd shape or their contact with children that need to be made from a material other than metal. These parts have been grouped into a single component as they all have similar physical requirements. An example of each type of part can be seen clearly in Figure 2.4.1.1., Figure 2.4.1.2, Figure 2.4.1.3, and Figure 2.4.1.4.

2.4.1 Forces Acting on Plastic Components

Each of these parts has some form of different load placed on them. To ensure that the chosen material will be sufficiently strong all parts were placed into stress simulations in Solidworks and analyzed to find their maximum Von Mises stress. Then the largest stress value was used as the criteria for material selection. The analysis of the three components under the greatest stress can be seen in figures Figure 2.4.1.5, Figure 2.4.1.6, Figure 2.4.1.7. The maximum Von Mises stress found was 6807 kPa in the bottom plate of the back seat.

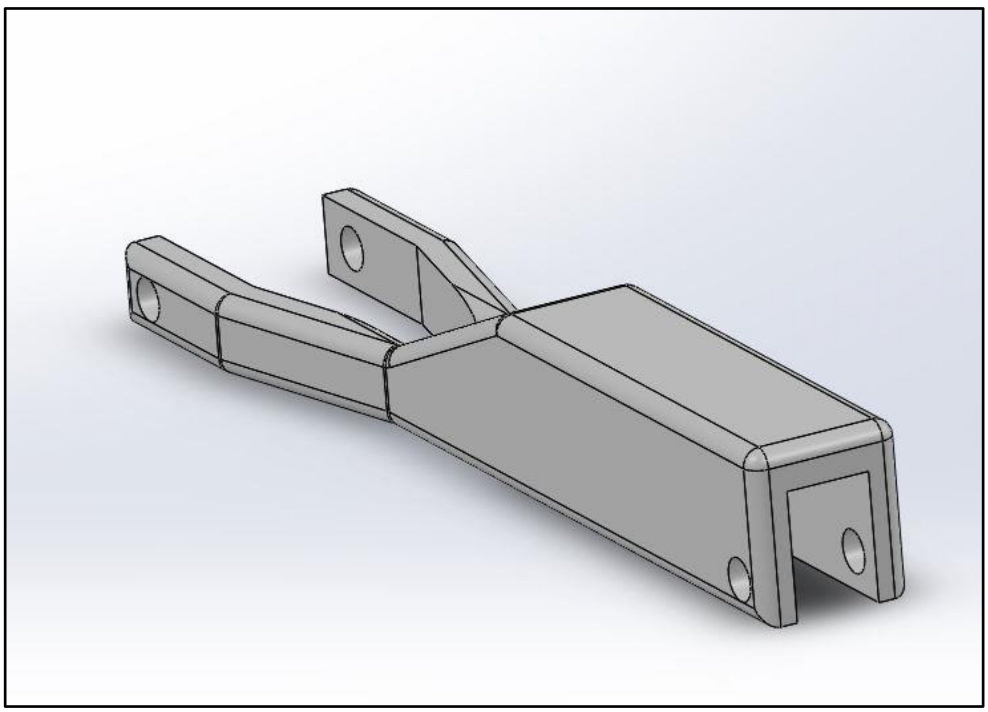


Figure 2.4.1.1: Back seat arm rest

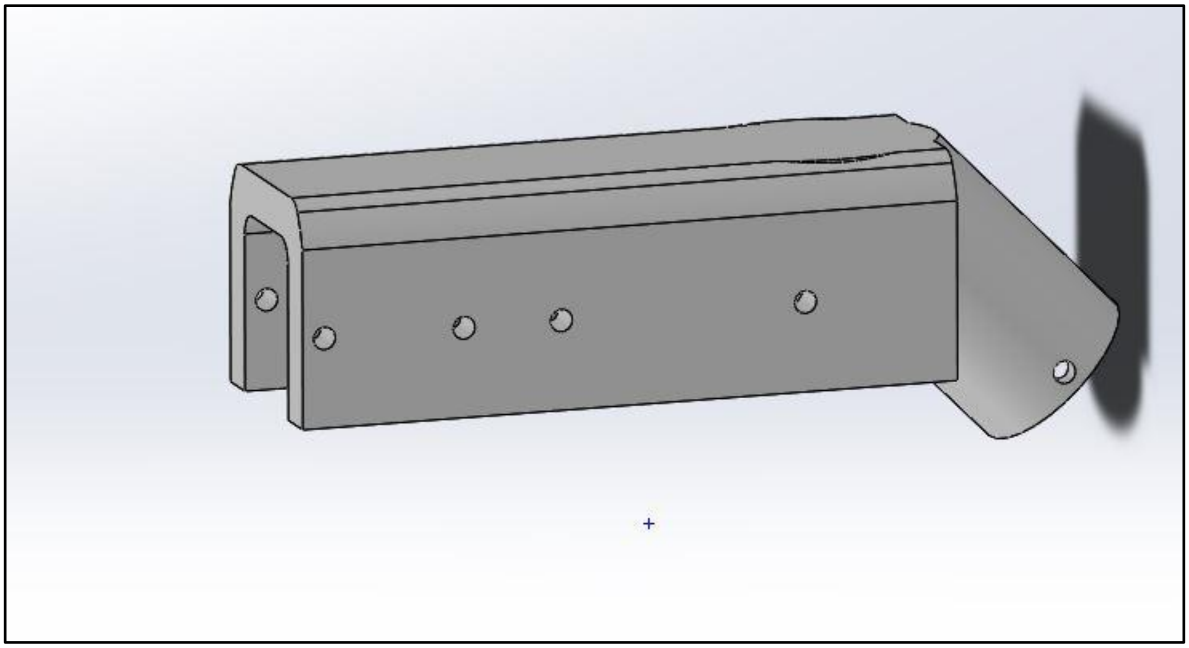


Figure 2.4.1.2: Main middle beam connector

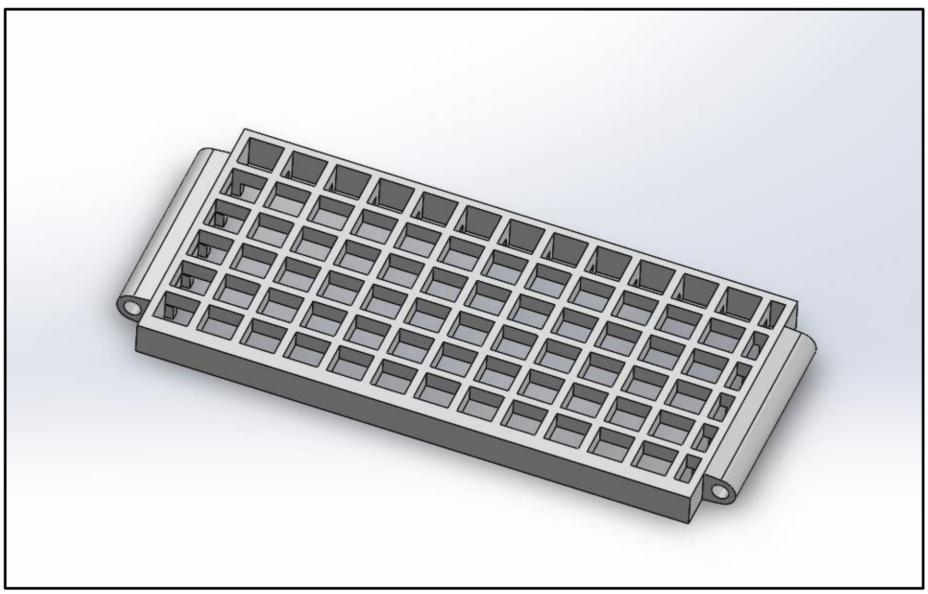


Figure 2.4.1.3: Back seat bottom plate

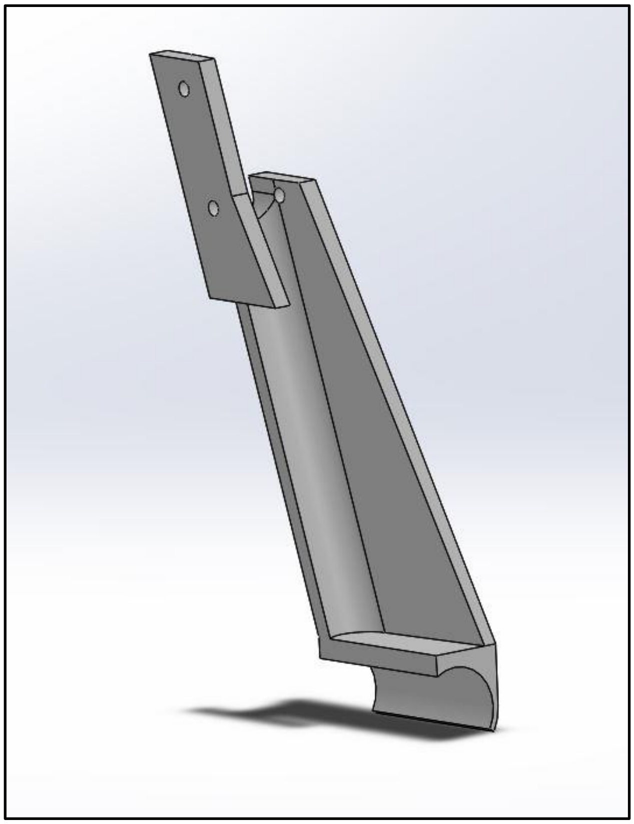


Figure 2.4.1.4: Handlebar connection joint

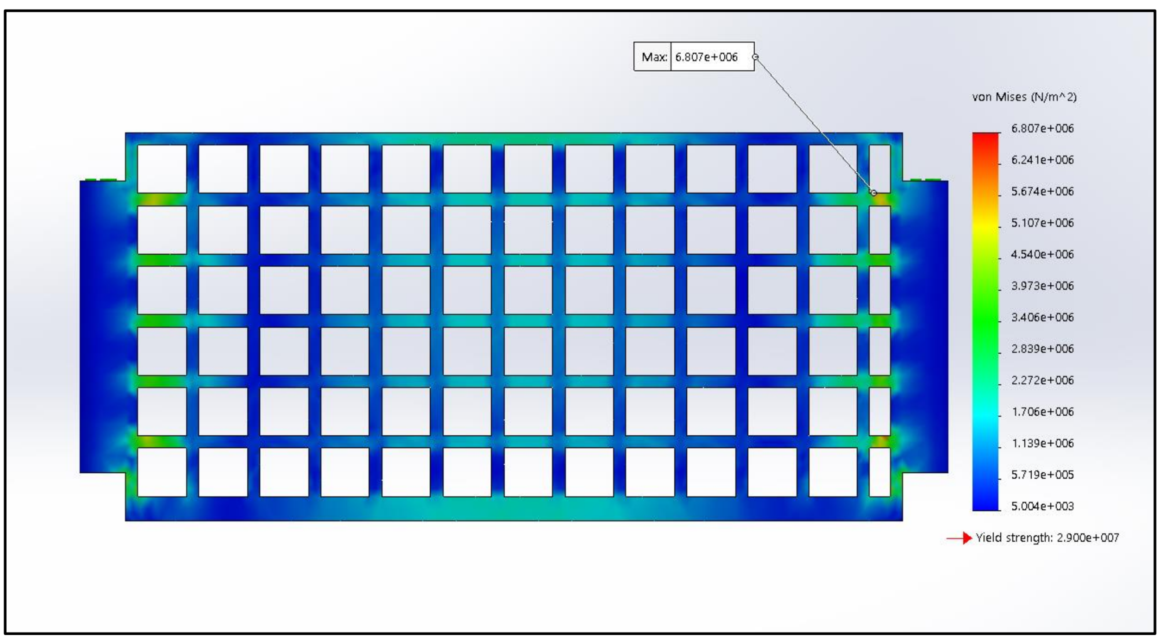


Figure 2.4.1.5: Back seat stress test

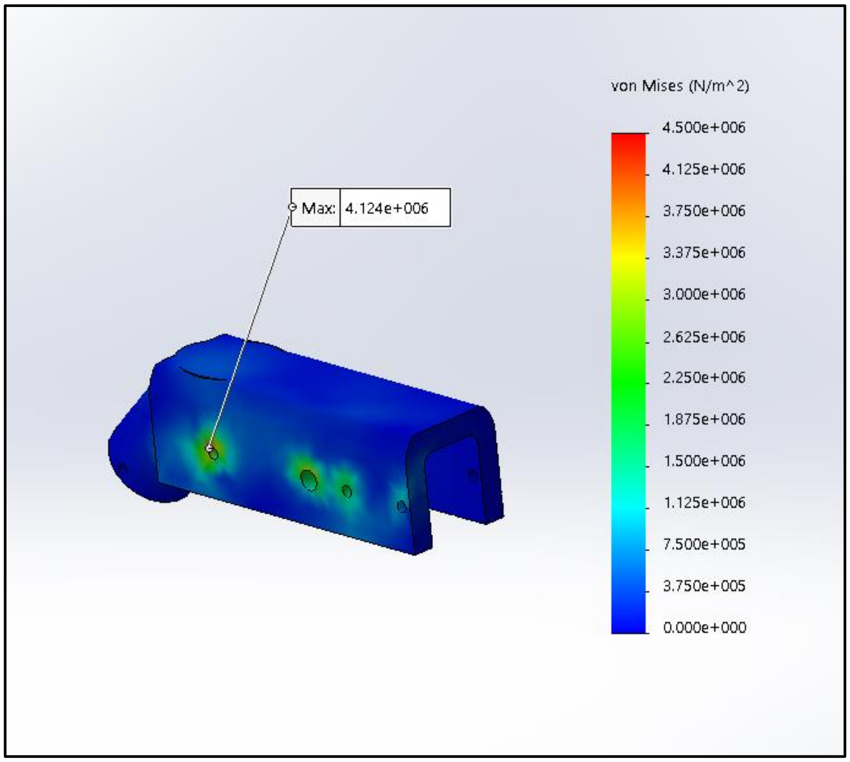


Figure 2.4.1.6: Main middle beam stress test

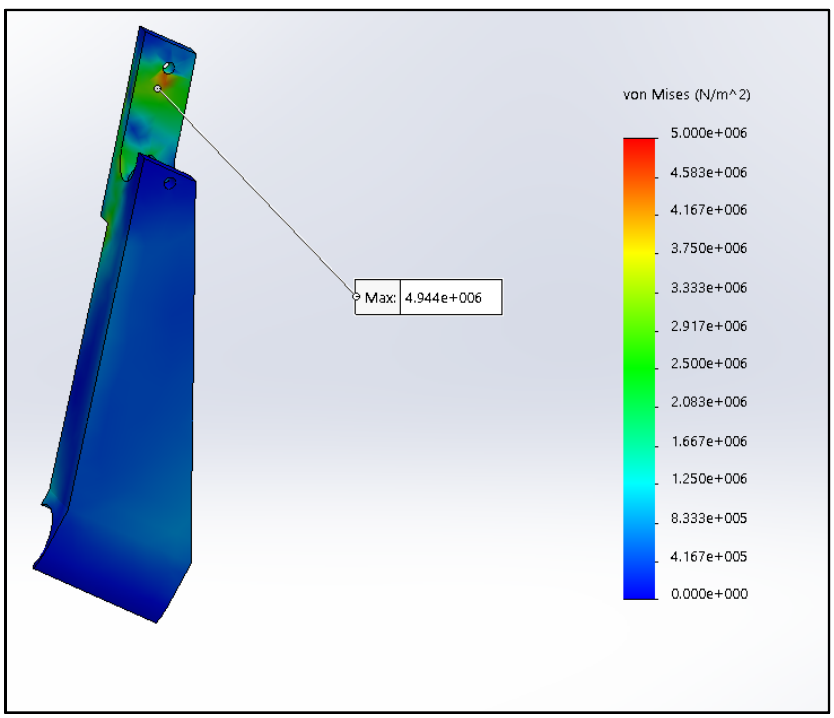


Figure 2.4.1.7: Handlebar connection joint stress test

2.4.2 Manufacturing

As some of the parts made of plastic are irregular in shape, it is important that the material is either easy to mold or cast into shape.

2.4.3 Fatigue

All plastic component will be placed under cyclical loading every time a child enters or exits the system. This means that it is important that the chosen material have a high fatigue life.

2.4.4 Thermal Properties

It is important that all materials considered for this section can retain their shape and strength within the range of standard outdoor temperatures (-20 °F to 120°F). It is also important that the material be a good thermal insulator to avoid transferring too much heat to the children.

2.4.5 Chemical Reactivity

It is important that any materials selected for this component be relatively chemically inert and nontoxic to ensure the safety of the children. It is also important that this component can withstand cleaning with normal household chemical cleaners.

2.4.6 Environmental Durability

All components must be able to withstand normal outdoor environments, but special attention must be given to this component to ensure that it does not break down under UV light or any form of water over time.

2.5 Fabric

Like most stroller systems our stroller will have some form of fabric that is stretched between the frame to form the seats themselves. The material for this component is likely to mixed with other materials to create the fabric itself. As such this component is was not evaluated for its mechanical properties as fabric mechanical properties are beyond the scope of my project. As this component was not include in the full model an example of this component can instead be seen covering the stroller in Figure 2.5.1.

2.5.1 Thermal Properties

As this is the component that is in the most contact with the children it is important that it can maintain its form under a normal range of temperatures. It also must function as a good thermal insulator to prevent heat transfer from the metal components of the stroller to the children.

2.5.2 Chemical Reactivity

Much like the plastic components it is important that this material is nontoxic and relatively chemically inert to ensure the safety of the children. It is also important that this material can hold up to all normal household cleaners and be safely washed.

2.5.3 Environmental Durability

This material must be resistant to water and UV lighting as it will cover most of the surface area of the system. It must be able to endure outdoor elements over the many years of the systems lifetime.

Figure 2.5.1: Baby Trend Sit N Stand Double Stroller

2.6 Housing

This component is the casing that holds our systems motor and batteries. It can be seen more clearly in Figure 2.6.1.1.

2.6.2 Strength

This component was loaded with forces representing the weight of both the batteries and the motor, 7 lbs and 2.86 lbs respectively, and run through a Solidworks' stress simulation to find the maximum Von Mises stress in the part. The test yielded a maximum von Mises stress of 3594000 Pa The analysis results can be seen in Figure 2.6.1.2.

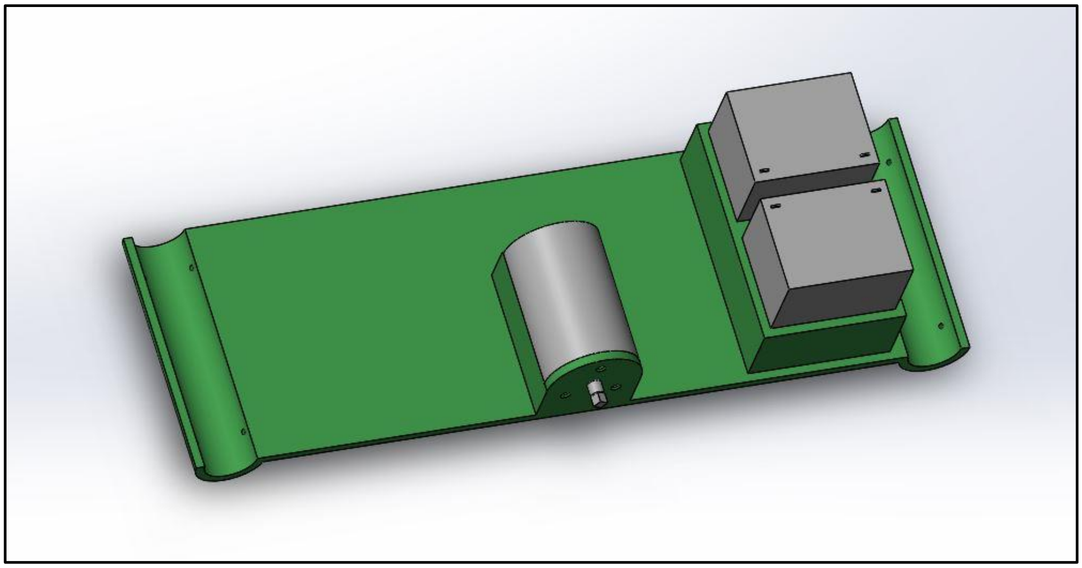


Figure 2.6.1.1: Housing assembly with motor and battery models in place

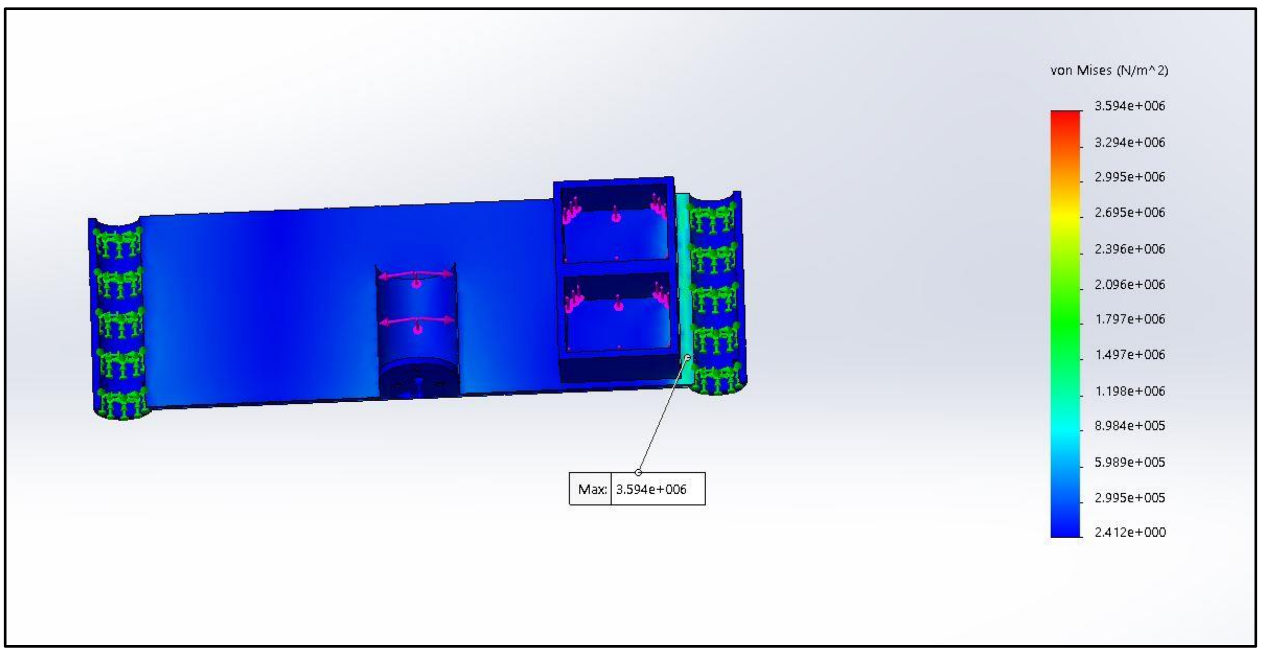


Figure 2.6.1.2: Stress simulation results

2.6.3 Thermal Properties

This casing must be able to withstand a temperature of at least 150°F as both the batteries and motor will generate heat when in use. It is also important that the material be flame resistant in the event of an unforeseen critical failure of the batteries.

2.6.4 Environmental Durability

Much like the axles this component is located on the underside of the stroller and exposed to more dirt and grime than the other components. This means the material chosen must be extremely resistant to all forms of corrosion and be able to withstand any reasonable amount of wear and grime it might accumulate from outdoor use.

3 Material Selection

The potential materials will be selected using the criteria listed in section 2. Then the potential materials will be compared on biased on their attributes and one will be selected as the chosen material. Again, each component will have its own section in this chapter.

To select the potential materials, I will be using a database called CED eduPack 2017. This software can compare the properties of hundreds of different materials and allows me find only the materials that fit my criteria and rank them by various properties.

3.1 Frame

As found in section 2.2 the material of the frame must be able to withstand at least 71920 kPa, be easy to weld, low in price, and have a resistance to environmental effects. In addition, it is desirable that the material be light weight and have a smaller environmental footprint. In accordance, the following criteria shown in Figure 3.1.1.1 was entered into CES eduPack's search system.

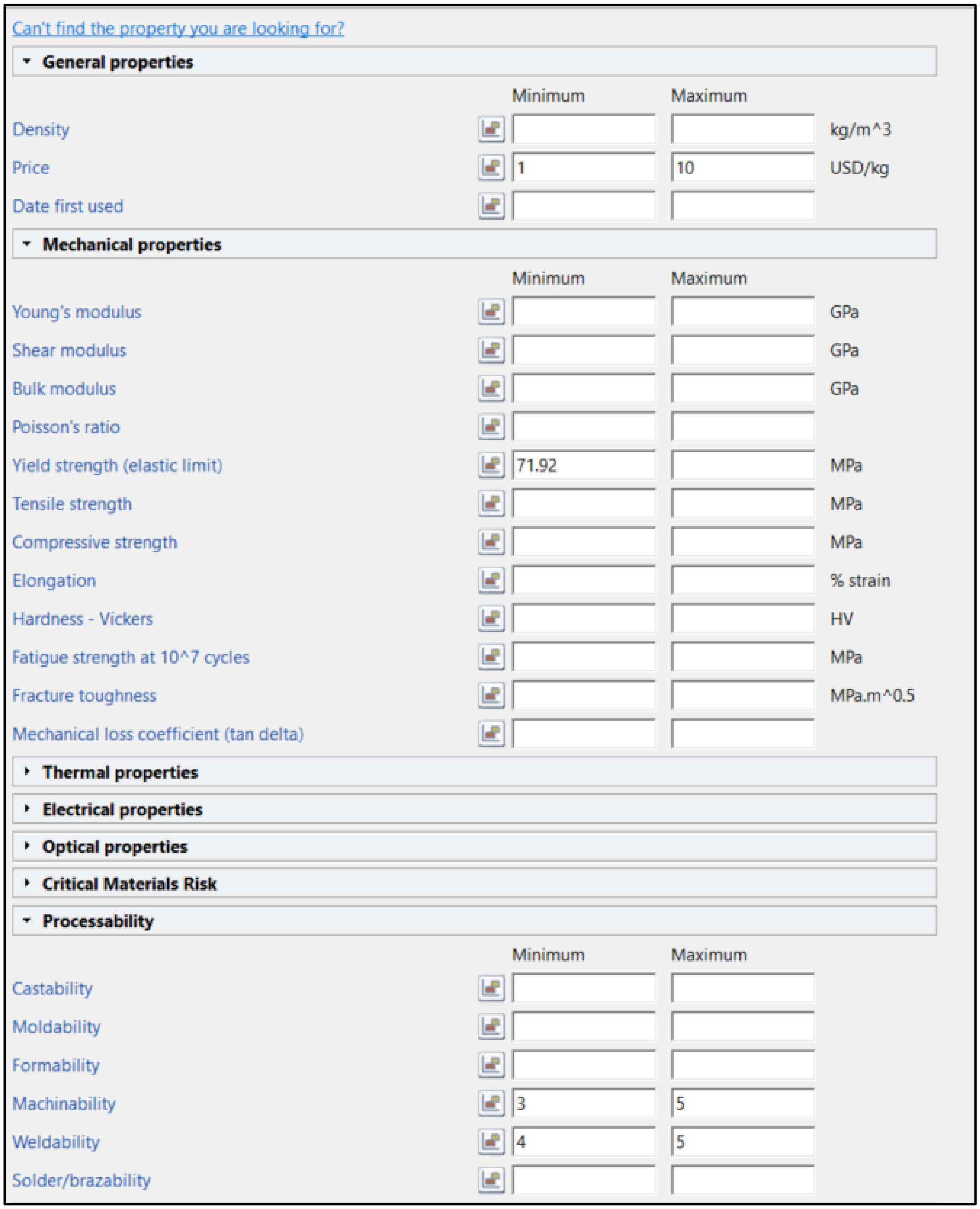


Figure 3.1.1.1: Frame material search criteria

In addition to the criteria above the software was asked to only return materials that poses good welding properties and have good environmental durability.

The resulting materials to be considered for use can be seen in Figure 3.1.1.2

Name	Price (USD/kg)
Non age-hardening wrought Al-alloys	1.9 - 2
Age-hardening wrought Al-alloys	1.9 - 2
Cast Al-alloys	1.96 - 2.1
Commercially pure zinc	2 - 2.2
Zinc die-casting alloys	2.21 - 2.42
Brass	4.29 - 5.03
Stainless steel	5.61 - 6.1
Bronze	5.97 - 6.98

Figure 3.1.1.2: Materials considered for frame

After looking over the list of materials, four materials were selected to be likely candidates based upon their characteristics, availability, and common sense. These materials are denoted by a star in Figure 3.1.1.2. These materials were compared using the decision matrix shown in Figure3.1.1.3.

Material	**Weight**	**Rating**	**Price**	**Rating**	**Strength**	**Rating**	**Corrosion Resistance**	**Rating**
Non-age hardening wrought Al - Alloys	5	5	5	5	4	3	3	4
Stainless Steel	5	3	5	2	4	5	3	5
Commercially Pure Zinc	5	4	5	4	4	3	3	2
Brass	5	3	5	3	4	4	3	3

Material	**Environmental Footprint**	**Rating**	**Totals**
Non-age hardening wrought Al - Alloys	2	3	80
Stainless Steel	2	2	64
Commercially Pure Zinc	2	5	68
Brass	2	3	61

Figure 3.1.1.3: Frame material decision matrix

In the decision matrix special consideration was given to material price and weight. As this component is the largest component in the system it is important that its lightweight to ensure the overall weight of the system is as low as possible and it is important to keep this section as low cost as possible to ensure that we meet our overall price limitation on the system. All materials were then plotted biased on density in (kg/m^3) and price in $(\mathrm{USD}/\mathrm{kg})$ as seen in Figure 3.1.1.4. As all materials have sufficient strength, lower density will result in an overall lower weight for the component.

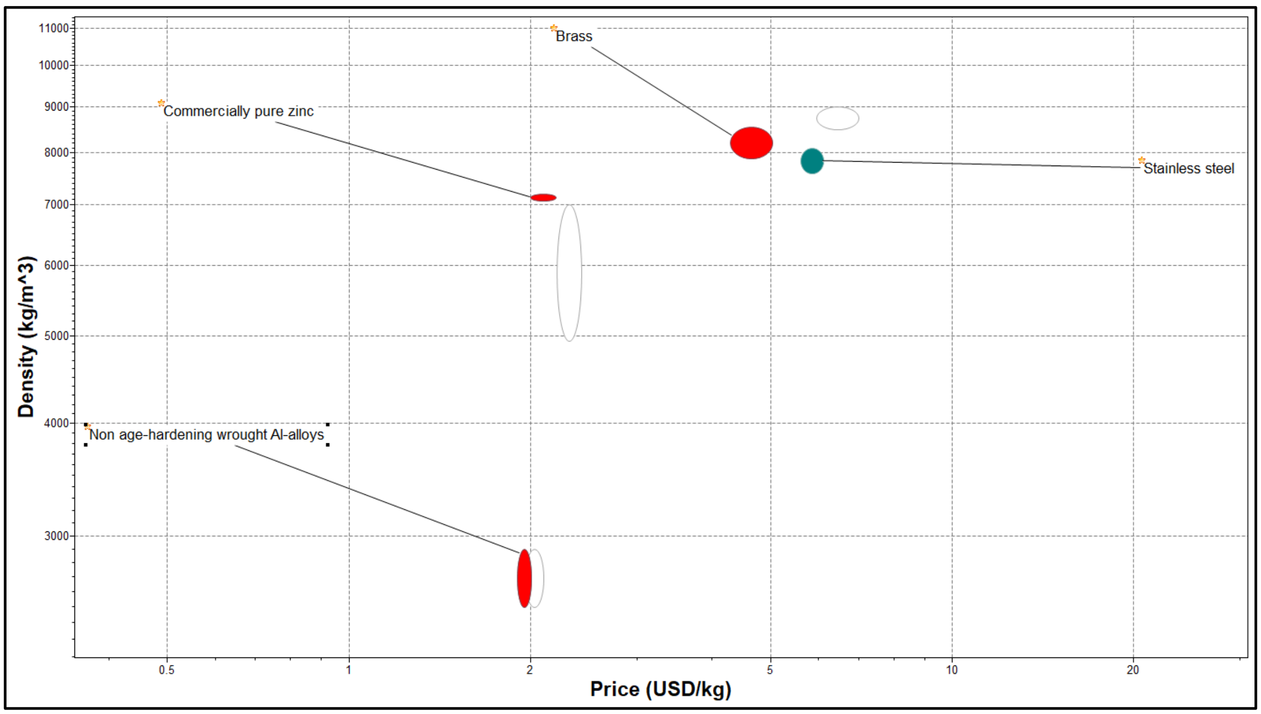


Figure 3.1.1.4: Material price v density

As seen in the decision matrix, a non-age hardening aluminum alloy is ideal for the constraints of our component as its low cost and weight make it the optimal material for our system Aluminum alloy 5052-0 was selected as our material due to its relative availability as well as possessing the needed physical properties for this application.

The material was applied to the frame and tested under a stress test in Solidworks which returned a minimum factor of safety of 1.634 as seen in Figure 3.1.1.5.

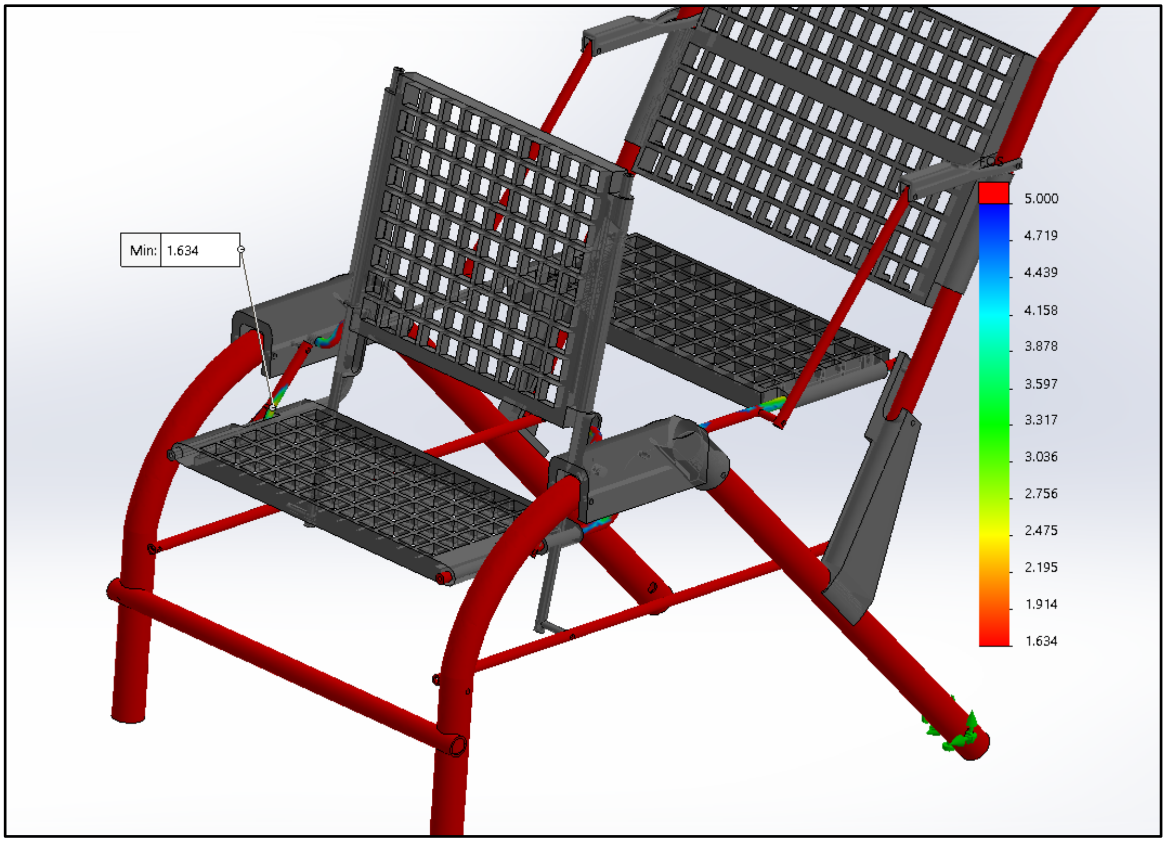


Figure 3.1.1.5: Frame stress test

3.2 Axles

As found in section 2.3 the material of the axles must be able to withstand at least 4401000 Pa be easy to weld, have a high resistance to environmental effects. In accordance, the following criteria shown in Figure 3.1.2.1 was entered into CES eduPack's search system.

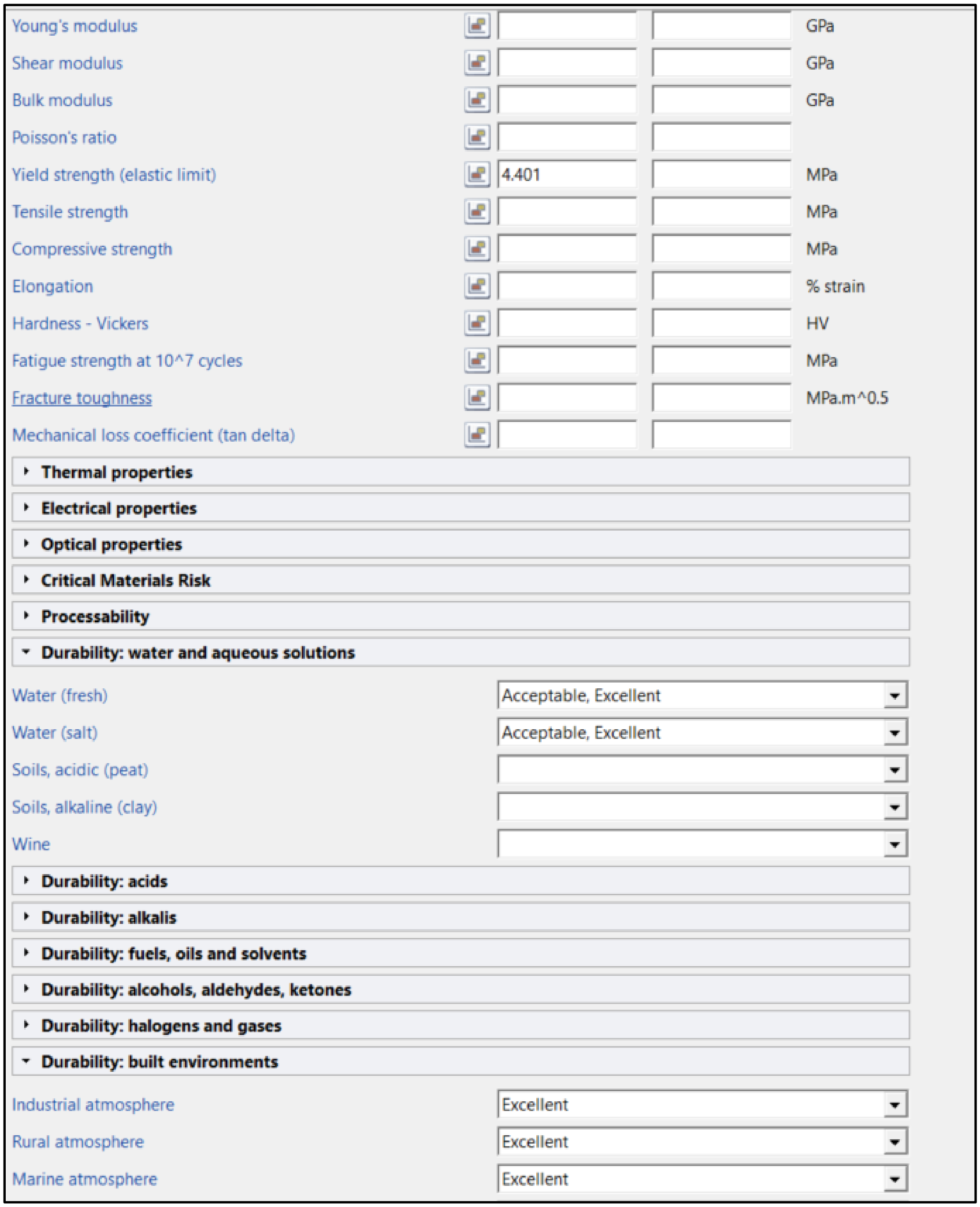


Figure 3.1.2.1: Axle material search criteria

In addition, the software was asked to only return materials that are cheaper than $15/kg, and easy to weld and machine.

The resulting materials to be considered for use can be seen in Figure 3.1.2.2

Name	Price (USD/kg)
Non age-hardening wrought Al-alloys	1.9 - 2
Age-hardening wrought Al-alloys	1.9 - 2
Cast Al-alloys	1.96 - 2.1
Stainless steel	5.61 - 6.1
Bronze	5.97 - 6.98
Commercially pure titanium	12.7 - 14.3
Nickel-chromium alloys	13.9 - 15.3

Figure 3.1.2.2: Axle materials for consideration

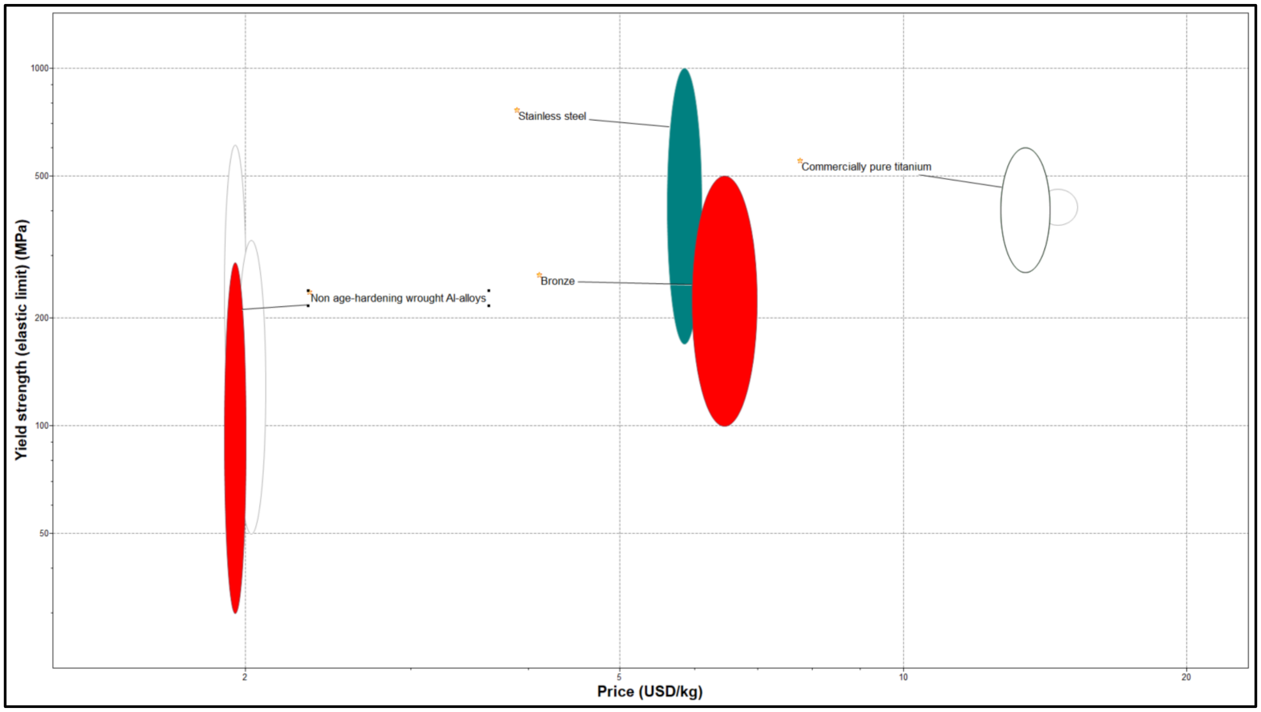
After looking over the list of materials, four materials were selected to be likely candidates based upon their characteristics, availability, and common sense. These materials are denoted by a star in Figure 3.1.2.2. These materials were compared using the decision matrix shown in Figure3.1.2.3.

Material	**Weight**	**Rating**	**Price**	**Rating**	**Strength**	**Rating**
Non-age hardening wrought Al - Alloys	1	5	2	5	5	3
Stainless Steel	1	3	2	2	5	5
Commercially Pure Zinc	1	4	2	4	5	3
Bronze	1	3	2	3	5	4

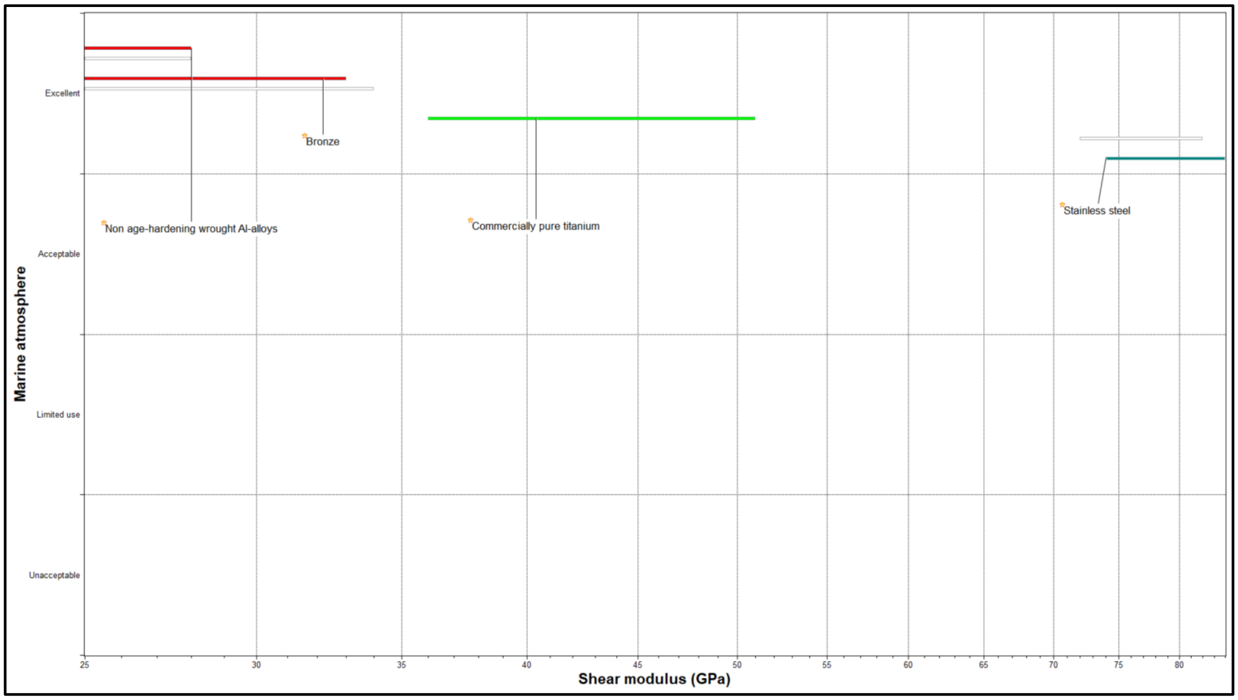
Material	**Environmental Durability**	**Rating**	**Environmental Footprint**	**Rating**	**Totals**
Non-age hardening wrought Al - Alloys	5	4	1	3	53
Stainless Steel	5	5	1	2	59
Commercially Pure Zinc	5	2	1	5	42
Bronze	5	3	1	3	47

Figure 3.1.2.3: Axle material decision matrix

In the decision matrix special consideration was given to strength and environmental resistance as this component will be supporting the entire weight of the system and be the most exposed to environmental effects. Figures 3.1.2.4 and 3.1.2.5 show Yield strength vs Price and Marine resistance vs Shear modulus.



Figures 3.1.2.4: Yield strength vs Price



Figures 3.1.2.5: Marine resistance vs Shear modulus

As seen in the decision matrix, stainless steel is the ideal material for this component as it has extremely high strength and very good resistance to all forms of corrosion. In addition, it is extremely easy to weld which is essential to ensure the overall strength of the component. In particular, AISI 321 annealed stainless steel was chosen for our testing due to its favorable properties.

When the material was applied to the components and tested under the approximated load in Solidworks, a minimum factor of safety of 53.27 was found. The simulation results can be seen in Figure 3.1.2.6 and Figure 3.1.2.7.

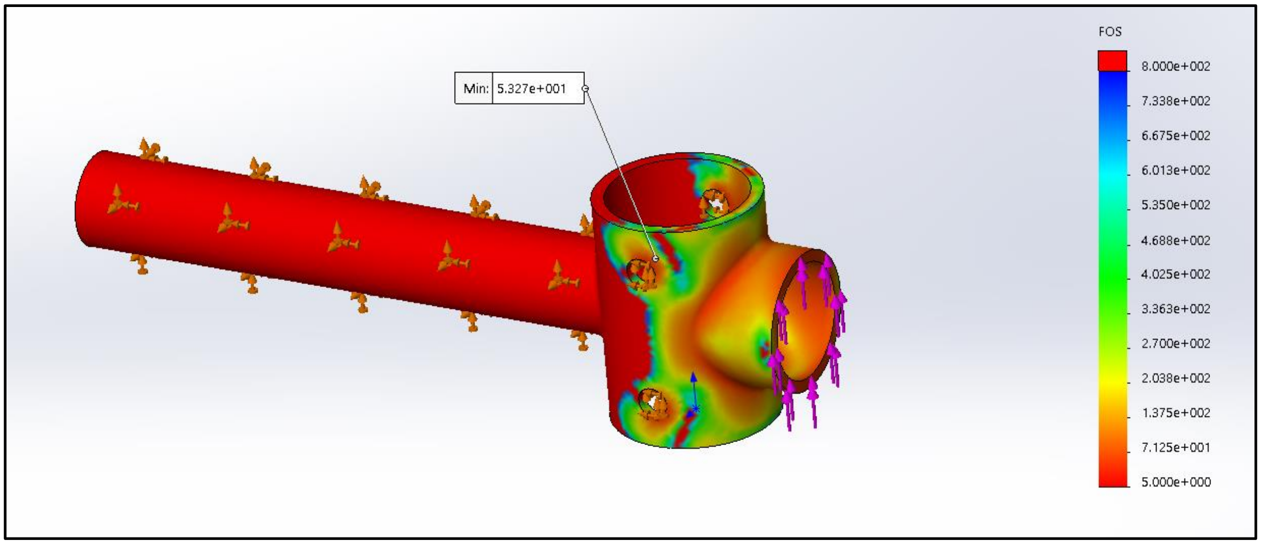


Figure 3.1.2.6 Axle mount factor of safety results

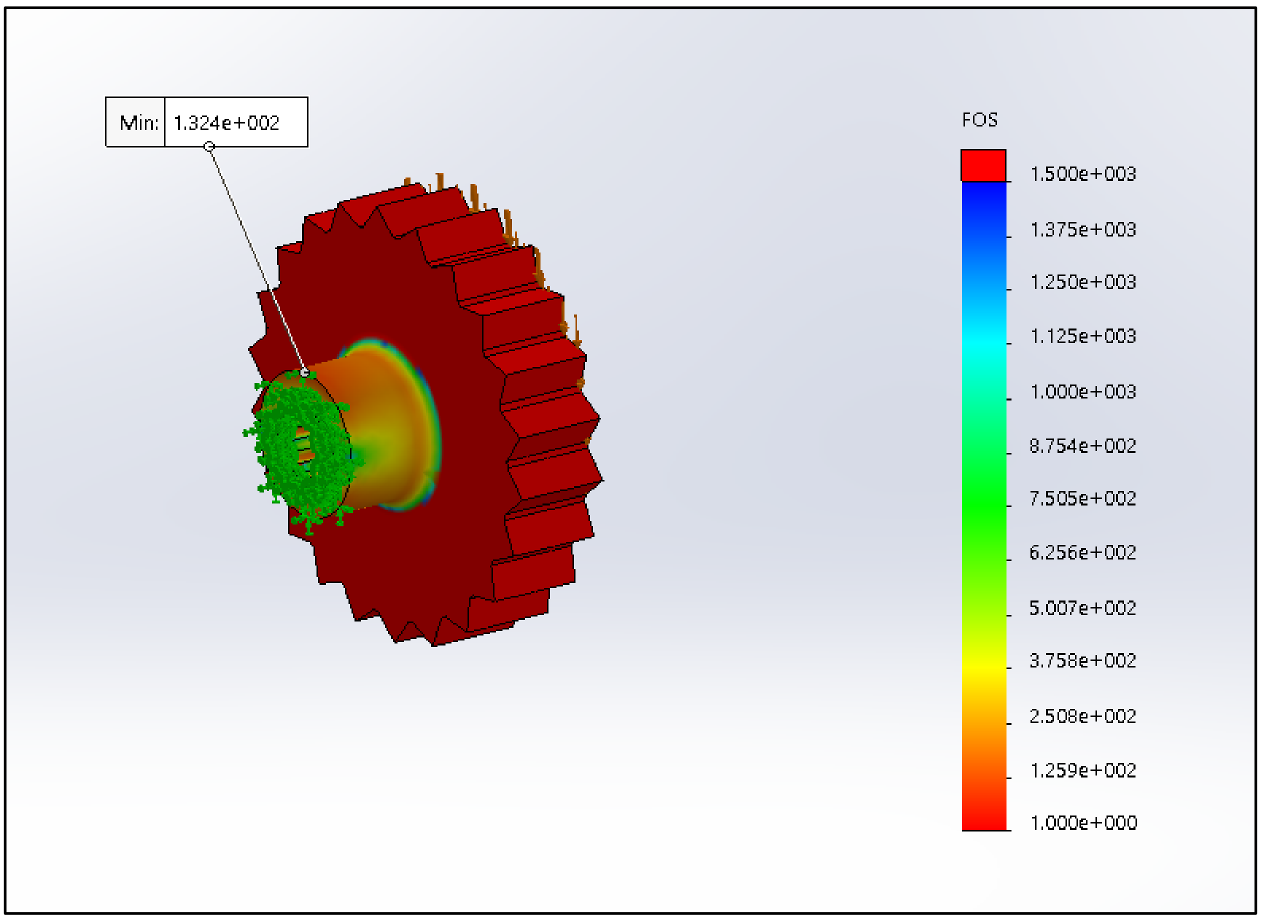


Figure 3.1.2.7: Wheel hub factor of safety

3.3 Plastics

As found in section 2.4, the material chosen for our plastic components must be able to withstand at least 6807000 Pa, able to withstand a temperature range of -20°F to 150 °F, have a good fatigue strength, good environmental resistance, and be relatively chemically inert. In accordance, the following criteria shown in Figure 3.1.3.1 was entered into CES EduPack's search system.

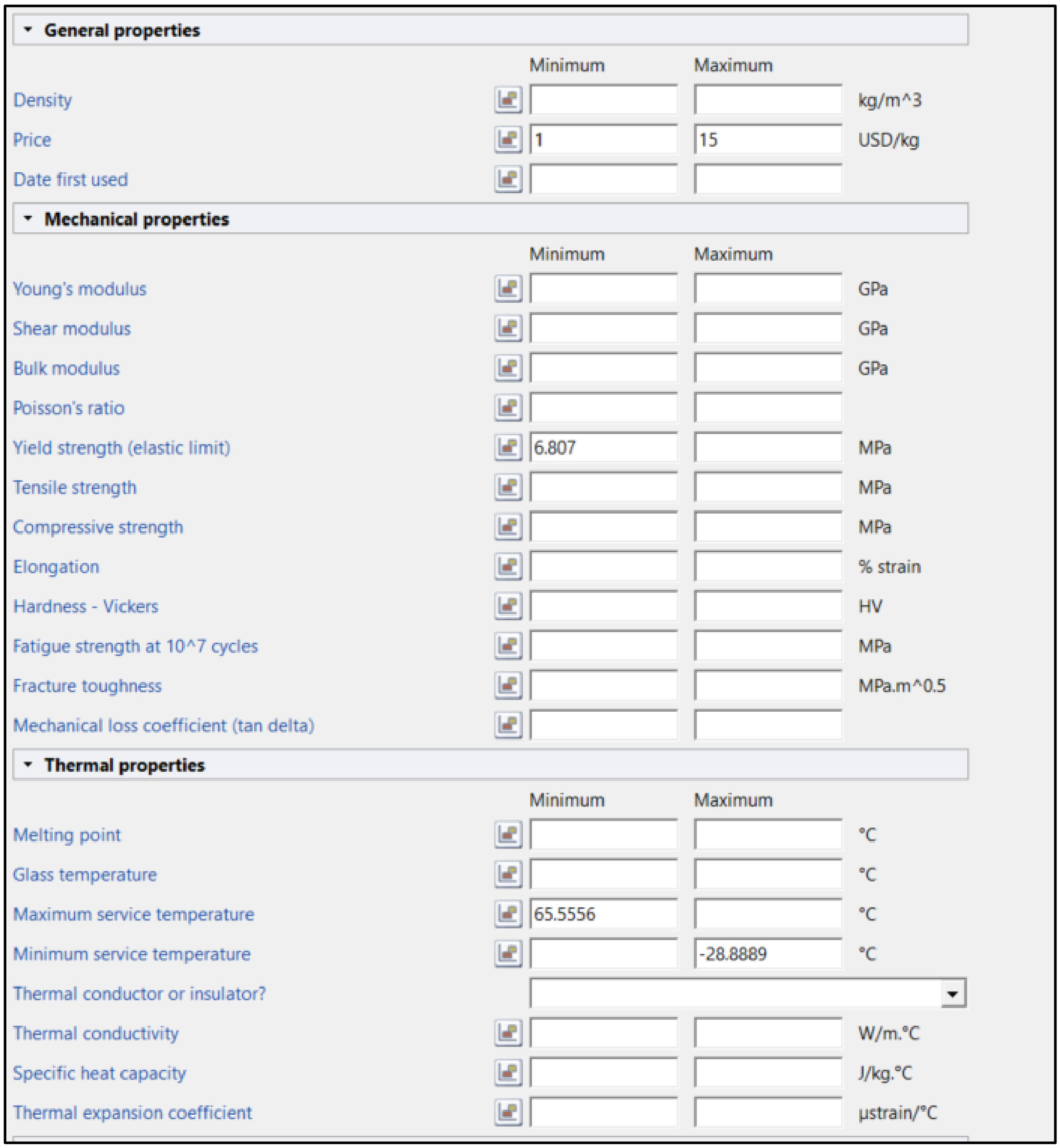


Figure 3.1.3.1: Plastic material search criteria

In addition, the software was asked to only return materials that have good environmental and UV durability and are non-toxic.

The resulting materials to be considered for use can be seen In Figure 3.1.3.2

Name	Price (USD/kg)
Polyvinylchloride (tpPVC)	1.4 - 1.6
Polyethylene (PE)	1.61 - 1.65
Phenolics	1.65 - 1.87
Polyethylene terephthalate (PET)	1.83 - 1.87
Epoxies	2.26 - 2.92
Polyamides (Nylons, PA)	2.58 - 2.8
Polycarbonate (PC)	3.4 - 3.64
Polyester	3.84 - 4.3
Polyurethane (tpPUR)	4.46 - 4.89
Cellulose polymers (CA)	4.92 - 6.3
Polytetrafluoroethylene (Teflon, PTFE)	14.8 - 16.9

Figure 3.1.3.2: Plastic materials considered

After looking over the list of materials, five materials were selected to be likely candidates based upon their characteristics, availability, and common sense. These materials are indicated by stars in Figure 3.1.3.2. These materials were compared using the decision matrix shown in Figure 3.1.3.3

Material	Fatigue	Rating	Price	Rating	Chemical Resistance	Rating
Cellulose polymers (CA)	2	2	4	2	4	2
Polyamides (Nylons, PA)	2	5	4	3	4	2
Polycarbonate (Pc)	2	3	4	3	4	5
Polyethylene (PE)	2	3	4	5	4	5
Polyvinylchloride (tpPVC)	2	3	4	5	4	4

Material	Environmental Resistance	Rating	Environmental Footprint	Rating	Totals
Cellulose polymers (CA)	4	2	3	4	40
Polyamides (Nylons, PA)	4	3	3	4	54
Polycarbonate (Pc)	4	3	3	3	59
Polyethylene (PE)	4	4	3	5	77
Polyvinylchloride (tpPVC)	4	5	3	2	68

Figure 3.1.3.3: Decision matrix for plastic materials

In the decision matrix special consideration was given to price, chemical resistance and environmental durability. Price is considered as there will be several different pieces constructed out of this material and chemical resistance and environmental durability are considered as many composites can dissolve or warp after extended exposure to outdoor environments and cleaning supplies. The materials were plotted by their durability in a marine atmosphere and price as seen in Figure 3.1.3.4.

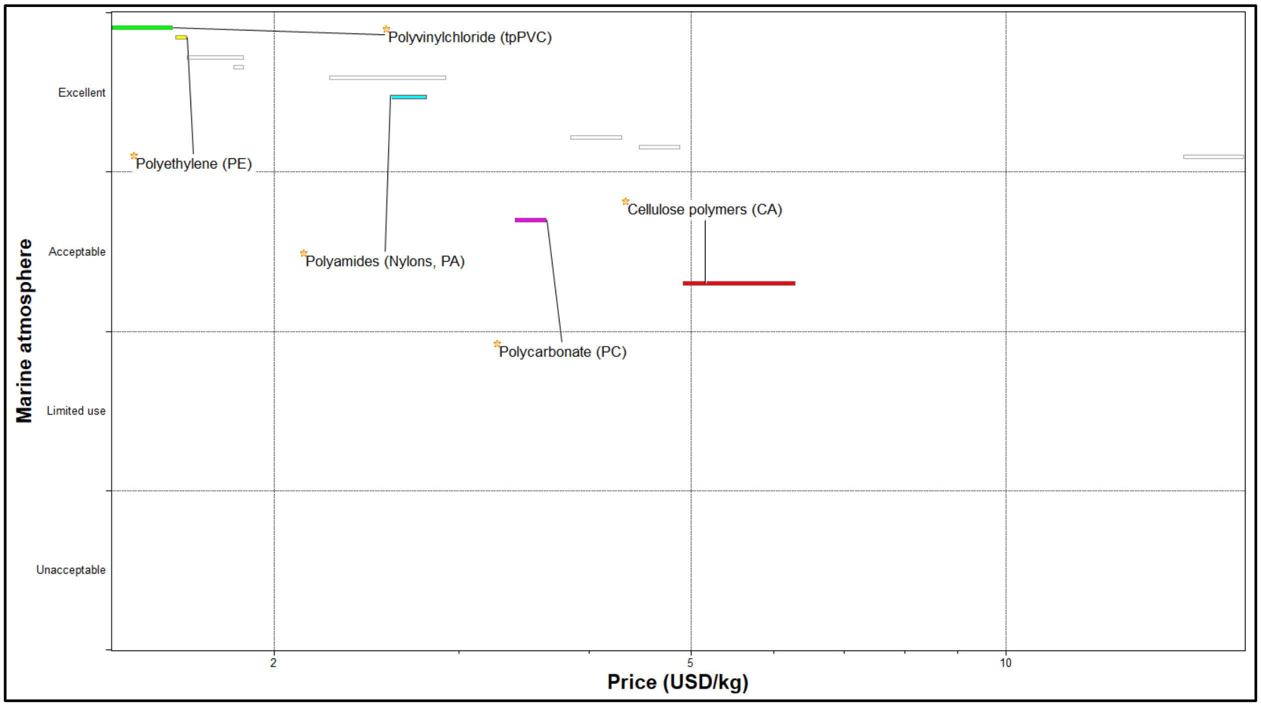


Figure 3.1.3.4: Plastic materials Marine atmosphere durability vs Price

As seen in the decision matrix, Polyethylene (PE) is the ideal material for this component as it is relatively cheap, strong, and extremely resistant to both environmental effects and chemical reactions. It is important to note that while pure Polyethylene (PE) does not hold up under UV light over time there are several types of UV stabilized Polyethylene that have exceptional resistance to UV light.

The material properties for high density polyethylene were applied to the components and placed under a stress test in Solidworks. A minimum factor of safety of 4.26 was returned as seen in Figure 3.1.3.5.

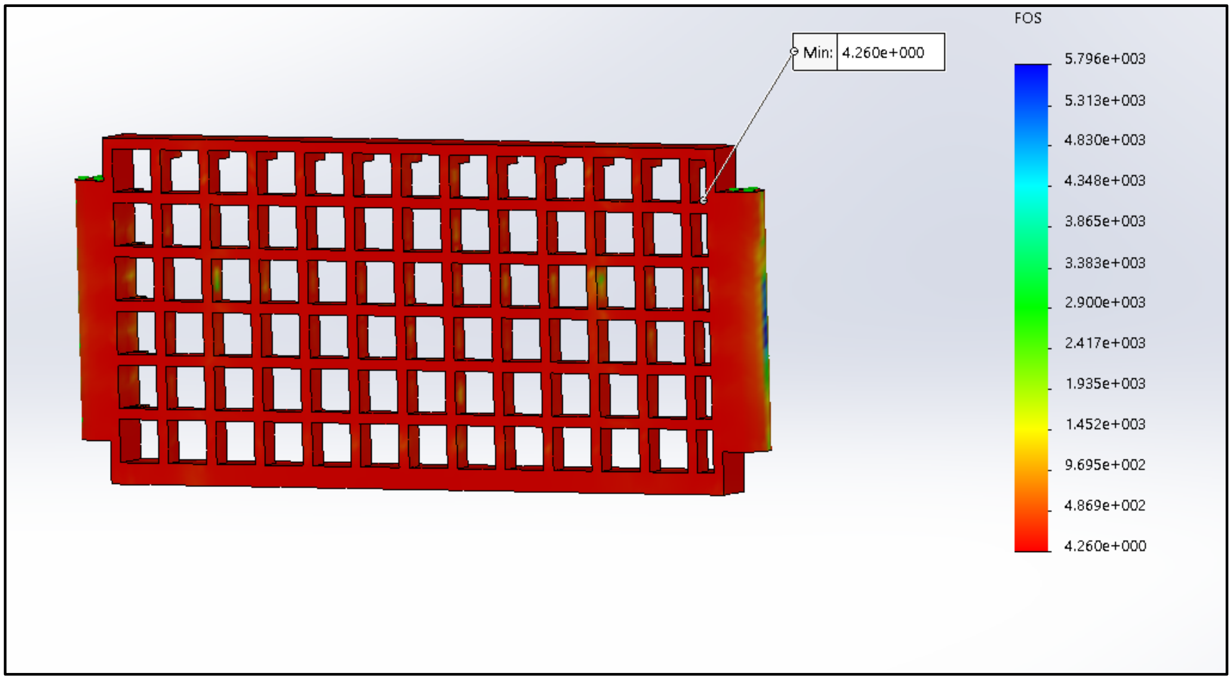


Figure 3.1.3.5: Back seat bottom plate Factor of Safety test results

3.4 Fabrics

As found in section 2.5 the material chosen for fabric components must be able to withstand a temperature range of -20°F to 150 °F, be relatively cheap, have good environmental resistance, and be relatively chemically inert. In accordance, the following criteria shown in Figure 3.1.4.1 was entered into CES eduPack's search system. It is important to note that the properties shown in CES eduPack's are not all the same properties that will be shown by these materials when they are in fabric form. The process of weaving and creating composite fabric can drastically alter most mechanical properties of a material. As such the only properties that will be considered for material selection are those that will not change due to the material's form. In accordance, the following criteria shown in Figure 3.1.4.1 was entered into CES eduPack's search system.

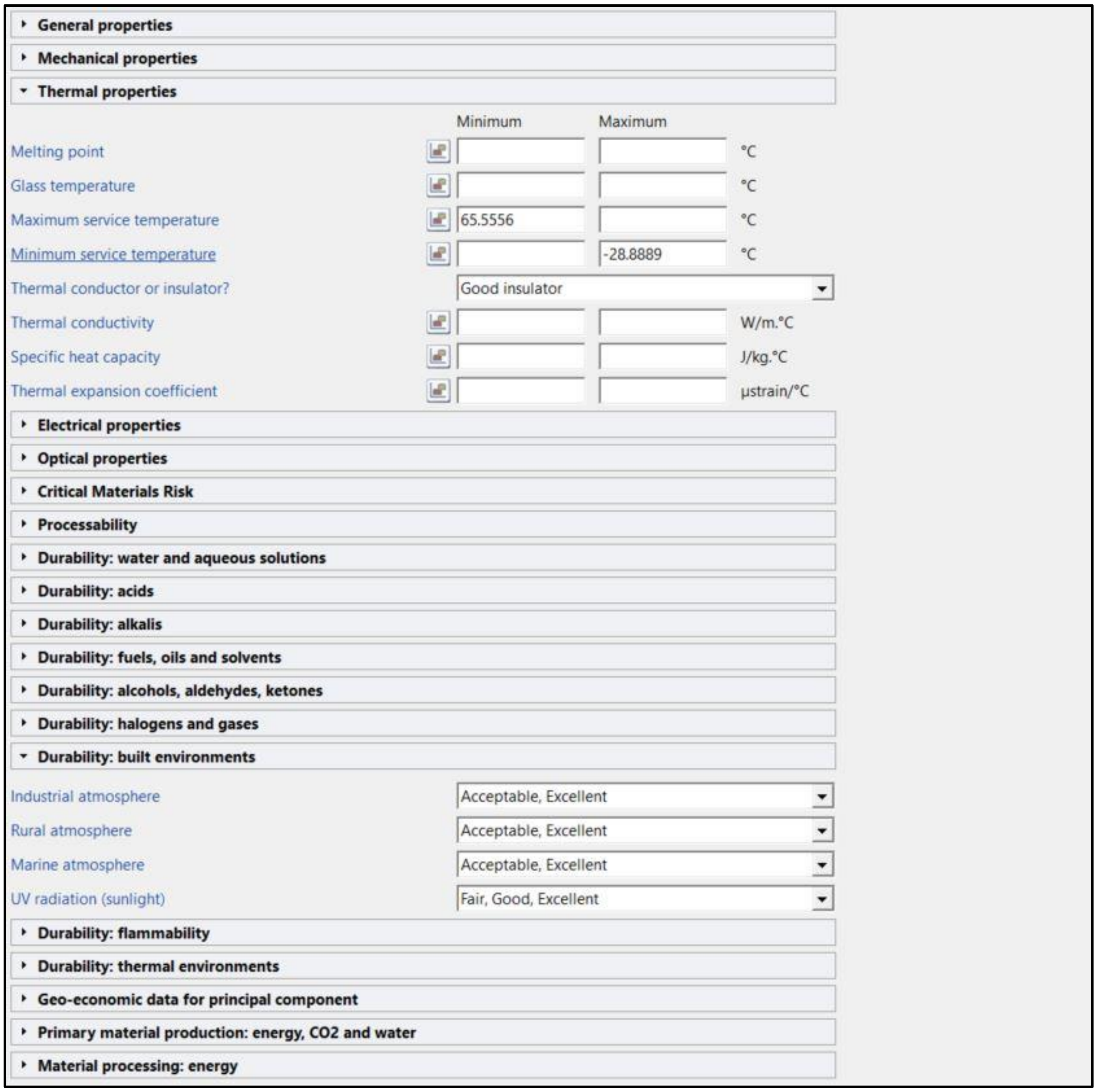


Figure 3.1.4.1: Fabric material search criteria

In addition, the software was asked to only return materials that are cheaper than $15/kg, and non-toxic.

The resulting materials to be considered for use can be seen in Figure 3.1.4.2

After looking over the list of materials four materials were selected to be likely candidates based upon their characteristics, availability, and common sense. These materials are denoted by a star in Figure 3.1.4.2. Materials were chosen that were commonly found in fabric mixes. These materials were compared by their valued properties using the decision matrix shown in Figure3.1.4.3

Name	Price (USD/kg)
Polyvinylchloride (tpPVC)	1.4 - 1.6
Polyethylene (PE)	1.61 - 1.65
Phenolics	1.65 - 1.87
Polyethylene terephthalate (PET)	1.83 - 1.87
Starch-based thermoplastics (TPS)	2.04 - 6.12
Epoxies	2.26 - 2.92
Polyamides (Nylons, PA)	2.58 - 2.8
Polycarbonate (PC)	3.4 - 3.64
Polyester	3.84 - 4.3
Polyurethane (tpPUR)	4.46 - 4.89
Cellulose polymers (CA)	4.92 - 6.3
Polyhydroxyalkanoates (PHA, PHB)	6 - 7
Polytetrafluoroethylene (Teflon, PTFE)	14.8 - 16.9

Figure 3.1.4.2: Fabric potential materials

Material	Environmental Footprint	Rating	Price	Rating	
Polyvinylchloride (tpPVC)	3	2	4	5	
Polyethylene terephthalate (PET)	3	5	4	4	
Polytetrafluoroethylene (Teflon/Gore -Tex)	3	3	4	1	
Polyester	3	1	4	2	
Material	**Environmental Resistance**	**Rating**	**Chemical Resistance**	**Rating**	**Totals**
Polyvinylchloride (tpPVC)	5	5	5	4	71
Polyethylene terephthalate (PET)	5	5	5	4	76
Polytetrafluoroethylene (Teflon/Gore -Tex)	5	5	5	5	63
Polyester	5	5	5	3	51

Figure 3.1.4.3: Fabric materials decision matrix

In the decision matrix special consideration was given to price, chemical resistance and environmental durability. Price is still considered in this component as the price given in CES EduPack is the material price in (USD/kg) which does affect the overall price of the resulting fabric. Chemical resistance and environmental durability are considered as many composites can dissolve or warp after extended exposure to outdoor environments and cleaning supplies. Figures 3.1.4.4 and 3.1.4.5 show UV durability vs Price and Marine environmental durability vs Price respectively.

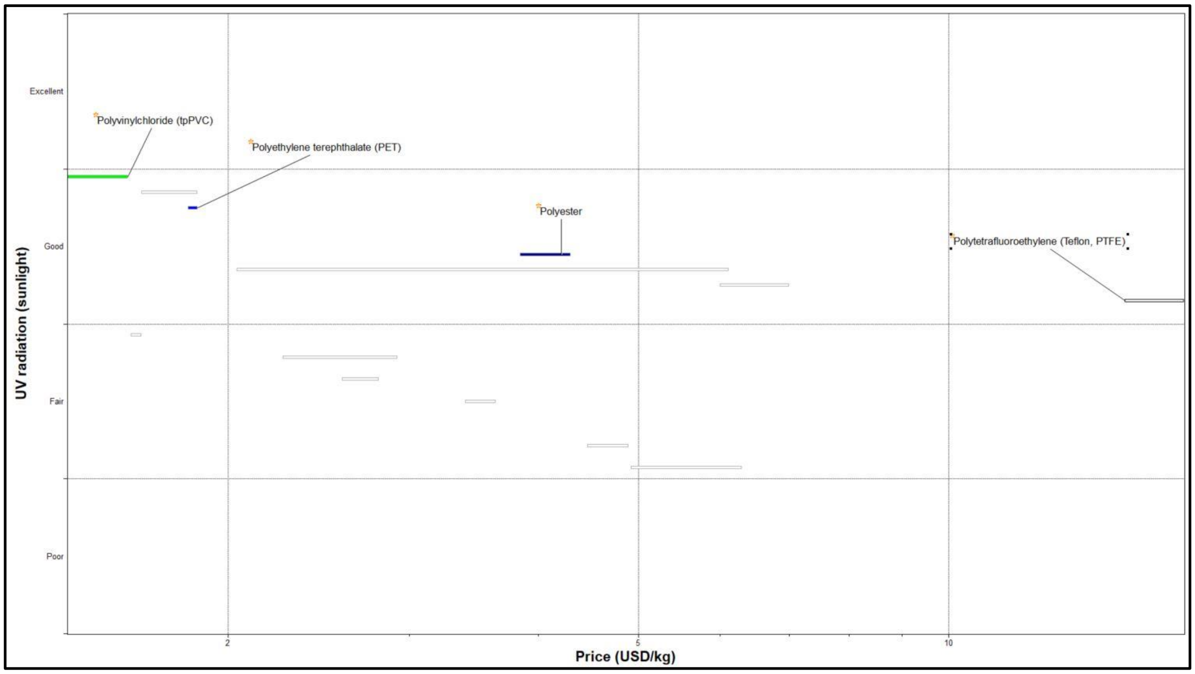


Figure 3.1.4.4: UV radiation durability vs Price

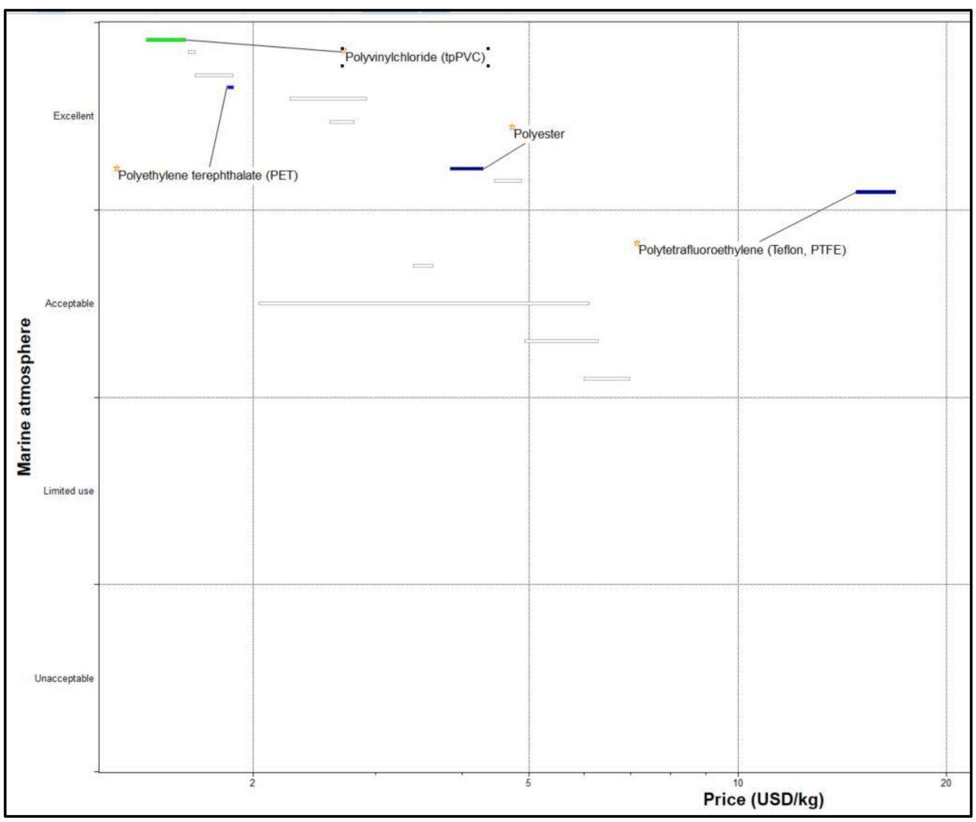


Figure 3.1.4.5: Marine atmosphere durability vs Price

As seen in the decision matrix, Polyethylene terephthalate (PET) is the ideal material for this component as it is relatively cheap, and extremely resistant to both environmental effects and chemical reactions. PET shares many of these traits with Polyvinylchloride (tpPVC) which was also considered but PET has less of an environmental impact than tpPVC, which can be very hard to recycle safely. This slight difference makes PET a better candidate for our purposes. In addition, PET is widely used to make various types of composite fabrics.

3.5 Housing

As found in section 2.6 the material chosen for our housing components must be able to withstand at least 3594000 Pa, have good environmental resistance and be relatively chemically inert. In accordance, the following criteria shown in Figure 3.1.5.1 was entered into CES eduPack’s search system.

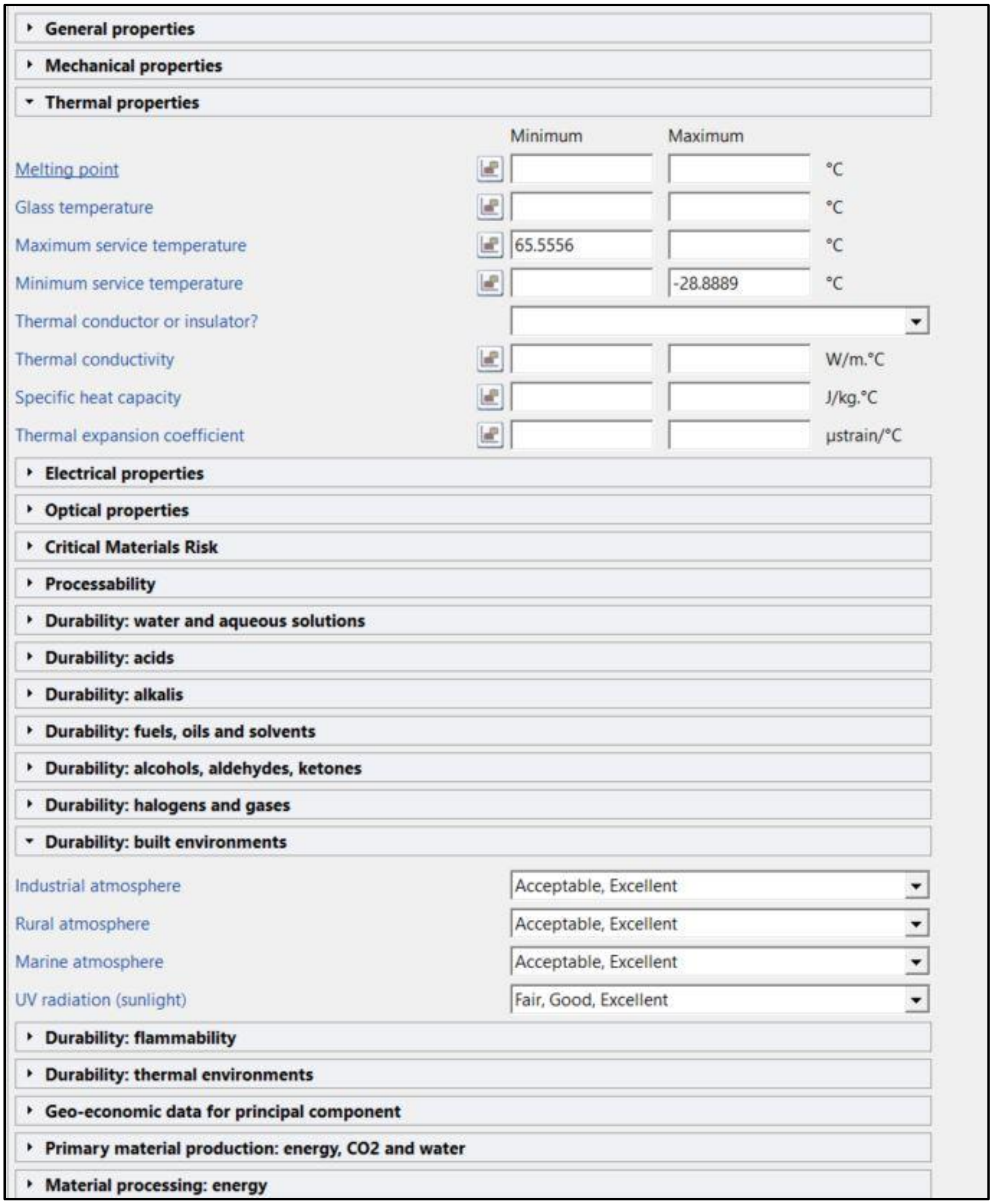


Figure 3.1.5.1: Housing materials search criteria

In addition, the software was asked to only return materials that are cheaper than $15/kg, nontoxic, and able to handle a minimum stress of 3594000 Pa.

The resulting materials to be considered for use can be seen In Figure 3.1.5.2

After looking over the list of materials, five materials were selected to be likely candidates based upon their characteristics, availability, and common sense. These materials are marked by a star beside their name in Figure 3.1.5.2. They were then compared by their desirable properties using a decision matrix as shown in Figure 3.1.5.3

Name	Price (USD/kg)
Polyvinylchloride (tpPVC)	1.4 - 1.6
Polyethylene (PE)	1.61 - 1.65
Phenolics	1.65 - 1.87
Polyethylene terephthalate (PET)	1.83 - 1.87
Epoxies	2.26 - 2.92
Polyamides (Nylons, PA)	2.58 - 2.8
Polycarbonate (PC)	3.4 - 3.64
Polyester	3.84 - 4.3
Polyurethane (tpPUR)	4.46 - 4.89
Cellulose polymers (CA)	4.92 - 6.3
Polytetrafluoroethylene (Teflon, PTFE)	14.8 - 16.9

Figure 3.1.5.2: Potential housing materials

Materials	Price	Rating	Thermal Properties	Rating	Chemical Resistance	Score
Cellulose polymers (CA)	2	4	5	3	3	2
Polyamides (Nylons, PA)	2	4	5	4	3	2
Polycarbonate (Pc)	2	4	5	4	3	5
Polyethylene (PE)	2	4	5	3	3	5
Polyvinylchloride (tpPVC)	2	4	5	3	3	4

Materials	Environmental Resistance	Rating	Strength	Rating	Environmental Footprint	Score	Totals
Cellulose polymers (CA)	3	2	4	2	3	4	55
Polyamides (Nylons, PA)	3	3	4	5	3	4	75
Polycarbonate (Pc)	3	3	4	5	3	3	81
Polyethylene (PE)	3	4	4	2	3	5	73
Polyvinylchloride (tpPVC)	3	5	4	3	3	2	68

Figure 3.1.5.3: Housing materials decision matrix

In the decision matrix special consideration was given to thermal properties, strength, chemical resistance and environmental durability. Strength is vital to this component as it is supporting the two heaviest parts of the system. Due to the heat generated by the batteries and motors this component will face higher temperatures than any other part making thermal properties essential. Figure 3.1.5.3 shows all considered materials compared by both yield strength and maximum service temperature. As this component will be low to the ground much like the axles, it will require good environmental durability and chemical resistance.

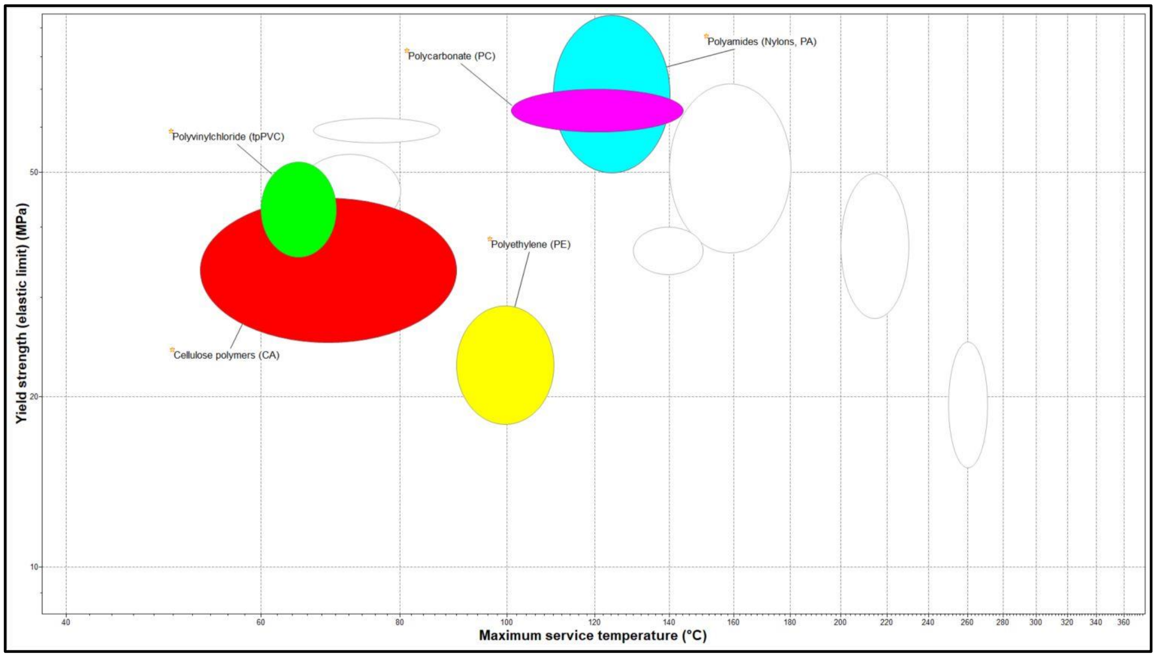


Figure 3.1.5.3: Yield Strength v.s. Maximum service temperature

As seen in the decision matrix, Polycarbonate (Pc) is the ideal material for this component due to its high strength, good thermal properties, and high resistance to chemical corrosion. In addition, it very easy to mold into shape, making manufacturing much easier.

When the material was applied to the component and tested under the approximated load in Solidworks, a minimum factor of safety of 27.56 was found. The simulation results can be seen in Figure 3.1.5.4.

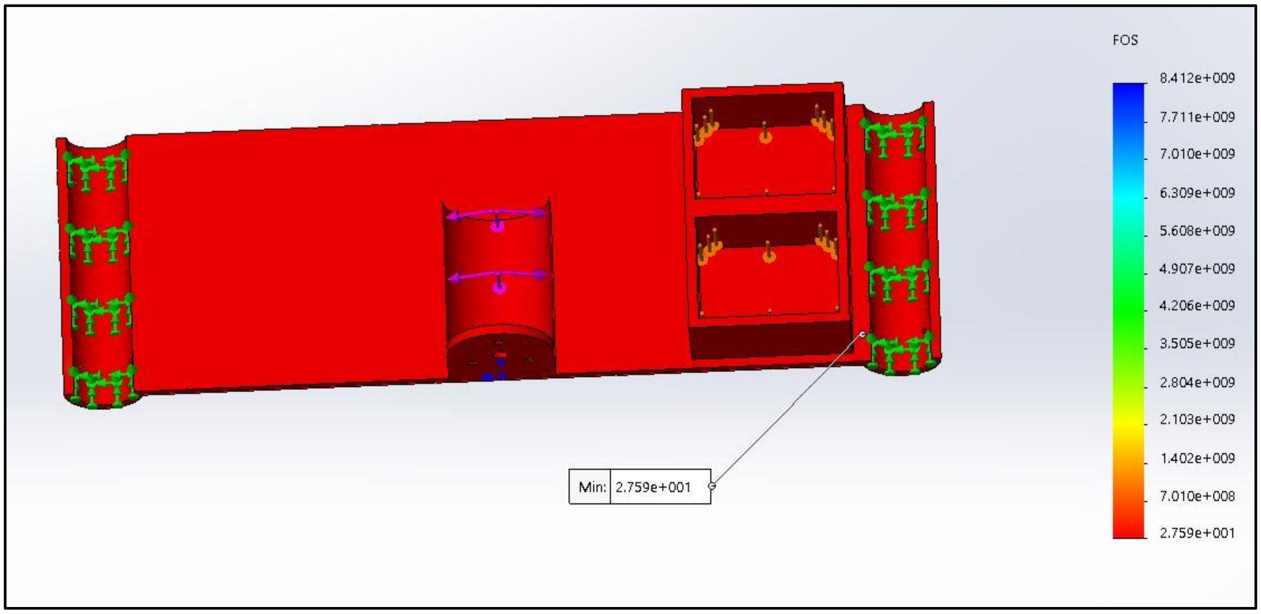


Figure 3.1.5.4: Factor of safety test results for housing component

4 References

Granta Design. (2017). CES EduPack (Version 2017) [Computer software].

Dassault Systèmes. (2017). SolidWorks (Version 2017) [Computer software]. SolidWorks Corporation.

Baby Trend Sit N Stand Double, Carbon : Tandem Strollers : Baby. (n.d.). Retrieved March 30, 2018, from https://www.amazon.com/Baby-Trend-Stand-Double-Carbon/dp/B008TKG7FA/ref=sr_1_4_s_it?s=baby-products&ie=UTF8&qid=1508966729&sr=1-4&refinements=p_n_feature_browse-bin:668896011&th=1

Online Materials Information Resource - MatWeb. (n.d.). Retrieved March 30, 2018, from http://www.matweb.com/

5 Appendix

5.1 Material data sheets

5.1.1 5052 – O Aluminum <MatWeb.com>

Aluminum 5052-O

Categories:	Metal; Nonferrous Metal; Aluminum Alloy; 5000 Series Aluminum Alloy
Material Notes:	This alloy has good workability, very good corrosion resistance, high fatigue strength, weldability, and moderate strength. This leads to its use in aircraft fuel/oil lines, fuel tanks, other transportation areas, sheet metal work, appliances and lighting, wire, and rivets. Data points with the AA note have been provided by the Aluminum Association, Inc. and are NOT FOR DESIGN. **Composition Notes**: Composition information provided by the Aluminum Association and is not for design.
Key Words:	UNS A95052; ISO AlMg2.5; Aluminium 5052-O; AA5052-O
Vendors:	No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

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Physical Properties	Metric	English	Comments
Density	2.68 g/cc	0.0968 lb/in³	AA; Typical

Mechanical Properties	Metric	English	Comments
Hardness, Brinell	47	47	AA; Typical; 500 g load; 10 mm ball
Tensile Strength, Ultimate	193 MPa	28000 psi	AA; Typical
	34.0 MPa @Temperature 371 °C	4930 psi @Temperature 700 °F	
	52.0 MPa @Temperature 316 °C	7540 psi @Temperature 601 °F	
	83.0 MPa @Temperature 260 °C	12000 psi @Temperature 500 °F	

	117 MPa @Temperature 204 °C	17000 psi @Temperature 399 °F	
	159 MPa @Temperature 149 °C	23100 psi @Temperature 300 °F	
	193 MPa @Temperature -28.0 °C	28000 psi @Temperature -18.4 °F	
	193 MPa @Temperature 24.0 °C	28000 psi @Temperature 75.2 °F	
	193 MPa @Temperature 100 °C	28000 psi @Temperature 212 °F	
	200 MPa @Temperature -80.0 °C	29000 psi @Temperature -112 °F	
	303 MPa @Temperature -196 °C	43900 psi @Temperature -321 °F	
Tensile Strength, Yield	89.6 MPa	13000 psi	AA; Typical
	21.0 MPa @Strain 0.200 %, Temperature 371 °C	3050 psi @Strain 0.200 %, Temperature 700 °F	
	38.0 MPa @Strain 0.200 %, Temperature 316 °C	5510 psi @Strain 0.200 %, Temperature 601 °F	
	52.0 MPa @Strain 0.200 %, Temperature 260 °C	7540 psi @Strain 0.200 %, Temperature 500 °F	
	76.0 MPa @Strain 0.200 %, Temperature 204 °C	11000 psi @Strain 0.200 %, Temperature 399 °F	
	90.0 MPa @Strain 0.200 %, Temperature -80.0 °C	13100 psi @Strain 0.200 %, Temperature -112 °F	
	90.0 MPa @Strain 0.200 %, Temperature -28.0 °C	13100 psi @Strain 0.200 %, Temperature -18.4 °F	
	90.0 MPa @Strain 0.200 %, Temperature 24.0 °C	13100 psi @Strain 0.200 %, Temperature 75.2 °F	
	90.0 MPa @Strain 0.200 %, Temperature 100 °C	13100 psi @Strain 0.200 %, Temperature 212 °F	
	90.0 MPa @Strain 0.200 %, Temperature 149 °C	13100 psi @Strain 0.200 %, Temperature 300 °F	
	110 MPa @Strain 0.200 %, Temperature -196 °C	16000 psi @Strain 0.200 %, Temperature -321 °F	
Elongation at Break	30 % @Temperature 24.0 °C	30 % @Temperature 75.2 °F	
	32 % @Temperature -28.0 °C	32 % @Temperature -18.4 °F	

	35 % @Temperature -80.0 °C	35 % @Temperature -112 °F	
	36 % @Temperature 100 °C	36 % @Temperature 212 °F	
	46 % @Temperature -196 °C	46 % @Temperature -321 °F	
	50 % @Temperature 149 °C	50 % @Temperature 300 °F	
	60 % @Temperature 204 °C	60 % @Temperature 399 °F	
	80 % @Temperature 260 °C	80 % @Temperature 500 °F	
	110 % @Temperature 316 °C	110 % @Temperature 601 °F	
	130 % @Temperature 371 °C	130 % @Temperature 700 °F	
	25 % @Thickness 1.59 mm	25 % @Thickness 0.0625 in	AA; Typical
	30 % @Diameter 12.7 mm	30 % @Diameter 0.500 in	AA; Typical
Modulus of Elasticity	70.3 GPa	10200 ksi	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Ultimate Bearing Strength	345 MPa	50000 psi	Edge distance/pin diameter = 2.0
Bearing Yield Strength	131 MPa	19000 psi	Edge distance/pin diameter = 2.0
Poissons Ratio	0.33	0.33	
Fatigue Strength	110 MPa @# of Cycles 5.00e+8	16000 psi @# of Cycles 5.00e+8	completely reversed stress; RR Moore machine/specimen
Machinability	30 %	30 %	0-100 Scale of Aluminum Alloys
Shear Modulus	25.9 GPa	3760 ksi	
Shear Strength	124 MPa	18000 psi	AA; Typical

Electrical Properties	Metric	English	Comments
Electrical Resistivity	0.00000499 ohm-cm @Temperature 20.0 °C	0.00000499 ohm-cm @Temperature 68.0 °F	AA; Typical

Thermal Properties	Metric	English	Comments

CTE, linear	22.1 µm/m-°C @Temperature -50.0 - 20.0 °C	12.3 µin/in-°F @Temperature -58.0 - 68.0 °F	
	23.8 µm/m-°C @Temperature 20.0 - 100 °C	13.2 µin/in-°F @Temperature 68.0 - 212 °F	AA; Typical; average over range
	24.8 µm/m-°C @Temperature 20.0 - 200 °C	13.8 µin/in-°F @Temperature 68.0 - 392 °F	
	25.7 µm/m-°C @Temperature 20.0 - 300 °C	14.3 µin/in-°F @Temperature 68.0 - 572 °F	
Specific Heat Capacity	0.880 J/g-°C	0.210 BTU/lb-°F	Estimated from trends in similar Al alloys.
Thermal Conductivity	138 W/m-K	960 BTU-in/hr-ft^2-°F	AA; Typical at 77°F
Melting Point	607.2 - 649 °C	1125 - 1200 °F	AA; Typical range based on typical composition for wrought products 1/4 inch thickness or greater
Solidus	607.2 °C	1125 °F	AA; Typical
Liquidus	649 °C	1200 °F	AA; Typical

Processing Properties	Metric	English	Comments
Annealing Temperature	343 °C	650 °F	holding at temperature not required
Hot-Working Temperature	260 - 510 °C	500 - 950 °F	

Component Elements Properties	Metric	English	Comments
Aluminum, Al	95.7 - 97.7 %	95.7 - 97.7 %	As remainder
Chromium, Cr	0.15 - 0.35 %	0.15 - 0.35 %	
Copper, Cu	<= 0.10 %	<= 0.10 %	
Iron, Fe	<= 0.40 %	<= 0.40 %	
Magnesium, Mg	2.2 - 2.8 %	2.2 - 2.8 %	
Manganese, Mn	<= 0.10 %	<= 0.10 %	
Other, each	<= 0.05 %	<= 0.05 %	
Other, total	<= 0.15 %	<= 0.15 %	
Silicon, Si	<= 0.25 %	<= 0.25 %	
Zinc, Zn	<= 0.10 %	<= 0.10 %	

5.1.2 AISI 321 Annealed Stainless Steel

AK Steel 321 Austenitic Stainless steel

Categories: Metal; Ferrous Metal; Austenitic; Stainless Steel; T 300 Series Stainless Steel

Material Notes: AK Steel 321 is a stabilized austenitic stainless steel similar to Type 304 but with a titanium addition. This titanium addition reduces or prevents carbide precipitation during welding and in 427 - 816°C service. It also improves the elevated temperature properties of the alloy. AK Steel 321 provides excellent resistance to oxidation and corrosion and possesses good creep strength. It is used primarily in applications involving continuous and intermittent service temperatures within the carbide precipitation range of 427 - 816°C.

Information provided by AK Steel

Vendors: No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.

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Physical Properties	Metric	English	Comments
Density	9.01 g/cc	0.326 lb/in³	

Mechanical Properties	Metric	English	Comments
Hardness, Rockwell B	80	80	
Tensile Strength, Ultimate	621 MPa	90100 psi	
Tensile Strength, Yield	276 MPa @Strain 0.200 %	40000 psi @Strain 0.200 %	
Elongation at Break	45 %	45 %	in 2 inches
Tensile Modulus	193 GPa	28000 ksi	
Poissons Ratio	0.24	0.24	Calculated
Shear Modulus	78.0 GPa	11300 ksi	torsion

Electrical Properties	Metric	English	Comments
Electrical Resistivity	0.0000720 ohm-cm	0.0000720 ohm-cm	

Magnetic Permeability	<= 1.02	<= 1.02	H = 200 Oersted, Annealed

Thermal Properties	Metric	English	Comments
CTE, linear	16.6 µm/m-°C @Temperature 0.000 - 100 °C	9.22 µin/in-°F @Temperature 32.0 - 212 °F	
	20.2 µm/m-°C @Temperature <=871 °C	11.2 µin/in-°F @Temperature <=1600 °F	
Specific Heat Capacity	0.500 J/g-°C @Temperature 0.000 - 100 °C	0.120 BTU/lb-°F @Temperature 32.0 - 212 °F	
Thermal Conductivity	16.0 W/m-K @Temperature 100 °C	111 BTU-in/hr-ft²-°F @Temperature 212 °F	
	22.0 W/m-K @Temperature 500 °C	153 BTU-in/hr-ft²-°F @Temperature 932 °F	
Melting Point	1371 - 1399 °C	2500 - 2550 °F	
Solidus	1371 °C	2500 °F	
Liquidus	1399 °C	2550 °F	

Component Elements Properties	Metric	English	Comments
Carbon, C	<= 0.080 %	<= 0.080 %	
Chromium, Cr	17 - 19 %	17 - 19 %	
Iron, Fe	65.295 - 74 %	65.295 - 74 %	As Remainder
Manganese, Mn	<= 2.0 %	<= 2.0 %	
Nickel, Ni	9.0 - 12 %	9.0 - 12 %	
Nitrogen, N	<= 0.10 %	<= 0.10 %	
Phosphorous, P	<= 0.045 %	<= 0.045 %	
Silicon, Si	<= 0.75 %	<= 0.75 %	
Sulfur, S	<= 0.030 %	<= 0.030 %	
Titanium, Ti	<= 0.70 %	<= 0.70 %	

5.1.3 High Density Polyethylene <MatWeb.com>

Overview of materials for High Density Polyethylene (HDPE), Injection Molded	
Categories:	Polymer; Thermoplastic; Polyethylene (PE); HDPE; High Density Polyethylene (HDPE), Injection Molded

Material Notes:	This property data is a summary of similar materials in the MatWeb database for the category "High Density Polyethylene (HDPE), Injection Molded". Each property range of values reported is minimum and maximum values of appropriate MatWeb entries. The comments report the average value, and number of data points used to calculate the average. The values are not necessarily typical of any specific grade, especially less common values and those that can be most affected by additives or processing methods.
Vendors:	**Bamberger Polymers** sells this and a wide range of thermoplastic resins such as polyethylene, polypropylene, polyester, EVA, and polystyrene worldwide. www.BambergerPolymers.com or phone 800-888-8959. Celanese is a global producer of polymers that helps customers bring their inspired ideas and innovations to life. With a broad portfolio of Materials Solutions and deep technical capabilities across the value chain, Celanese has experience with customers in a wide range of applications including automotive, medical devices, and consumer products. **Click here to view all available suppliers for this material.** Please click here if you are a supplier and would like information on how to add your listing to this material.

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Physical Properties	Metric	English	Comments
Density	0.924 - 2.55 g/cc	0.0334 - 0.0921 lb/in³	Average value: 0.962 g/cc Grade Count:431
Apparent Bulk Density	0.590 - 0.610 g/cc	0.0213 - 0.0220 lb/in³	Average value: 0.595 g/cc Grade Count:17
Water Absorption	0.000 - 0.0700 %	0.000 - 0.0700 %	Average value: 0.0157 % Grade Count:21
Moisture Absorption at Equilibrium	0.0100 - 0.0500 %	0.0100 - 0.0500 %	Average value: 0.0200 % Grade Count:4
Particle Size	5.00 - 1200 µm	5.00 - 1200 µm	Average value: 614 µm Grade Count:4
Viscosity	32000 - 200000 cP @Temperature 190 - 190 °C	32000 - 200000 cP @Temperature 374 - 374 °F	Average value: 89000 cP Grade Count:7
	32000 - 200000 cP @Shear Rate 300 - 5000 1/s	32000 - 200000 cP @Shear Rate 300 - 5000 1/s	Average value: 89000 cP Grade Count:7
Environmental Stress Crack Resistance	1.00 - 3000 hour	1.00 - 3000 hour	Average value: 157 hour Grade Count:105
	2.00 - 500 hour @Temperature 50.0 - 50.0 °C	2.00 - 500 hour @Temperature 122 - 122 °F	Average value: 109 hour Grade Count:24
	2.00 - 10.0 hour @Temperature 50.0 - 50.0 °C	2.00 - 10.0 hour @Temperature 122 - 122 °F	Average value: 109 hour Grade Count:12
	2.00 - 10.0 hour @Thickness 1.90 - 2.00 mm	2.00 - 10.0 hour @Thickness 0.0748 - 0.0787 in	Average value: 109 hour Grade Count:12
Oxidative Induction Time (OIT)	20.0 - 100 min	20.0 - 100 min	Average value: 47.5 min Grade Count:4
Linear Mold Shrinkage	0.00800 - 0.0400 cm/cm	0.00800 - 0.0400 in/in	Average value: 0.0192 cm/cm Grade Count:26

Linear Mold Shrinkage, Transverse	0.00960 - 0.0300 cm/cm	0.00960 - 0.0300 in/in	Average value: 0.0162 cm/cm Grade Count:7
Melt Flow	0.0250 - 1610 g/10 min	0.0250 - 1610 g/10 min	Average value: 27.0 g/10 min Grade Count:410
Base Resin Melt Index	2.00 - 20.0 g/10 min	2.00 - 20.0 g/10 min	Average value: 7.00 g/10 min Grade Count:8
Spiral Flow	15.5 - 55.8 cm	6.10 - 22.0 in	Average value: 33.9 cm Grade Count:50
Ash	0.0300 - 0.0500 %	0.0300 - 0.0500 %	Average value: 0.0433 % Grade Count:3

Mechanical Properties	Metric	English	Comments
Hardness, Rockwell R	33.0 - 66.0	33.0 - 66.0	Average value: 48.7 Grade Count:7
Hardness, Shore D	50.0 - 76.0	50.0 - 76.0	Average value: 64.4 Grade Count:217
Ball Indentation Hardness	35.0 - 45.0 MPa	5080 - 6530 psi	Average value: 41.4 MPa Grade Count:9
Tensile Strength, Ultimate	7.60 - 43.0 MPa	1100 - 6240 psi	Average value: 21.3 MPa Grade Count:156
Film Tensile Strength at Yield, MD	21.0 - 35.0 MPa	3050 - 5080 psi	Average value: 28.9 MPa Grade Count:5
Film Tensile Strength at Yield, TD	23.0 - 37.5 MPa	3340 - 5440 psi	Average value: 31.1 MPa Grade Count:5
Tensile Strength, Yield	11.0 - 43.0 MPa	1600 - 6240 psi	Average value: 26.1 MPa Grade Count:363
Film Elongation at Break, MD	595 - 900 %	595 - 900 %	Average value: 709 % Grade Count:5
Film Elongation at Break, TD	650 - 950 %	650 - 950 %	Average value: 860 % Grade Count:5
Elongation at Break	3.20 - 2080 %	3.20 - 2080 %	Average value: 555 % Grade Count:311
Elongation at Yield	3.00 - 80.0 %	3.00 - 80.0 %	Average value: 11.3 % Grade Count:86
Modulus of Elasticity	0.450 - 1.50 GPa	65.3 - 218 ksi	Average value: 0.927 GPa Grade Count:56
Flexural Yield Strength	13.8 - 48.3 MPa	2000 - 7000 psi	Average value: 29.2 MPa Grade Count:22

Flexural Modulus	0.280 - 1.81 GPa	40.6 - 263 ksi	Average value: 1.10 GPa Grade Count:322
Compressive Yield Strength	4.00 - 23.0 MPa	580 - 3340 psi	Average value: 12.6 MPa Grade Count:8
Secant Modulus	0.750 - 1.54 GPa	109 - 224 ksi	Average value: 1.06 GPa Grade Count:30
Izod Impact, Notched	0.196 - 5340 J/cm	0.367 - 10000 ft-lb/in	Average value: 0.777 J/cm Grade Count:145
	0.224 - 5340 J/cm @Temperature -40.0 - -18.0 °C	0.420 - 10000 ft-lb/in @Temperature -40.0 - -0.400 °F	Average value: 1.65 J/cm Grade Count:30
Izod Impact, Unnotched	0.300 - 5340 J/cm	0.562 - 10000 ft-lb/in	Average value: 0.300 J/cm Grade Count:3
	5338.47 - 5338.47 J/cm @Temperature -18.0 - -18.0 °C	10001.1 - 10001.1 ft-lb/in @Temperature -0.400 - -0.400 °F	Grade Count:2
Izod Impact, Notched (ISO)	2.00 - 80.1 kJ/m²	0.952 - 38.1 ft-lb/in²	Average value: 29.1 kJ/m² Grade Count:15
Izod Impact, Unnotched (ISO)	8.00 - 20.0 kJ/m²	3.81 - 9.52 ft-lb/in²	Average value: 16.0 kJ/m² Grade Count:3
Charpy Impact Unnotched	NB	NB	Grade Count:7
Charpy Impact, Notched	0.200 - 11.0 J/cm²	0.952 - 52.4 ft-lb/in²	Average value: 2.40 J/cm² Grade Count:40
Tensile Impact Strength	34.0 - 330 kJ/m²	16.2 - 157 ft-lb/in²	Average value: 121 kJ/m² Grade Count:13
	208 - 349 kJ/m² @Temperature -40.0 - -40.0 °C	99.1 - 166 ft-lb/in² @Temperature -40.0 - -40.0 °F	Average value: 289 kJ/m² Grade Count:6
Falling Dart Impact	31.2 - 176 J @Temperature -40.0 - -40.0 °C	23.0 - 130 ft-lb @Temperature -40.0 - -40.0 °F	Average value: 125 J Grade Count:3
Coefficient of Friction	0.0270 - 0.300	0.0270 - 0.300	Average value: 0.136 Grade Count:3
Tensile Creep Modulus, 1 hour	400 - 570 MPa	58000 - 82700 psi	Average value: 465 MPa Grade Count:4
Tensile Creep Modulus, 1000 hours	270 - 400 MPa	39200 - 58000 psi	Average value: 318 MPa Grade Count:4
Tear Strength Test	23.5 - 30.0	23.5 - 30.0	Average value: 28.4 Grade Count:4
Elmendorf Tear Strength, MD	0.600 - 1.60 g/micron	15.2 - 40.6 g/mil	Average value: 0.940 g/micron Grade Count:5

Elmendorf Tear Strength, TD	1.70 - 23.0 g/micron	43.2 - 584 g/mil	Average value: 10.5 g/micron Grade Count:5
Dart Drop	1.50 - 2.00 g/micron	38.1 - 50.8 g/mil	Average value: 1.67 g/micron Grade Count:4
Film Tensile Strength at Break, MD	35.6 - 55.0 MPa	5160 - 7980 psi	Average value: 47.1 MPa Grade Count:5
Film Tensile Strength at Break, TD	28.0 - 50.0 MPa	4060 - 7250 psi	Average value: 42.2 MPa Grade Count:5
Tangent Modulus	1170 - 1280 MPa	170000 - 185000 psi	Average value: 1230 MPa Grade Count:5

Electrical Properties	Metric	English	Comments
Electrical Resistivity	1.00e+6 - 1.00e+17 ohm-cm	1.00e+6 - 1.00e+17 ohm-cm	Average value: 1.27e+16 ohm-cm Grade Count:17
Surface Resistance	1.00e+6 - 1.00e+14 ohm	1.00e+6 - 1.00e+14 ohm	Average value: 3.62e+13 ohm Grade Count:13
Dielectric Constant	2.10 - 3.00	2.10 - 3.00	Average value: 2.40 Grade Count:18
Dielectric Strength	18.7 - 150 kV/mm	475 - 3810 kV/in	Average value: 58.3 kV/mm Grade Count:19
Dissipation Factor	0.0000400 - 0.00100	0.0000400 - 0.00100	Average value: 0.000309 Grade Count:17
Comparative Tracking Index	600 V	600 V	Average value: 600 V Grade Count:10

Thermal Properties	Metric	English	Comments
CTE, linear	20.0 - 225 µm/m-°C	11.1 - 125 µin/in-°F	Average value: 143 µm/m-°C Grade Count:26
Thermal Conductivity	0.288 - 0.480 W/m-K	2.00 - 3.33 BTU-in/hr-ft²-°F	Average value: 0.396 W/m-K Grade Count:9
Melting Point	118 - 137 °C	244 - 279 °F	Average value: 131 °C Grade Count:90
Crystallization Temperature	108 - 120 °C	226 - 248 °F	Average value: 115 °C Grade Count:25
Maximum Service Temperature, Air	70.0 - 120 °C	158 - 248 °F	Average value: 96.8 °C Grade Count:10
Deflection Temperature at 0.46 MPa (66 psi)	42.8 - 93.3 °C	109 - 200 °F	Average value: 72.2 °C Grade Count:114

Deflection Temperature at 1.8 MPa (264 psi)	37.6 - 86.1 °C	99.7 - 187 °F	Average value: 47.5 °C Grade Count:43
Vicat Softening Point	64.0 - 194 °C	147 - 381 °F	Average value: 122 °C Grade Count:253
Minimum Service Temperature, Air	-200 - -60.0 °C	-328 - -76.0 °F	Average value: -137 °C Grade Count:7
Brittleness Temperature	-180 - 76.0 °C	-292 - 169 °F	Average value: -73.8 °C Grade Count:145
Flammability, UL94	HB	HB	Grade Count:23
Oxygen Index	17.0 - 20.0 %	17.0 - 20.0 %	Average value: 18.9 % Grade Count:11

Optical Properties	Metric	English	Comments
Yellow Index	-1.00 - 4.00 %	-1.00 - 4.00 %	Average value: 2.18 % Grade Count:22

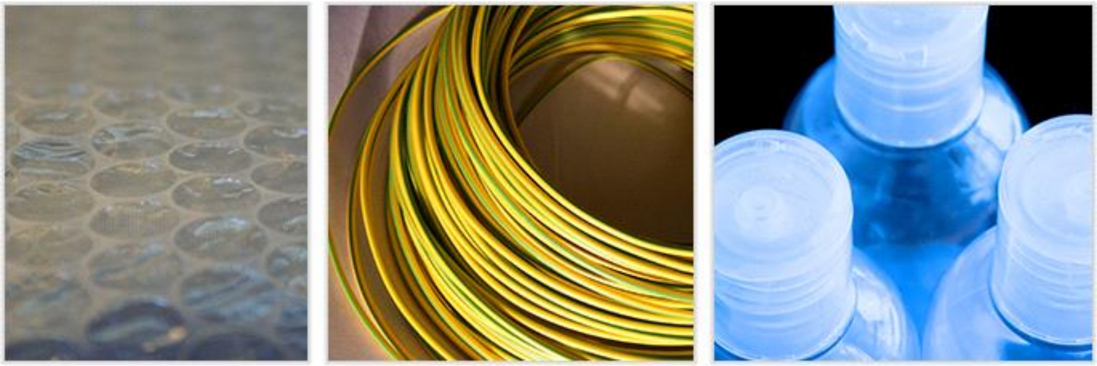
Processing Properties	Metric	English	Comments
Processing Temperature	82.2 - 274 °C	180 - 525 °F	Average value: 210 °C Grade Count:18
Nozzle Temperature	160 - 275 °C	320 - 527 °F	Average value: 241 °C Grade Count:26
Melt Temperature	130 - 280 °C	266 - 536 °F	Average value: 221 °C Grade Count:59
Mold Temperature	5.00 - 65.6 °C	41.0 - 150 °F	Average value: 29.4 °C Grade Count:19
Drying Temperature	37.8 - 70.0 °C	100 - 158 °F	Average value: 59.3 °C Grade Count:5
Injection Pressure	2.76 - 103 MPa	400 - 15000 psi	Average value: 56.2 MPa Grade Count:9

5.1.4 Polycarbonate <CES Edupack>

Polyethylene (PE)

Description

Image



Caption

1. Bubble wrap © PublicDomainPictures at Pixabay [Public domain] 2. Cable insulation © Byrev at Pixabay [Public domain] 3. PE bottles © HebiFot at Pixabay [Public domain]

The material

POLYETHYLENE, (-CH2-)n, first synthesized in 1933, looks like the simplest of molecules, but the number of ways in which the - CH2 - units can be linked is large. It is the first of the polyolefins, the bulk thermoplastic polymers that account for a dominant fraction of all polymer consumption. Polyethylene is inert, and extremely resistant to fresh and salt water, food, and most water-based solutions. Because of this it is widely used in household products, food containers like Tupperware and chopping boards. Polyethylene is cheap, and particularly easy to mold and fabricate. It accepts a wide range of colors, can be transparent, translucent or opaque, has a pleasant, slightly waxy feel, can be textured or metal coated, but is difficult to print on.

Composition (summary)

(-CH2-CH2-)n

General properties

Density		939	-	960	kg/m^3
Price	*	1.61	-	1.65	USD/kg
Date first used		1936			

Mechanical properties

Young's modulus		0.621	-	0.896	GPa
Shear modulus	*	0.218	-	0.314	GPa
Bulk modulus		2.15	-	2.25	GPa
Poisson's ratio	*	0.418	-	0.434	
Yield strength (elastic limit)		17.9	-	29	MPa
Tensile strength		20.7	-	44.8	MPa
Compressive strength		19.7	-	31.9	MPa
Elongation		200	-	800	% strain
Hardness - Vickers		5.4	-	8.7	HV
Fatigue strength at 10^7 cycles		21	-	23	MPa
Fracture toughness	*	1.44	-	1.72	MPa.m^0.5
Mechanical loss coefficient (tan delta)	*	0.0446	-	0.0644	

Thermal properties

Melting point		125	-	132	°C
Glass temperature		-25.2	-	-15.2	°C
Maximum service temperature	*	90	-	110	°C
Minimum service temperature	*	-123	-	-73.2	°C
Thermal conductor or insulator?		Good insulator			
Thermal conductivity		0.403	-	0.435	W/m.°C
Specific heat capacity	*	1.81e3	-	1.88e3	J/kg.°C
Thermal expansion coefficient		126	-	198	µstrain/°C

Electrical properties

Electrical conductor or insulator?		Good insulator			
Electrical resistivity		3.3e22	-	3e24	µohm.cm
Dielectric constant (relative permittivity)		2.2	-	2.4	
Dissipation factor (dielectric loss tangent)	*	3e-4	-	6e-4	
Dielectric strength (dielectric breakdown)		17.7	-	19.7	1000000 V/m

Optical properties

Transparency		Translucent			
Refractive index		1.5	-	1.52	

Critical Materials Risk

High critical material risk?		No

Processability

Castability	1	-	2
Moldability	4	-	5
Machinability	3	-	4
Weldability	5		

Durability: water and aqueous solutions

Water (fresh)	Excellent
Water (salt)	Excellent
Soils, acidic (peat)	Excellent
Soils, alkaline (clay)	Excellent
Wine	Excellent

Durability: acids

Acetic acid (10%)	Excellent
Acetic acid (glacial)	Excellent
Citric acid (10%)	Excellent
Hydrochloric acid (10%)	Excellent
Hydrochloric acid (36%)	Excellent
Hydrofluoric acid (40%)	Excellent
Nitric acid (10%)	Excellent
Nitric acid (70%)	Acceptable
Phosphoric acid (10%)	Excellent
Phosphoric acid (85%)	Excellent
Sulfuric acid (10%)	Excellent
Sulfuric acid (70%)	Excellent

Durability: alkalis

Sodium hydroxide (10%)	Excellent
Sodium hydroxide (60%)	Excellent

Durability: fuels, oils and solvents

Amyl acetate	Excellent
Benzene	Acceptable
Carbon tetrachloride	Acceptable
Chloroform	Limited use
Crude oil	Acceptable
Diesel oil	Excellent
Lubricating oil	Excellent
Paraffin oil (kerosene)	Excellent
Petrol (gasoline)	Excellent
Silicone fluids	Acceptable
Toluene	Acceptable
Turpentine	Excellent
Vegetable oils (general)	Excellent
White spirit	Excellent

Durability: alcohols, aldehydes, ketones

Acetaldehyde	Excellent
Acetone	Acceptable
Ethyl alcohol (ethanol)	Excellent
Ethylene glycol	Excellent
Formaldehyde (40%)	Excellent
Glycerol	Excellent
Methyl alcohol (methanol)	Excellent

Durability: halogens and gases

Chlorine gas (dry)	Acceptable
Fluorine (gas)	Limited use
O2 (oxygen gas)	Unacceptable
Sulfur dioxide (gas)	Excellent

Durability: built environments

Industrial atmosphere	Excellent
Rural atmosphere	Excellent
Marine atmosphere	Excellent
UV radiation (sunlight)	Fair

Durability: flammability

Flammability	Highly flammable

Durability: thermal environments

Tolerance to cryogenic temperatures		Unacceptable			
Tolerance up to 150 C (302 F)		Acceptable			
Tolerance up to 250 C (482 F)		Unacceptable			
Tolerance up to 450 C (842 F)		Unacceptable			
Tolerance up to 850 C (1562 F)		Unacceptable			
Tolerance above 850 C (1562 F)		Unacceptable			

Geo-economic data for principal component

Annual world production, principal component		6.8e7	-	6.9e7	tonne/yr
Reserves, principal component	*	1.66e9	-	1.88e9	tonne

Primary material production: energy, CO2 and water

Embodied energy, primary production	*	77	-	85.1	MJ/kg
CO2 footprint, primary production	*	2.64	-	2.92	kg/kg
Water usage	*	55.3	-	61.1	l/kg
Eco-indicator 95		330			millipoints/kg
Eco-indicator 99		287			millipoints/kg

Material processing: energy

Polymer extrusion energy	*	5.9	-	6.52	MJ/kg
Polymer molding energy	*	20.8	-	23	MJ/kg
Coarse machining energy (per unit wt removed)	*	0.688	-	0.76	MJ/kg
Fine machining energy (per unit wt removed)	*	2.6	-	2.88	MJ/kg
Grinding energy (per unit wt removed)	*	4.73	-	5.23	MJ/kg

Material processing: CO2 footprint

Polymer extrusion CO2	*	0.442	-	0.489	kg/kg
Polymer molding CO2	*	1.56	-	1.73	kg/kg
Coarse machining CO2 (per unit wt removed)	*	0.0516	-	0.057	kg/kg
Fine machining CO2 (per unit wt removed)	*	0.195	-	0.216	kg/kg
Grinding CO2 (per unit wt removed)	*	0.355	-	0.392	kg/kg

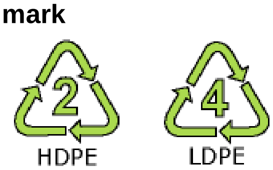
Material recycling: energy, CO2 and recycle fraction

Recycle		True			
Embodied energy, recycling	*	47.1	-	52	MJ/kg
CO2 footprint, recycling	*	3.7	-	4.09	kg/kg
Recycle fraction in current supply		7.5	-	9.5	%
Downcycle		True			
Combust for energy recovery		True			
Heat of combustion (net)	*	44	-	46.2	MJ/kg
Combustion CO2	*	3.06	-	3.22	kg/kg
Landfill		True			
Biodegrade		False			
Non-toxic					
A renewable resource?		False			

Environmental notes

PE is FDA compliant - indeed it is so non-toxic that it can be embedded in the human body (heart valves, hip-joint cups, artificial artery). PE, PP and PVC are made by processes that are relatively energy-efficient, making them the least energy-intensive of commodity polymers. The ethylene from which it is made at present is an oil derivative, but PE can be produced from renewable resources - from alcohol derived from the fermentation of sugar or starch, for instance. Its utility per kilogram far exceeds that of gasoline or fuel-oil (and its energy is stored and still accessible), so that production from oil will not disadvantage it in the near future. Polyethylene is readily recyclable if it has not been coated with other materials, and - if contaminated - it can be incinerated to recover the energy it contains.

Recycle mark



Supporting information

Design guidelines

PE is commercially produced as film, sheet, rod, foam and fiber. Drawn PE fiber has exceptional mechanical stiffness and strength, exploited in geo-textile and structural uses. PE is a good electrical insulator with low dielectric loss, so suitable for containers for microwave cooking. It has poor resistance to aromatics and chlorine; it is slow burning in fire. PE is cheap, easy to form, biologically inert and recyclable; it is one of the materials of the next 20 years.

Technical notes

Low density polyethylene (LDPE), used for film and packaging, has branched chains which do not pack well, making it less dense than water. Medium (MDPE) and High (HDPE) density polyethylenes have longer, less branched chains, making them stiffer and stronger; they are used for containers and pipes. Modern catalysis allows side-branching to be suppressed and molecular length to be controlled precisely, permitting precise tailoring both of the processing properties critical for drawing, blow molding, injection molding or extrusion and the use-properties of softening temperature, flexibility and toughness. Linear low-density polyethylene (LLPDE) is an example. In its pure form it is less resistant to organic solvents, but even this can be overcome by converting its surface to a fluoro-polymer by exposing it to fluorine gas. Treated in this way (when it known is known as 'Super PE') it can be used for petrol tanks in cars and copes with oil, cleaning fluid, cosmetics and that most corrosive of substances: cola concentrate. Very low density polyethylene (VDLPE) is similar to EVA and plasticized PVC.

Typical uses

Oil container, street bollards, milk bottles, toys, beer crate, food packaging, shrink wrap, squeeze tubes, disposable clothing, plastic bags, paper coatings, cable insulation, artificial joints, and as fibers - low cost ropes and packing tape reinforcement.

Tradenames

Alathon, Aquathene, Bapolene, Dowlex, Eltex, Empee, Eraclene, Ferrene, Fortiflex, HiVal, Hid, Kemcor, Lacqtene, Lupolen, Marlex, Nortuff, Novapol, Paxon, Petrothene, Polyfort, Rigidex, Sclair, Stamylyn, Statoil, Unival, Zemid

Links

Reference
ProcessUniverse
Producers
Values marked * are estimates.
No warranty is given for the accuracy of this data

5.1.5 Polyethylene terephthalate (PET) <Ces Edupack>

Polyethylene terephthalate (PET)

Description

Image

Caption

PET drinks containers, pressurized and unpressurized. © Tee design and printing Ltd

The material

The name polyester derives from a combination of 'Polymerization' and 'esterification'. Saturated polyesters are thermoplastic - examples are PET and PBT; they have good mechanical properties to temperatures as high as 175 C. PET is crystal clear, impervious to water and CO2, but a little oxygen does get through. It is tough, strong, easy to shape, join and sterilize - allowing reuse. When its first life comes to an end, it can be recycled to give fibers and fleece materials for clothing and carpets. Unsaturated polyesters are thermosets; they are used as the matrix material in glass fiber/polyester composites. Polyester elastomers are resilient and stretch up to 45% in length; they have good fatigue resistance and retain flexibility at low temperatures.

Composition (summary)

(CO-(C6H4)-CO-O-(CH2)2-O)n

General properties

Density		1.29e3	-	1.4e3	kg/m^3
Price	*	1.83	-	1.87	USD/kg
Date first used		1941			

Mechanical properties

Young's modulus		2.76	-	4.14	GPa
Shear modulus	*	0.994	-	1.49	GPa
Bulk modulus		4.95	-	5.2	GPa
Poisson's ratio	*	0.381	-	0.396	
Yield strength (elastic limit)		56.5	-	62.3	MPa
Tensile strength		48.3	-	72.4	MPa
Compressive strength		62.2	-	68.5	MPa
Elongation		30	-	300	% strain
Hardness - Vickers		17	-	18.7	HV
Fatigue strength at 10^7 cycles	*	19.3	-	29	MPa
Fracture toughness		4.5	-	5.5	MPa.m^0.5
Mechanical loss coefficient (tan delta)	*	0.00966	-	0.0145	

Thermal properties

Melting point		212	-	265	°C
Glass temperature		67.9	-	79.9	°C
Maximum service temperature		66.9	-	86.9	°C
Minimum service temperature	*	-123	-	-73.2	°C
Thermal conductor or insulator?		Good insulator			
Thermal conductivity		0.138	-	0.151	W/m.°C
Specific heat capacity	*	1.42e3	-	1.47e3	J/kg.°C
Thermal expansion coefficient		115	-	119	µstrain/°C

Electrical properties

Electrical conductor or insulator?		Good insulator			
Electrical resistivity		3.3e20	-	3e21	µohm.cm
Dielectric constant (relative permittivity)		3.5	-	3.7	
Dissipation factor (dielectric loss tangent)	*	0.003	-	0.007	
Dielectric strength (dielectric breakdown)		16.5	-	21.7	1000000 V/m

Optical properties

Transparency		Transparent			
Refractive index		1.57	-	1.58	

Critical Materials Risk

High critical material risk?	No

Processability

Castability	1	-	2
Moldability	4	-	5
Machinability	3	-	4
Weldability	5		

Durability: water and aqueous solutions

Water (fresh)	Excellent
Water (salt)	Excellent
Soils, acidic (peat)	Acceptable
Soils, alkaline (clay)	Limited use
Wine	Excellent

Durability: acids

Acetic acid (10%)	Acceptable
Acetic acid (glacial)	Excellent
Citric acid (10%)	Excellent
Hydrochloric acid (10%)	Excellent
Hydrochloric acid (36%)	Limited use
Hydrofluoric acid (40%)	Limited use
Nitric acid (10%)	Excellent
Nitric acid (70%)	Unacceptable
Phosphoric acid (10%)	Excellent
Phosphoric acid (85%)	Acceptable
Sulfuric acid (10%)	Excellent
Sulfuric acid (70%)	Limited use

Durability: alkalis

Sodium hydroxide (10%)	Limited use
Sodium hydroxide (60%)	Unacceptable

Durability: fuels, oils and solvents

Amyl acetate	Limited use
Benzene	Excellent

Carbon tetrachloride		Excellent			
Chloroform		Excellent			
Crude oil		Acceptable			
Diesel oil		Excellent			
Lubricating oil		Excellent			
Paraffin oil (kerosene)		Excellent			
Petrol (gasoline)		Excellent			
Silicone fluids		Acceptable			
Toluene		Limited use			
Turpentine		Limited use			
Vegetable oils (general)		Excellent			
White spirit		Acceptable			

Durability: alcohols, aldehydes, ketones

Acetaldehyde		Excellent			
Acetone		Limited use			
Ethyl alcohol (ethanol)		Excellent			
Ethylene glycol		Excellent			
Formaldehyde (40%)		Excellent			
Glycerol		Excellent			
Methyl alcohol (methanol)		Excellent			

Durability: halogens and gases

Chlorine gas (dry)		Excellent			
Fluorine (gas)		Unacceptable			
O2 (oxygen gas)		Unacceptable			
Sulfur dioxide (gas)		Excellent			

Durability: built environments

Industrial atmosphere		Excellent			
Rural atmosphere		Excellent			
Marine atmosphere		Excellent			
UV radiation (sunlight)		Good			

Durability: flammability

Flammability		Highly flammable			

Durability: thermal environments

Tolerance to cryogenic temperatures		Unacceptable			
Tolerance up to 150 C (302 F)		Acceptable			
Tolerance up to 250 C (482 F)		Unacceptable			
Tolerance up to 450 C (842 F)		Unacceptable			
Tolerance up to 850 C (1562 F)		Unacceptable			
Tolerance above 850 C (1562 F)		Unacceptable			

Geo-economic data for principal component

Annual world production, principal component		9e6	-	9.2e6	tonne/yr
Reserves, principal component	*	2.58e8	-	2.6e8	tonne

Primary material production: energy, CO2 and water

Embodied energy, primary production	*	80.9	-	89.5	MJ/kg
CO2 footprint, primary production	*	3.76	-	4.15	kg/kg
Water usage	*	126	-	140	l/kg
Eco-indicator 95		380			millipoints/kg
Eco-indicator 99		276			millipoints/kg

Material processing: energy

Polymer extrusion energy	*	5.8	-	6.42	MJ/kg
Polymer molding energy	*	18.2	-	20.1	MJ/kg
Coarse machining energy (per unit wt removed)	*	1.08	-	1.19	MJ/kg
Fine machining energy (per unit wt removed)	*	6.54	-	7.22	MJ/kg
Grinding energy (per unit wt removed)	*	12.6	-	13.9	MJ/kg

Material processing: CO2 footprint

Polymer extrusion CO2	*	0.435	-	0.481	kg/kg
Polymer molding CO2	*	1.36	-	1.51	kg/kg
Coarse machining CO2 (per unit wt removed)	*	0.0811	-	0.0896	kg/kg
Fine machining CO2 (per unit wt removed)	*	0.49	-	0.542	kg/kg
Grinding CO2 (per unit wt removed)	*	0.945	-	1.04	kg/kg

Material recycling: energy, CO2 and recycle fraction

Recycle		True			

Embodied energy, recycling	*	36.9	-	40.7	MJ/kg
CO2 footprint, recycling	*	2.9	-	3.2	kg/kg
Recycle fraction in current supply		20	-	22	%
Downcycle		True			
Combust for energy recovery		True			
Heat of combustion (net)	*	23	-	24.2	MJ/kg
Combustion CO2	*	2.24	-	2.35	kg/kg
Landfill		True			
Biodegrade		False			
Toxicity rating		Non-toxic			
A renewable resource?		False			

Environmental notes

PET bottles take less energy to make than glass bottles of the same volume, and they are much lighter - saving fuel in delivery. Thick-walled bottles can be reused; thin-walled bottles can be recycled - and are, particularly in the US.

Recycle mark

PET

Supporting information

Design guidelines

There are four grades of thermoplastic polyesters: unmodified, flame retardant, glass-fiber reinforced and mineral-filled. Unmodified grades have high elongation; flame retardant grades are self -extinguishing; glass-fiber reinforced grades (like Rynite) are some of the toughest polymers but there are problems with dimensional stability; and mineral-filled grades are used to counter warping and shrinkage although some strength is lost. The PET used in carbonated drink containers is able to withstand pressure from within, it is recyclable and lighter than glass. The limits of the material's permeability to oxygen is overcome by sandwiching a layer of polyethylvinylidene-alcohol between two layers of PET giving a multi-layer material that can still be blow molded. Polyester can be optically transparent, clear, translucent, white or opaque; the resin is easily colored.

Technical notes

Polyesters are made by a condensation reaction of an alcohol like ethyl alcohol (the one in beer) and an organic acid like acetic acid (the one in vinegar). The two react, releasing water, and forming an ester. PET, PBT and PCT are not cross-linked and thus are thermoplastic. The polyesters that are used as the matrix polymer in bulk and sheet molding compounds are thermosets

Typical uses

Electrical fittings and connectors, blow molded bottles, packaging film, photographic and X-ray film, audio/visual tapes, industrial strapping, capacitor film, drawing office transparencies, fibers. Decorative film, metallized balloons, carbonated drink containers, ovenproof cookware, windsurfing sails, credit cards.

Tradenames

Arnite, Eastabond, Eastapak, Ektar, Grilpet, Impet, Kodapak, Melinar, Petra, Plenco, Polyclear, Rynite, Selar, Techster, Valox

Links

Reference
ProcessUniverse
Producers
Values marked * are estimates.
No warranty is given for the accuracy of this data