MERICAN STUDIO

LEI

Lisa Eco Innovations

MATERIALISE

An eco-friendly bike frame

Lara Merican • 02382776 • 2023

Contents

Technical summary

Merican Studio was consulted by Lisa Eco Innovations (LEI) to choose the most suitable material for their upcoming product - an eco-friendly bike frame. LEI is a product design company which prioritises making a positive impact on the environment while making their products affordable.

This report goes into depth explaining the material selection process made by Merican Studio. By understanding LEI's values, Merican Studio was able to develop the given brief to outline various figures of merit. To build a basic understanding of bike frames, background research was carried out to analyse the structure of a bike frame and its currently used materials. To set a criteria based on the developed brief, limits were defined by mechanics calculations and comparing property values from currently used materials. From there, two methods were used to filter and select the materials: filtration through Ashby plots and Semantic Differential Scales (SDS). Results from these methods were compiled and analysed by considering various factors to ultimately arrive at a conclusion.

In the final analysis, Merican Studio chose **Low alloy steel** as the most suitable material. Its property values of the chosen figures of merit fit the criteria in the developed brief and sufficiently fell within the predetermined limits. It also had a satisfactory result for the SDS - being the one material that was consistently scoring a relatively good score.

1 Introduction

Merican Studio is a design consultancy company based in London, United Kingdom which works with various product design companies. This report focuses on the brief provided by Merican Studio's most recent client, Lisa Eco Innovations (LEI) based in Oregon, United States.

1.1 Understanding company values

LEI aims to produce affordable and eco-friendly products that are accessible to the general public of Oregon. LEI consulted Merican Studio to determine the most suitable material for a bike frame that aligns with their values.

1.2 Brief development

Following the criteria given by LEI as mentioned above, Merican Studio narrowed down figures of merit of the material:

General properties

- Price: LEI aims to create affordable products - price should be low to maximise profit.
- Density: A low density bike frame has a greater ability of absorbing road vibration. Therefore, a low density would be ideal for the consumer to have a comfortable ride.

Mechanical properties

- Young's modulus: Refers to the stiffness of the material and its resistance to elastic deformation. The bike frame should be stiff for safety, so a high Young's modulus is required.
- Tensile strength: Refers to the maximum stress that can be applied before fracture occurs. This should be maximised to prevent fracture.

Chemical properties

- Durability in freshwater: Bicycles are mostly used outdoors and can be exposed to rain. Hence, the material should withstand corrosion from water to have a long lifespan.

Environmental properties

- Embodied energy: Refers to the amount of energy used in material production. This should be minimised to align with LEI's values.
- CO_2 footprint: Determines the amount of CO_2 emitted from material production. This should also be minimised to align with LEI's values.
- Recyclability: To prevent unnecessary waste in landfills, the bike frame should be recyclable.

2 Background research

2.1 Structure of a bike frame

A typical bike frame is made up of 2 triangles - the 'main triangle' and the 'rear triangle' as shown in Figure 1.

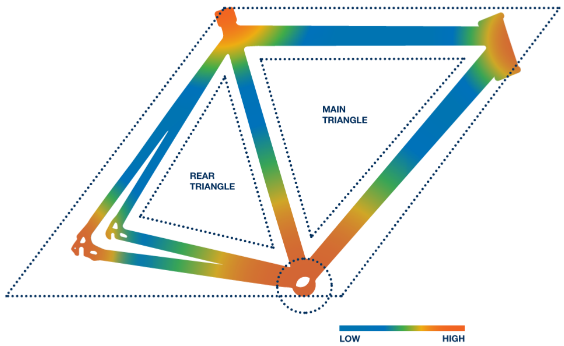


Figure 1: Stress analysis of a bike frame (1)

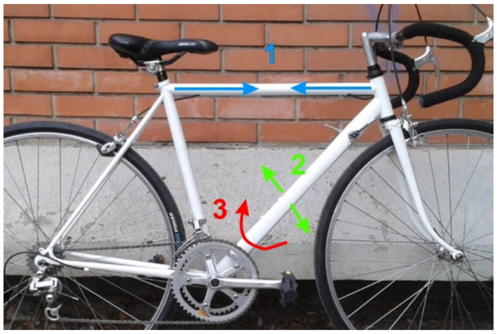


Figure 2: Stresses on frame tubes (2)

Frame tubes mainly undergo compressive and torsional stresses. As shown in Figure 2, blue arrows refer to compressive stress, green arrows refer to out of plane bending and the red arrow refers to the torsional stress. From Figure 1, the area of highest stress is where the pedals are connected to.

2.2 Currently used materials

Data from Table 1 was created from online resources (3-5) and Level 1 CES Edupack.

Table 1: Properties of currently used materials for a bike frame

	General		***Mechanical***		***Chemical***	***Environmental***		
Material	Price (GBP/kg)	Density (kg/m^3)	Young's modulus (GPa)	Tensile strength (MPa)	Durability in freshwater	Embodied energy (MJ/kg)	CO_2 footprint (kg/kg)	Recyclable
Aluminium alloy	1.59 - 1.72	2.64×10^3 - 2.81×10^3	69 - 75	186 - 510	Excellent	186 - 205	12.4 - 13.7	Yes
Low alloy steel	0.565 - 0.677	7.80×10^3	200 - 210	699 - 1.8×10^3	Acceptable	29.5 - 32.6	2.37 - 2.61	Yes
Titanium alloy	19.1 - 20.9	4.43×10^3 - 4.79×10^3	100 - 120	552 - 1.17×10^3	Excellent	587 - 647	33.9 - 37.4	Yes
Carbon fibre	28.6 - 31.8	1.50×10^3 - 1.60×10^3	69 - 150	550 - 1.05×10^3	Excellent	655 - 723	45.8 - 50.5	No

2.3 Further analysis of materials

From data in Table 1 and online resources (3-6), a summary qualitative analysis was made.

Aluminium alloy
Aluminium alloy is the most popular material for a bike frame (5). It has a significantly lower price compared to titanium alloy and carbon fibre, the second lowest value for density, is water resistant and has relatively favourable environmental properties. However, having low stiffness and strength makes it difficult to repair and will be unlikely to return to original quality after reparation (6).

Low alloy steel
Steel used to be the most popular material for a bike frame (5) due to its high Young's modulus and tensile strength values as well as low price. It also has favourable environmental properties. However, it is significantly heavier than other materials as shown in Table 1 with the highest density out of the 4 materials. It is also not as water resistant as other materials which may pose a problem in more humid environments.

Titanium alloy
Titanium alloy is a very strong and stiff material, with a high resistance to water corrosion. It can be recycled, but it has a high embodied energy and CO_2 footprint. It is difficult and costly to manufacture. Titanium itself is relatively rare, so it is expensive - reflected by its price value.

Carbon fibre
In the professional bike racing industry, carbon fibre is a popular choice (5) due to its low density, high tensile strength and aerodynamic properties. It is the most expensive and brittle material, prone to fracture - this is very dangerous if collision occurs. Moreover, it has a high embodied energy and CO_2 footprint, making it environmentally harmful to manufacture. As it is a composite material, it cannot be recycled. In terms of LEI's values, carbon fibre does not fit any of the criteria.

3 Material selection

3.1 Defining limits

Following the description of the figures of merit from '1.2 Brief development', the following limits were defined:

3.1.1 General properties

Price
From Table 1, the price ranges from 0.565 - 31.8 GBP/kg. The most expensive materials (titanium alloy and carbon fibre) are mainly used for professional biking. LEI wanted their product to be affordable and accessible to the general public, hence Merican Studio ignored the prices of these materials and set the maximum limit to 1.72 GBP/kg.

Density
By simplifying the shape of a bike frame as a uniform, cylindrical rod, we estimated a minimum value for density using the values: $r = 2 \times 10^{-2}\, m,\ L = 0.7\, m$.

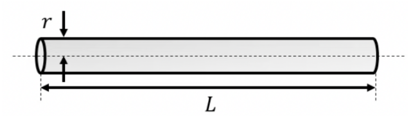


Figure 3: Simplification of a bike frame (with radius and length) (7)

$$V = \pi r^2 L = \pi \times (2 \times 10^{-2})^2 \times (0.7) = 8.80 \times 10^{-4}\, m^3\ (3\ s.f.)$$

A typical bike frame weighs around 0.965 kg (3 s.f.), calculated from the mean of 21 bicycles (8).

$$\rho = \frac{m}{V} = \frac{0.965}{8.80\times10^{-4}} = 1100\ kg/m^3\ (3\ s.f.)$$

Hence, Merican Studio allocated a minimum density of 1100 kg/m^3.

3.1.2 Mechanical properties

Young's modulus
Using the same simplification as above, the following calculation for Young's modulus was made with the values: $F = 100N,\ r = 2 \times 10^{-2}\, m,\ L = 0.7m,\ \delta = 1 \times 10^{-3} m$.

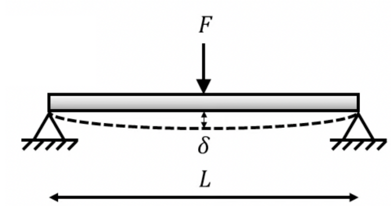


Figure 4: Simplification of a bike frame (with force, deflection and length) (7)

Substituted the moment of inertia of a circle $I = \frac{\pi r^4}{4}$ into the equation of central deflection for beams bent about principal axis equation:

$$\delta = \frac{FL^3}{48EI} = \frac{FL^3}{12E\pi r^4}$$

Rearranged to make Young's modulus the subject, and calculated:

$$E = \frac{FL^3}{12\delta\pi r^4} = \frac{100\times(0.7)^3}{12\times(1\times10^{-3})\times\pi\times(2\times10^{-2})^4} = 5.69 \times 10^9\ Pa = 5.69\ GPa\ (3\ s.f.)$$

Hence, Merican Studio allocated a minimum Young's modulus of 5.69 GPa.

Tensile strength
Seeing how aluminium alloy frames are most popular despite low tensile strength, Merican Studio set the minimum limit to the lower bound of aluminium alloy's tensile strength - 186 MPa.

3.1.3 Chemical properties

Durability in freshwater
Oregon ranks 35th out of the 50 states in the US for relative humidity (9). Thus, Merican Studio concluded a ranking of 'Acceptable' and above was sufficient.

3.1.4 Environmental properties

Limits on environmental properties were much stricter due to LEI's priority on the environment.

Embodied energy
Ignoring values from titanium alloys and carbon fibre, the values for embodied energy ranges from 29.5 - 205 MJ/kg. Hence, the maximum limit was set to 205 MJ/kg.

CO_2 footprint
Ignoring values again from titanium alloys and carbon fibre, the values for CO_2 footprint ranges from 2.37 - 13.7 kg/kg. Hence, the maximum limit was set to 13.7 kg/kg.

Recyclability
Recyclability was set to 'Yes'.

3.2 Initial Ashby plot

Considering that LEI values a positive impact on the environment, we filtered out unfavourable environmental properties first. This stage reduced the number of available materials from 69 to 30.

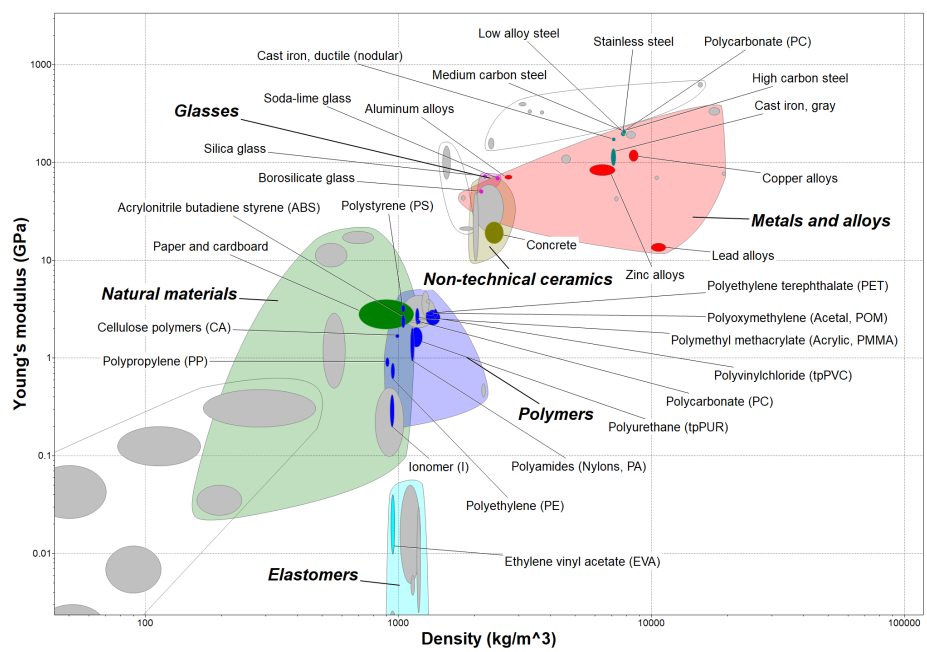


Figure 5: Initial "Young's modulus vs Density" Ashby plot showing 30 materials

3.3 Performance index

Referring to Figure 3, the volume of the rod is $V = \pi r^2 L$, hence by substitution and rearrangement:

$$m = \rho V \rightarrow m = \pi r^2 L\rho \rightarrow r = \sqrt{\frac{m}{\pi L\rho}}$$

Substituted radius into the deflection equation from the "Young's modulus" section from 3.1.2:

$$\delta = \frac{FL^3}{12E\pi r^4} = \frac{FL^3}{12E\pi(\sqrt{\frac{m}{\pi L\rho}})^4} = \frac{FL^3}{12E\pi(\frac{m^2}{\pi^2 L^2\rho^2})} = \frac{FL^5\rho^2\pi}{12Em^2}$$

By making mass the subject, we analysed the terms in the equation:

$$m = \sqrt{\frac{FL^5\pi}{12\delta}} \bullet \frac{\rho}{\sqrt{E}}$$

1. Geometric/load: $\sqrt{\frac{FL^5\pi}{12\delta}}$
2. Material: $\frac{\rho}{\sqrt{E}}$

Following the "Brief Development" in section 1.2, we aimed for a low density. Hence, according to material properties, $\frac{\rho}{\sqrt{E}}$ must be minimised. We defined a performance index to be maximised:

$$P = \frac{\sqrt{E}}{\rho}$$

To suit our logarithmic Ashby plot, we converted the equation into a logarithmic equation:

$$\sqrt{E} = P\rho \rightarrow log\sqrt{E} = log(P\rho) \rightarrow \frac{1}{2}log\,E = log\,P + log\,\rho \rightarrow log\,E = 2log\,P + 2log\,\rho$$

3.4 Final Ashby plot

Comparing the logarithmic equation to y=mx+c, it showed that 2 is the gradient of the performance index line. By filtering with the performance index line, general properties, mechanical properties and chemical properties, we managed to reduce the available materials from 30 to 6.

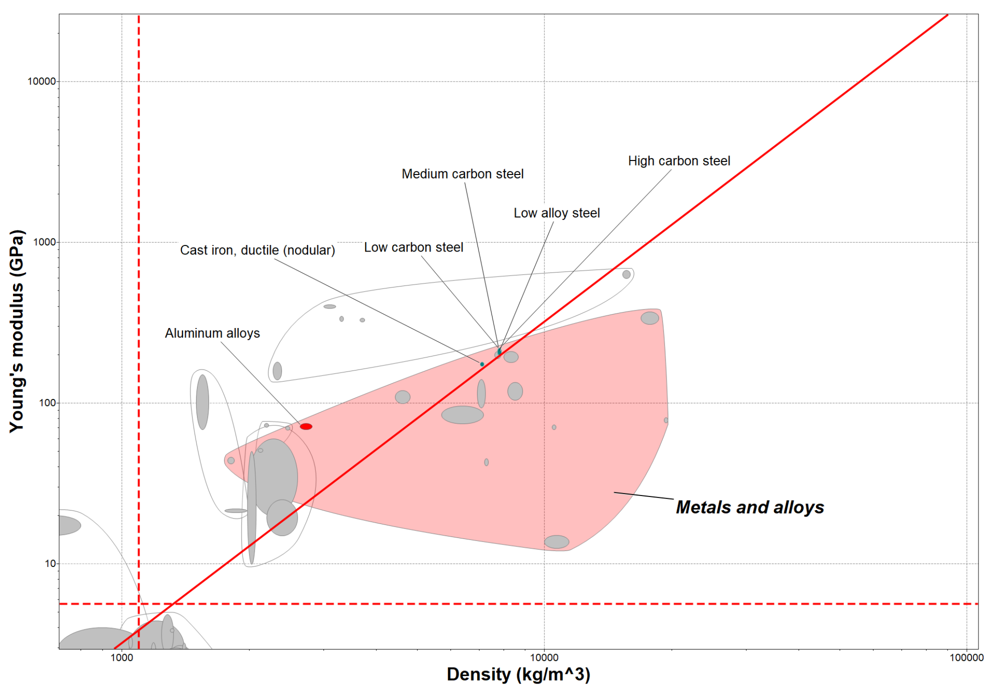


Figure 6: Final "Young's modulus vs Density" Ashby plot showing 6 materials

Merican Studio then decided to set out a table of the 6 remaining materials to compare properties. (All remaining materials are recyclable, hence the recyclability column was omitted.)

Table 2: Properties of 6 remaining materials from final Ashby plot

	General		***Mechanical***		***Chemical***	***Environmental***		
Material	Price (GBP/kg)	Density (kg/m^3)	Young's modulus (GPa)	Tensile strength (MPa)	Durability in freshwater	Embodied energy (MJ/kg)	CO_2 footprint (kg/kg)	Performance index
Aluminium alloy	1.59 - 1.72	2.64×10^3 - 2.81×10^3	69 - 75	186 - 510	Excellent	186 - 205	12.4 - 13.7	3.11×10^{-3}
Low alloy steel	0.565 - 0.677	7.80×10^3	200 - 210	699 - 1.8×10^3	Acceptable	29.5 - 32.6	2.37 - 2.61	1.86×10^{-3}
Low carbon steel	0.524 - 0.552	7.80×10^3 - 7.82×10^3	200 - 220	379 - 532	Acceptable	29.3 - 32.3	2.21 - 2.44	1.86×10^{-3}
Medium carbon steel	0.524 - 0.552	7.80×10^3	200 - 220	591 - 1.19×10^3	Acceptable	30.8 - 34.0	2.26 - 2.49	1.86×10^{-3}
High carbon steel	0.533 - 0.562	7.80×10^3	200 - 220	721-1.39×10^3	Acceptable	30.8 - 34.0	2.26 - 2.49	1.85×10^{-3}
Cast iron, ductile (nodular)	0.213	7.05×10^3 - 7.15×10^3	170 - 180	400-900	Acceptable	30.8 - 34.0	2.26 - 2.49	1.84×10^{-3}

3.5 Semantic Differential Scales

Merican Studio carried out the explicit method of Semantic Differential Scales to assess the public's perceptions of the different materials, collecting 12 sets of results through an online survey.

Table 3: Summary of findings from Semantic Differential Scales (SDS)

Property	***Relevance***	***Outcome***
Eco-friendly vs Eco-unfriendly	LEI's core value is to have eco-friendly products which save the environment.	**Aluminium alloy** was perceived as the most eco-friendly with a mean score of 3.33. This is an interesting result as the data in Table 2 shows the opposite, having the highest values for energy and CO_2.
Strong vs Weak	If customers perceive the product to be strong, they will be more likely to buy it.	**High carbon steel** was perceived to be the strongest material with a mean score of 2.50. It corresponds with the data in Table 2 - high Young's modulus and tensile strength.
High quality vs Low quality	Most buyers would want to invest in a high quality bike frame. If it looks high in quality, they will invest in it.	**Medium carbon steel** was perceived to be the material with the best quality with a mean score of 2.75. However, all the materials ranked quite similarly with the highest mean score being 3.58.
Cheap vs Expensive	LEI aims to sell affordable and accessible products - if it looks cheap, the more likely they will buy it.	**Low carbon steel** was perceived to be the cheapest material with a mean score of 2.92. All other materials had a mean score over 3. In reality the price of cast iron is lower, as shown in Table 2.

4 Discussion

4.1 Analysing results

In the Ashby plots, the filtration of materials narrowed down the available materials from 69 to 6 which were within the limits of the chosen properties. The green coloured boxes in Table 2 show the 'best values' based on the property requirements from '1.2 Brief development'. **Aluminium alloy** and **Low carbon steel** were the materials with the most number of 'best values'.

Aluminium alloy had the best performance index, the lowest density and the best durability against freshwater. In the SDS, it scored the best score for being 'eco-friendly', despite the material values showing that it has a significantly higher embodied energy and CO_2 footprint (about 6 times greater) compared to the steels. As LEI heavily prioritises a positive impact on the environment, Merican Studio decided that **<u>Aluminium alloy was not a suitable material</u>**.

Low carbon steel had the best values for Young's modulus, embodied energy and CO_2 footprint. It also had the second best value for performance index and price. In the SDS, it was perceived to be the cheapest material. Ultimately, Merican Studio decided that **<u>Low carbon steel was not a suitable material</u>** as it had a significantly low tensile strength and the other steels had extremely similar values for most of the properties.

Despite its very low price, **<u>Cast iron was not a suitable material</u>** due to its low Young's modulus and tensile strength. The performance index was the lowest, and none of the environmental property values were outstanding. Moreover, there was not a good perception of it in the SDS.

4.2 Method limitations

It is important to note that the Ashby plot filtrations did not take some properties into account, such as experiential properties. Moreover, we did not consider manufacturing methods, and this may have produced different results.

The SDS had a small sample size of 12. As the 6 resulting materials were all metals/alloys, they had very similar visual and tactile properties, reflected by the large standard deviation in results. People were unsure about how to differentiate the different materials, especially people with no knowledge of materials. The results were unreliable, so they were only taken into account when needed.

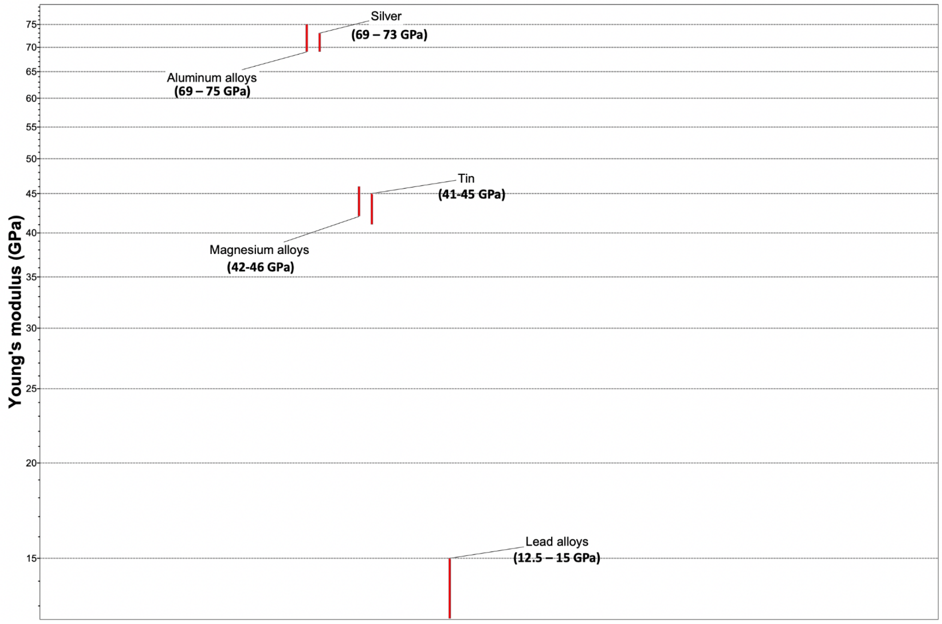
5 Conclusion

Ultimately, Merican Studio chose **<u>Low alloy steel as the most suitable material</u>**. From Table 2, it had the highest tensile strength, the second highest performance index and Young's modulus, and the second lowest embodied energy. All values were significantly greater/smaller compared to the set limits. It was also the one material that had relatively good, consistent scores in the SDS.

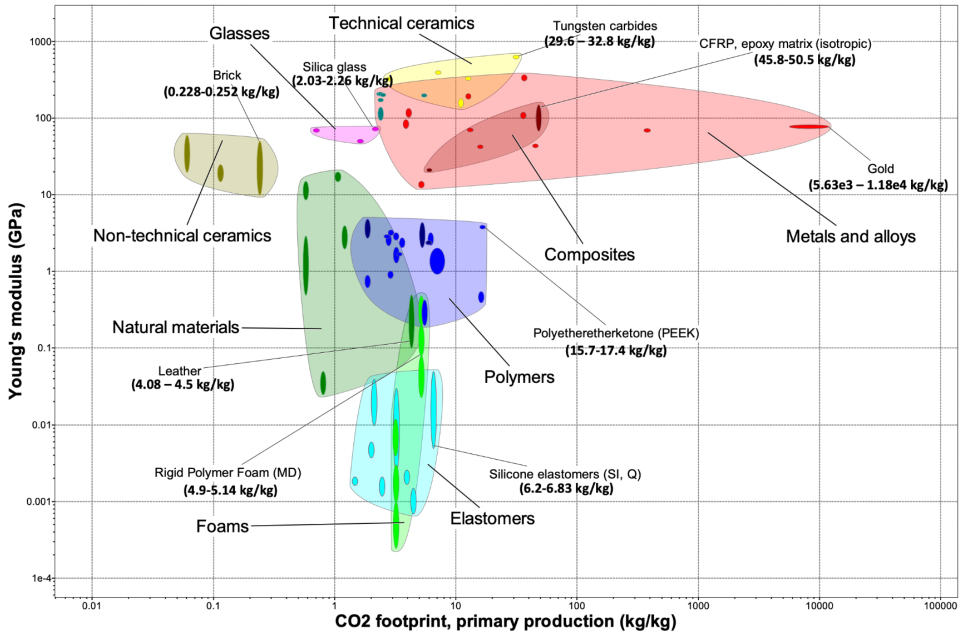
6 Appendices

6.1 Lab Tasks

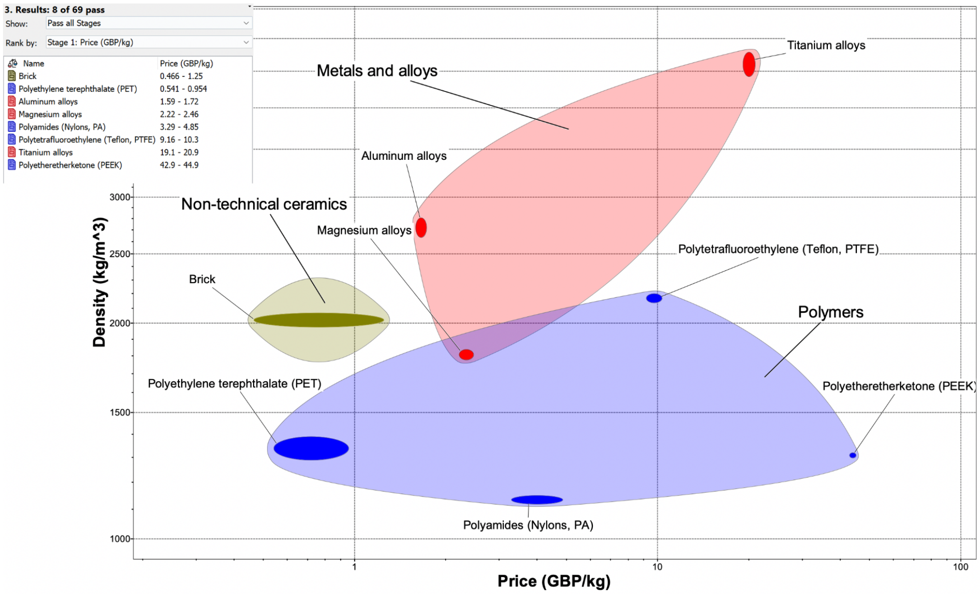
Task 1: Metals, alloys, polymers and elastomers with a Young's modulus between 5-70 GPa



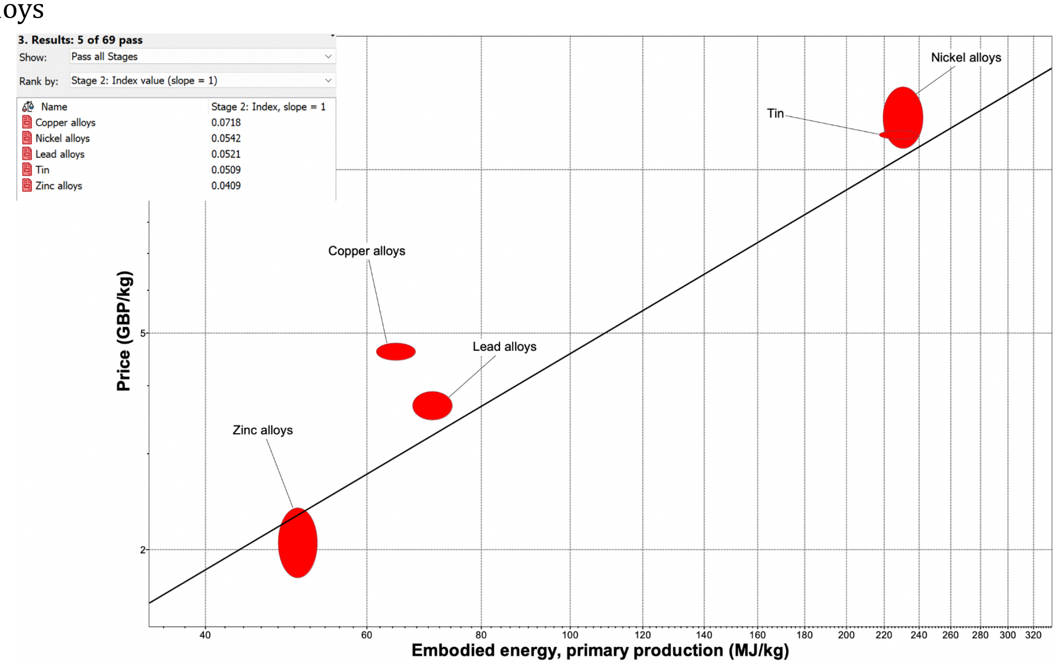
Task 2: Young's modulus (GPa) vs CO_2 footprint (kg/kg) of all materials



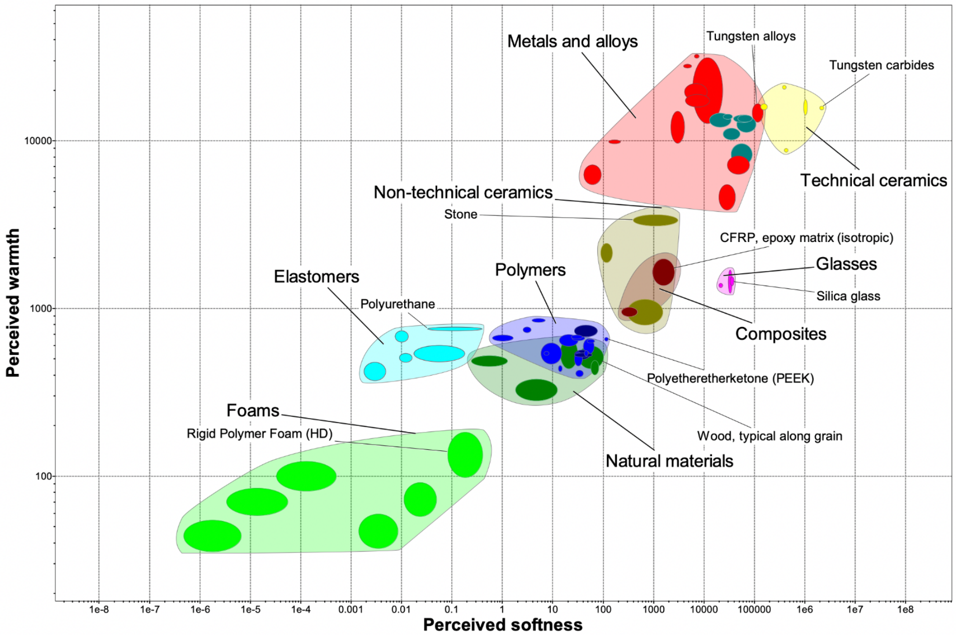
Task 3: Density (kg/m^3) vs Price (GBP/kg) of all materials with filters: density between 500-5000 kg/m^3, cost between 0.5-50 GBP/kg, Young's modulus less than 100 GPa and melting temperature more than 200˚C



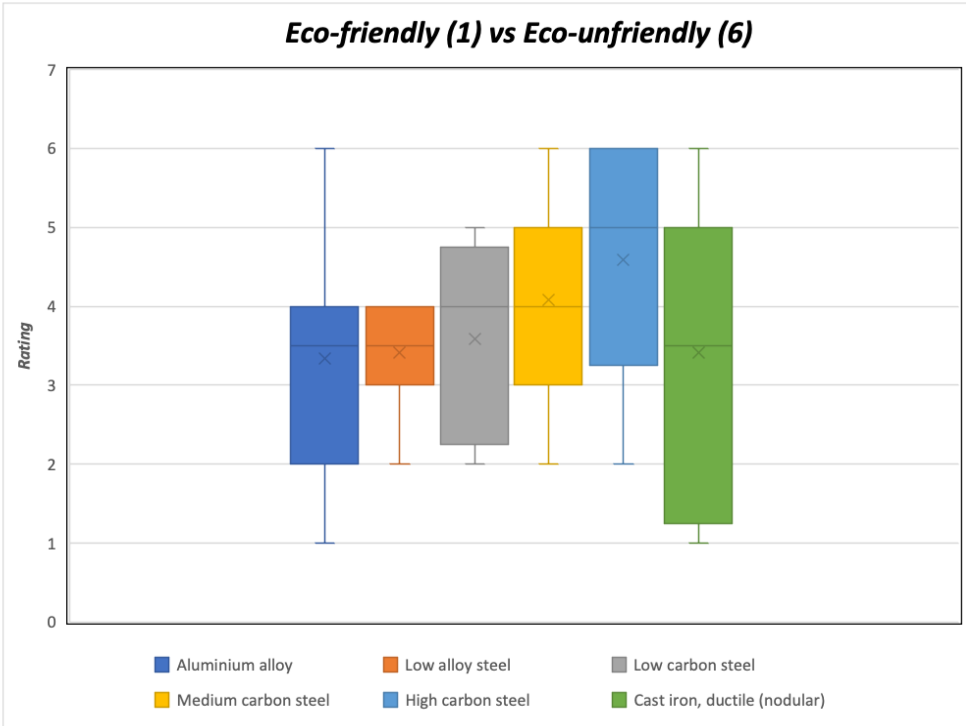
Task 4: Price (GBP/kg) vs Embodied energy (MJ/kg) of electrical conductors (good and poor) with filters: tensile strength more than 10 MPa, can be cast and has a price/embodied ratio greater than Zinc alloys

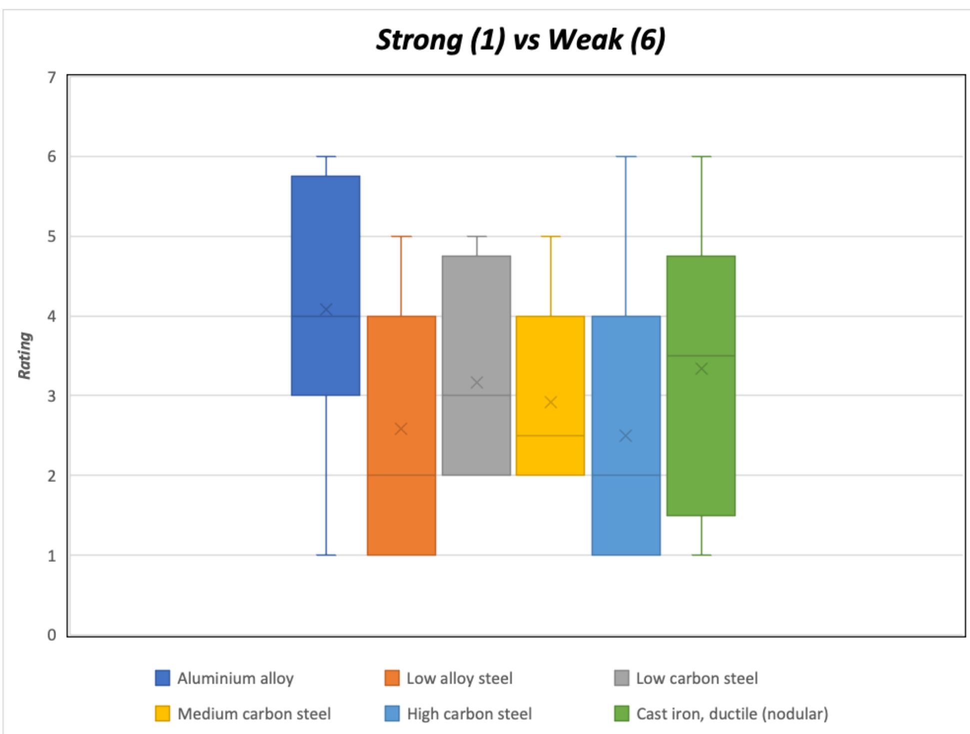


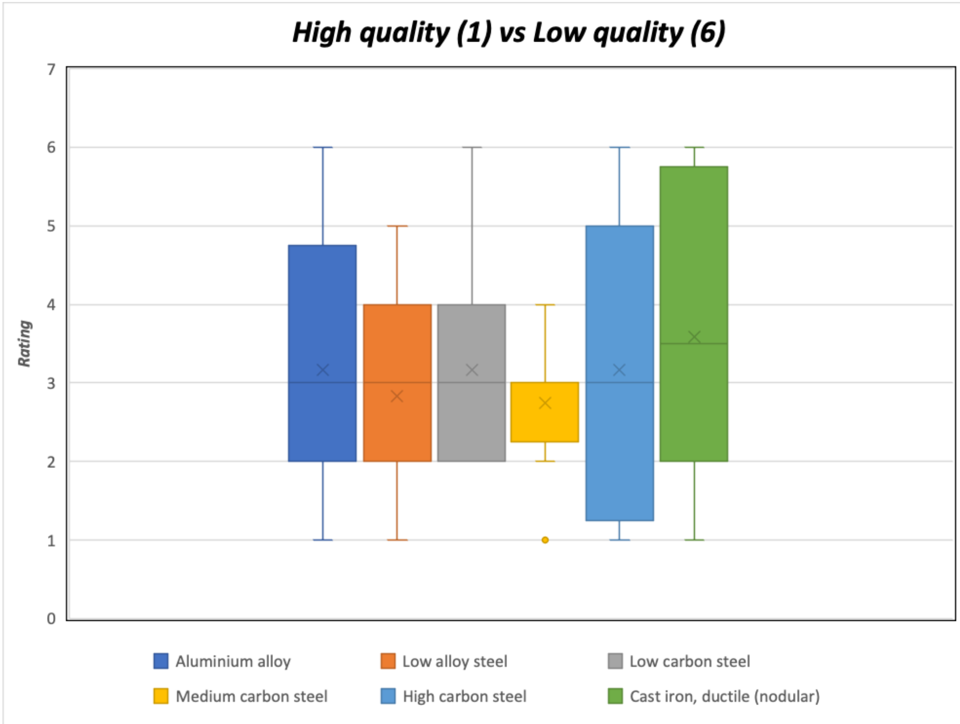
Task 5: Perceived warmth vs Perceived softness of all materials



6.2 Semantic Differential Scales






High quality (1) vs Low quality (6)
Rating
7
6
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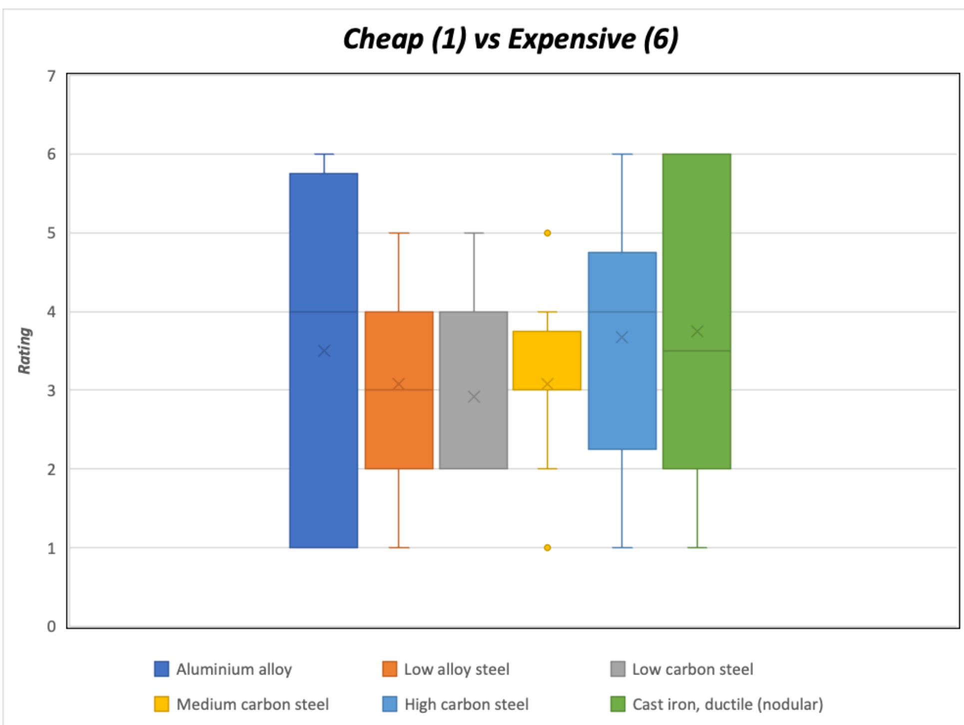
4
3
2
1
0
Aluminium alloy
Low alloy steel
Low carbon steel
Medium carbon steel
High carbon steel
Cast iron, ductile (nodular)


Cheap (1) vs Expensive (6)
Rating
7
6
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1
0
Aluminium alloy
Low alloy steel
Low carbon steel
Medium carbon steel
High carbon steel
Cast iron, ductile (nodular)

7 References

1. West Virginia University. *Science Behind the Sport | Frames*. https://sciencebehindthesport.wvu.edu/cycling/frames [Accessed 28th November 2023].
2. Novović R. *Bicycle frame design explained*. BikeGremlin. https://bike.bikegremlin.com/11319/bicycle-frame-design/ [Accessed 28th November 2023].
3. Novović R. *Bicycle frame materials - explained*. BikeGremlin. https://bike.bikegremlin.com/11144/bicycle-frame-materials-explained/ [Accessed 4th December 2023].
4. REI Co-op. *Understanding Bike Frame Materials*. REI. https://www.rei.com/learn/expert-advice/bike-frame-materials.html [Accessed 4th December 2023].
5. Sumner J, Hurford M. *The Difference Between Your Bike Frame Materials Depends on Your Budget and Intended Use*. Bicycling. https://www.bicycling.com/bikes-gear/a21784287/bike-frame-materials-explained/ [Accessed 4th December 2023].
6. BMCR. *Bike frames explained | Tips from the pro bicycle mechanics*. BMCR. https://bmcr.com.au/articles/best-bicycle-frame-material/ [Accessed 30th November 2023].
7. Wu B. *How to select materials using Ashby plots and performance indexes*. [Video] 2020. https://www.youtube.com/watch?v=9RQkvcsRzbo [Accessed 29th November 2023].
8. McHale M. *The Truth About Road Bike Frame Testing*. Bournemouth Cycleworks. 2012. https://www.bournemouthcycleworks.co.uk/news/the-truth-about-road-bike-frame-testing/ [Accessed 5th December 2023].
9. Brettschneider B. *Oh The Humidity. Which State Is The Most Humid?*. https://www.forbes.com/sites/brianbrettschneider/2018/08/23/oh-the-humidity-why-is-alaska-the-most-humid-state/?sh=21d50f95330c [Accessed 4th December 2023].