MERCHANTPRO

Materialise Coursework – Bike Frame

By Alex Merchant
CID: 4723

Table of Contents

Technical Summary

MerchantPro Materials Consultancy acted for Lisa Simpson to configure the optimal material selection for her company's latest product – a top of the range racing bike. They began by developing the general brief into a well-defined criterion based upon the client's business concept. They then conducted background research into the current bike frame materials and the load cases that bike frames are designed from. From the developed brief, they then calculated the boundary conditions to initially filter the materials. After deriving a performance index based on strength and density, they ranked the remaining materials using Ansys Granta Edupack. Lastly, they defined the required material experiential properties and collected data to rank the final materials using semantic differential scales. Through both performance characteristics and semantic data, they provided their material recommendation with thorough justification.

Introduction

MerchantPro is a London based company focused on helping clients to select the best material for their given application from the ever-growing list. They are aware that without professional methods and services, this task can be extremely challenging. MerchantPro removes all stress and can assure the client that their final material shortlist will be optimized for their specific product, as well as come with detailed and technical rational on the selection process. This report documents their work to help provide the client with a thorough understanding of the process to make an informed decision on which material to select.

Developed Brief

The client – Lisa Simpson – was looking to develop a new high-performance bike that can outperform all others in the current market. She hired MerchantPro to select the most optimal material for the bike frame. Her brand focused on the development of top end bikes designed for the highly competitive and highly skilled rider who often have sponsors. This resulted in the material focus being on performance characteristics over cost and difficulty of manufacture.
After sitting down with the client and further discussing the goal behind the brand, the following requirements were selected:

Physical Properties:

- Extremely low density to reduce bike weight.
- Aesthetically pleasing to help attract customers to buy the product.

Mechanical Properties:

- High yield strength to withstand the forces exerted when riding.
- High stiffness to help transfer the rider's power efficiently.

Background Research

Current Bike Frame Technology

Initially, the existing materials used for bike frames were researched and data was collected as shown in Table 1 below.

Table 1: Existing Materials and Their Properties (1)

Material:	Young's Modulus (GPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)	Density (kg/m^3)	Price (GBP/kg)	Embodied Energy (MJ/kg)
CFRP	69 - 150	550 - 1050	150 - 300	1500 - 1600	28.6 – 31.8	655 - 723
Aluminium 6061 T4	66.6 - 70	206 - 240	91.1 - 106	2690 - 2730	1.52 – 1.75	186 - 205
Steel 4130	201 - 216	500 - 620	262 - 307	7800 - 7900	0.596 – 0.788	28.9 – 31.8
Titanium Ti-3Al-2.5V	91 - 95	621 - 750	363 - 432	4470 - 4490	17.2 – 21.1	622 - 686

Current Bike Frame Design

From online research (2), current bike frame designs are based on forces from the following load cases:

- Full effort standing start – assume 150%/25% of the rider's weight split between pedals. This produces a torsional strain on the frame.
- Steady state pedaling – assume 100% of the rider's weight downwards onto the frame.
- Cornering force – assume 2x the rider's weight down onto the pedals and through the frame from the centripetal acceleration.
- Maximum jump landing force – assume 20 cm for the maximum height drop on a racing bike.
- Also, the typical safety factor for the frame of a racing bike is between 1.67 and 2.22. (3)

These load cases were used to calculate the boundary conditions for the material properties.

Material Selection

Defining Technical Requirements

From the background research, it was found that the metrics of interest should be:

- Density:
    - The material must have a high strength to density ratio in order to have the tensile strength required to support the loads but also be as light as possible to minimize the force required by the rider.
- Shear Modulus: > 4.28 GPa
    - One of the highest forces exerted on a racing bike frame is during cornering. The material needs to be able to withstand these high torsional loads due to the centripetal forces from the rider. A measure of the torsional strength or shear strength is the shear modulus.

- The formula for this is (4):
- $n = \frac{Fl}{A\Delta x}$
- The highest torsional load will be in the top tube as that is the longest section of the frame and by looking at the formula, the shear modulus is proportional to the length. By using the dimensions of the top of the range Canyon Racing Bike, the minimum value required for the shear modulus was obtained.

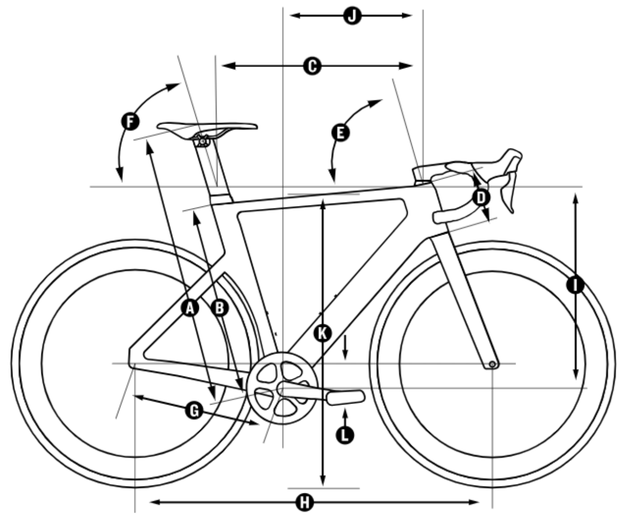

Figure 1: Canyon Bike Dimensions (5)

- The Canyon Aeroad CF SLX 8 Di2 comes in a range of sizes. However, as the formula includes a ratio of the length of the frame section to its cross-sectional area, and the value of the cross-sectional area increases proportionally to the length of the frame in the different sizes, it is irrelevant which size to use. In this case, the large size was used. The length of the top tube (c) was given as 0.57 m.
- The shear force (*F*) exerted on the frame when cornering was then calculated:
- $F = ma$
- Centripetal acceleration $= a = \frac{v^2}{r}$
- Therefore $F = \frac{mv^2}{r}$
    - *m* was set as 120 kg, the maximum weight of a rider given by the data for the Canyon Racing bike web page.
    - *r* was set as 6 m as this is the minimum cornering radius that racing cyclists would achieve at speed
    - v^2 was set as 9 m/s or 20 mph as this is the max cornering speed for the minimum cornering radius of 6 m.
- Using this: $F_{max} = \frac{120*9^2}{6} = 1620N$
- Next, the cross-sectional area (*A*) was calculated for the frame. This was not given in the technical data but by extrapolating from the images, the rectangular bar was 0.04 m wide and 0.03 m in height. Therefore, $A = 0.04 * 0.03 = 0.0012\ m^2$
- The final part was to obtain the value for the maximum deflection possible by the material.
- $\delta = \frac{PL^3}{48EI}$
- Where $I = \frac{bh^3}{12}$

- P = load (1620 N)
- $L^3 = 0.57^3\ m^3$
- E = Young's Modulus. This was set at 60 GPa, the value of E for CFRP as this is the material currently used with the lowest value of E. This means that E > 60 GPa will have to be a requirement for the material.
- b = 0.04 m
- h = 0.03 m

- Therefore: $\delta = \frac{1620*(0.57)^3}{48*(60*10^9)*\frac{0.04*0.03^3}{12}}$
- $\delta = \Delta x = 0.0012\ m$
- Lastly, these values were substituted into the shear modulus formula.

$$n = \frac{1.67 * 1620 * 0.57}{0.04 * 0.03 * 0.5 * 0.5 * 0.0012}$$

- Therefore, the material must have $n > 4.28\ GPa$
- This calculation included a safety factor of 1.67 as suggested in the background research, along with two multipliers of 0.5 at the bottom. One was for a safety factor on the deflection and the other was because the calculation for the deflection was for the centre of the bar, so by doubling it you get the deflection at the end.

- Young's Modulus: > 60 GPa
  - This value must be set to at least 60 GPa as this is the minimum value assumed by the deflection calculation for the shear modulus.
- Tensile Strength: > 181 MPa
  - $\sigma = \frac{F}{A}$
  - The max force occurs if the rider goes over a curb or other small drop.
  - To calculate the force:
    - $S = displacement = 0.3\ m$
    - $U = initial\ velocity = 0\ m/s$
    - $V = final\ velocity = ?$
    - $A = acceleration = 9.81\ m/s^2$
    - $T = time = ?$
    - $V^2 = U^2 - 2AS$
    - $V^2 = 0 - 2 * 9.81 * 0.3$
    - $V = 2.426\ m/s$
    - $F = \frac{m(v-u)}{t}$ = rate of change of momentum during collision with ground
      - $m = 120 + 7 = 127\ Kg$ = max rider weight + bike weight
      - $t = 0.002\ s$ = impact time
      - $F = \frac{120(2.426-0)}{0.002}$ = 145560 N
  - A = cross sectional area of frame tube
    - By extrapolating dimensions of the square tubing from the Canyon Bike image
    - $A = (0.1 * 0.04) - (0.1 - 0.006) * (0.04 - 0.006) = 8.04 * 10^{-4}\ m^2$
  - $\sigma = \frac{145560}{8.04*10^{-4}} = 181\ MPa$
- Fatigue Strength:
  - The frame will go through many cycles of high load each time to rider uses the bike. Therefore, it needs to be able to withstand repetitive high loads without deforming or losing strength characteristics.

- Cost: < 40 GBP/kg
    - Although the client is looking to market to the top end athletes with many sponsors, they do need to be able to produce an economically viable product and so by limiting the price to 40 GBP/kg, it filtered out the unsuitable materials such as gold and silver.

Initial Filtering

To initially filter out materials that would be overall unsuitable for the product, the previously derived boundary conditions were set, and the resulting Ashby plot is shown below.

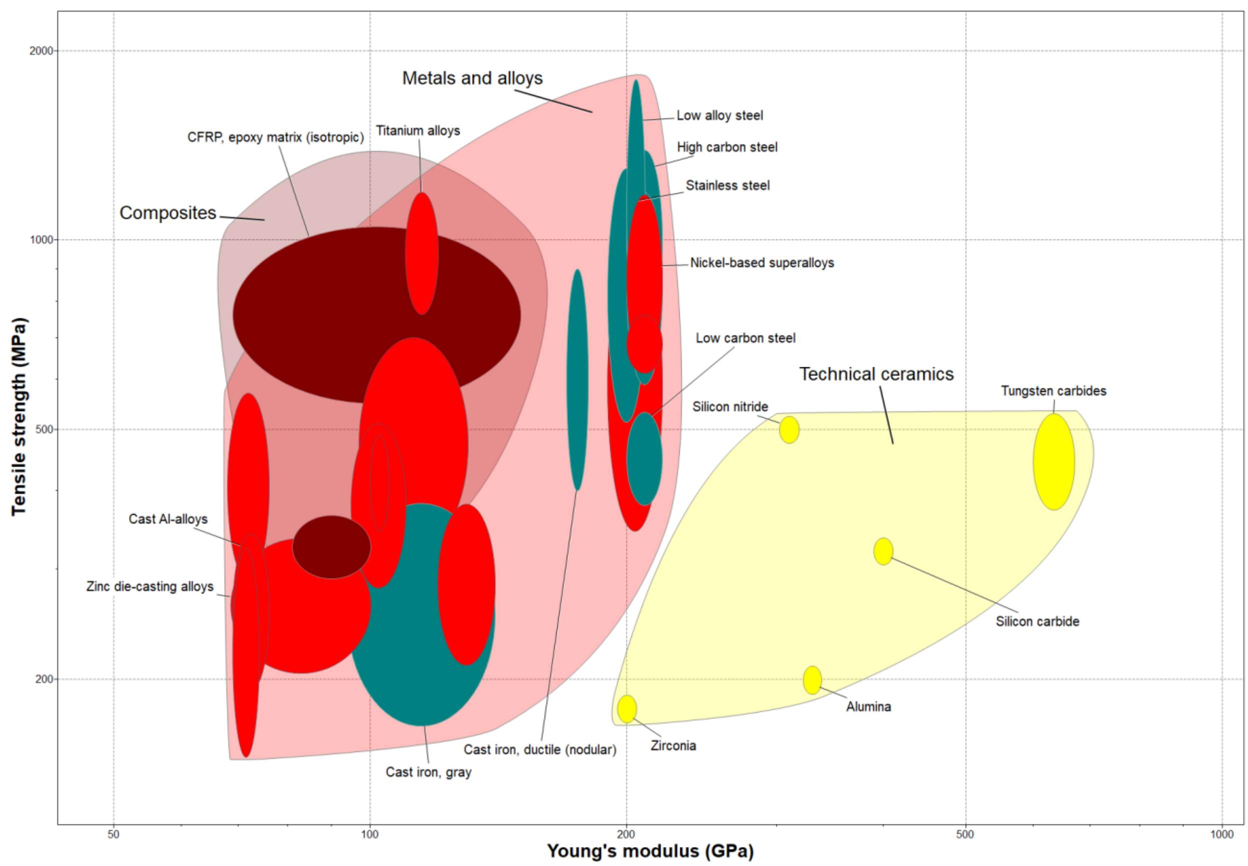

Figure 2: First Ashby Plot – Tensile Strength vs Young's Modulus

This filtered the materials down to 26/100 and included the currently used materials from the background research such as CFRP, aluminium, steel and titanium which suggested that the refinements were suitable. It also included materials with higher strengths and shear modulus' such as the technical ceramics. These may be too brittle and would also be extremely difficult to manufacture into the bike frame.

Deriving the Performance Index

Now that the remaining materials were all guaranteed to have the suitable mechanical properties to function in the bike frame, it was important to refine these further by ranking them with a performance index.

From the developed brief, the selected material should have the highest strength to weight ratio as its key feature. The derivation for the performance index equation relating these characteristics is as follows:

Using Figure 8 in Appendix A:

Bending stress **=** $\boldsymbol{\sigma = \frac{MC}{I}}$

Where ***M*** = bending Moment $= \boldsymbol{\frac{FL^2}{8}}$ (where F = Force applied)

C = distance from the neutral axis to the outermost fibre $= \boldsymbol{\frac{L}{2}}$ (where L is the length).

I = moment of inertia $= \boldsymbol{\frac{a^4}{12}}$ (where a = cross sectional area)

Therefore $\boldsymbol{a = (L1 - l)^2}$ for square tubing where ***L1*** is the outer length and ***l*** is the thickness of the tubing.

Substituting in these values to the bending stress equation:

$$\boldsymbol{\sigma = \frac{MC}{I} = \frac{\frac{FL^2}{8} * \frac{L}{2}}{\frac{(L1 - l)^4}{12}}}$$

Inserting mass:

$$\boldsymbol{\rho = m/v}$$

$\boldsymbol{v = L(L1 - l)^2}$ (where **L** = length of beam)

$\boldsymbol{\rho = \frac{m}{L(L1-l)^2}}$ Rearranging for $\boldsymbol{(L1 - l)^2}$: $\boldsymbol{(L1 - l)^2 = \frac{m}{\rho L1}}$

Substituting into **σ** equation:

$$\boldsymbol{\sigma = \frac{\frac{FL^2}{8} * \frac{L}{2}}{\frac{\left(\frac{m}{\rho L1}\right)^2}{12}} = \frac{3FL^5\rho^2}{4m^2}}$$

Rearranging for ***m***:

$$\boldsymbol{m = \left(\frac{3FL^5\rho^2}{4\sigma}\right)^{\frac{1}{2}} = \left(\frac{3FL^5}{4}\right)^{\frac{1}{2}} * \frac{\rho}{(\sigma)^{\frac{1}{2}}}}$$

This is the full performance index equation, with the geometric variables on the left and mechanical properties of the material on the right. Therefore, the performance index is as shown below:

$$\boldsymbol{P = \frac{\rho}{\sigma^{\frac{1}{2}}}}$$

However, we want to minimise density and maximise strength. Therefore, by inverting the equation, our performance index is:

$$\boldsymbol{P = \frac{\sigma^{\frac{1}{2}}}{\rho}}$$

Taking logs of both sides:

$$\boldsymbol{\log(P) = \frac{1}{2}\log(\sigma) - \log(\rho)} \qquad \boldsymbol{\log(\sigma) = 2\log(P) + 2\log(\rho)}$$

This equation is now in the (y = mx + c) formula and was used to form selection lines in an Ashby Plot

Final Filtering

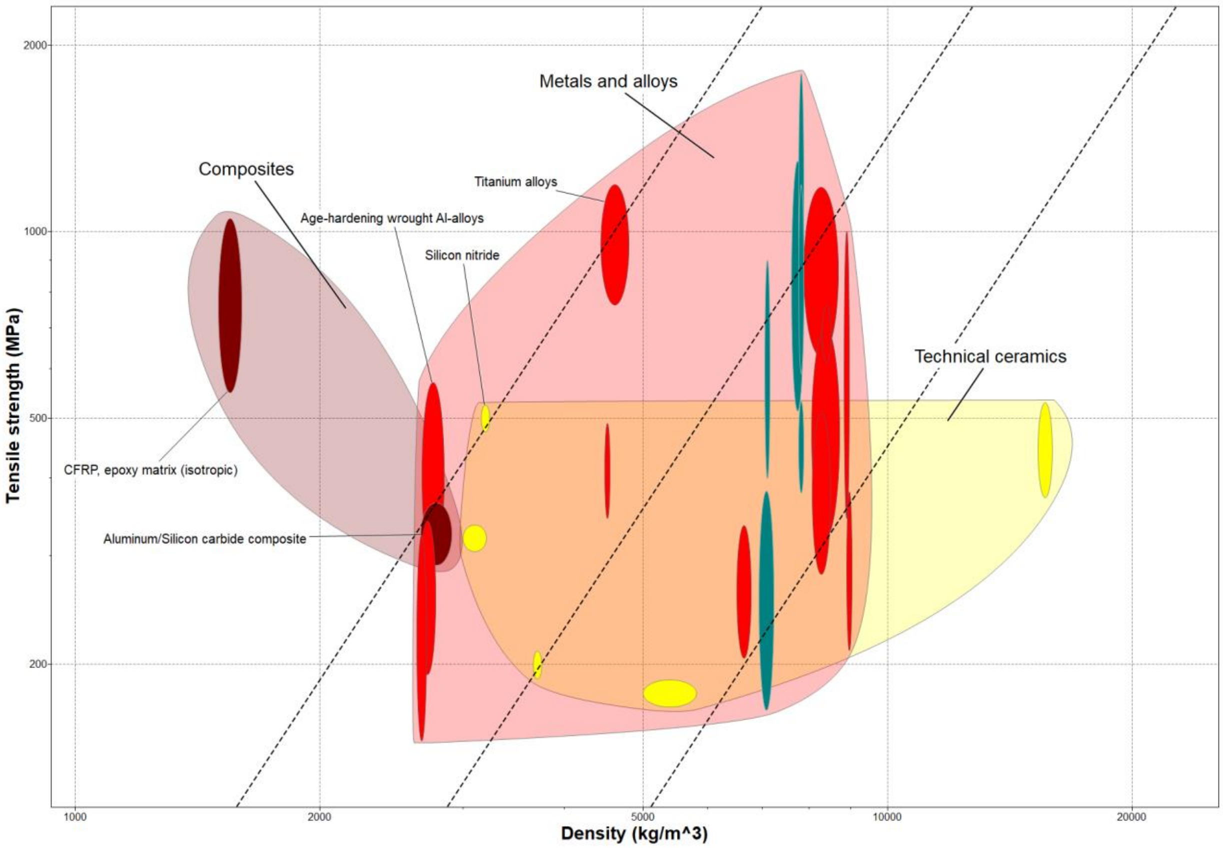

Figure 3: Second Ashby Plot – Tensile Strength vs Density

After plotting the Tensile Strength against the Density and using performance index lines of gradient 2 from the derive equation, the materials can be compared accurately. The line was adjusted to select the top 5 materials.

Table 2: Filtered Materials and Their Performance Index Ratings

Material	Tensile Strength (MPa)	Density (Kg/m^3)	Performance Index	Cost (GBP/Kg)
CFRP	550 - 1050	1500 -1600	0.0178	28.6 – 31.8
Age Hardening Wrought Al Alloys	288 - 571	2670 - 2840	0.00731	2.67 – 2.82
Silicon Nitride	476 - 525	3160 - 3230	0.007	26.3 – 40.3
Titanium Alloys	763 - 1990	4430 - 4790	0.0067	19.1 – 20.9
Aluminium/Silicon Carbide Composite	290 - 364	2660 - 2900	0.00649	3.89 – 5.18

From Table 2 above, CFRP was the highest rated material choice. This was because of its very low density relative to how strong it is. It can also be easily formed into moulds making it a perfect material for a bike frame.

Age hardening wrought Al alloys and Titanium alloys would also be very suitable for a bike frame due to their ability to be moulded and welded. Silicon Nitride, however, is harder to manufacture as it must be formed through processes such as sintering and powder injection moulding. It is also very brittle which could pose issues within the bike frame if too much of a force was applied. Therefore, it was discarded from the shortlist.

Aluminium/Silicon Carbide composite has the optimum properties in terms of strength, toughness, ductility and low density. However, it too is difficult to manufacture. There is a high startup cost for the machining and the silicon carbide can cause issues when welding (6) as it can break down and react to form aluminium carbide which is extremely weak – it can dissolve in water. To combat this, a highly skilled welder is required.

Selection Via Semantic Differential Scales

The client was looking to design a product that not only had optimal performance characteristics but looks and feels high quality. These are what are known as materials experience and can be ranked using semantic differential scales.

Firstly, the client helped to define the bipolar criteria for the scales:

- Cheap vs Expensive (What level of quality does the visual appearance of the material give?)
- Rough vs Smooth (How does the material feel? This relates to the aerodynamics as smoother materials have a lower drag coefficient)
- Warm vs Cold (In the context of a bike frame, a 'colder' material would be considered higher quality by the user)
- Basic vs Innovative (Does the material present itself as a development?)

A survey was then conducted to obtain data for this scale using the filtered materials. The materials were scored from 0-10 on the four criteria. This was then represented by the box plots shown in the appendix. The overall score of the materials from the median values of their user experience perspective rating is shown in Table 3 below.

Table 3: Further Filtered Materials and Their Material Experience Ratings

Material	Cheap vs Expensive	Rough vs Smooth	Warm vs Cold	Basic vs Innovative	Total Score
CFRP	6.45	8.15	3.05	8.8	26.45
Age Hardening Wrought Al Alloys	6.35	7.45	6.75	4.2	24.75
Titanium Alloys	7.45	7.45	7.9	6.4	29.2
Aluminium/Silicon Carbide Composite	4.5	3.1	3.95	8.1	19.65

From Table 3, you can see that the highest scoring materials were Titanium Alloys. This was due to their high-quality appearance, feel and perception. The lowest scoring was Aluminium/Silicon Carbide Composite due to its rougher surface finish resulting in it having a less shiny appearance and unpleasant feel.

Conclusion

After the performance rankings and then semantic rankings, the two highest scoring materials were CFRP and Titanium Alloys. CFRP had a higher performance index of 0.0178 but was more expensive with a cost of 28.6 – 31.8 GBP/kg. Titanium Alloys also had a strong performance index of 0.0067 but this was still 265 % lower than that of CFRP. However, it scored higher on the semantic differential scale with a value 9.5 % higher and is 66 % cheaper. Interestingly, people perceived Titanium Alloys to be higher quality than CFRP perhaps due to its favoured anodised coating giving it the unnatural, shiny and coloured appearance. The view on CFRP may have been hindered by the increase in use of 'fake' Carbon Fibre wraps that can end up subtracting from the appearance if of a product. It is worth noting that the standard deviation in the data for Cheap Vs Expensive for Titanium alloys was larger than that of Carbon Fibre, suggesting that people have more mixed opinions for Titanium Alloys.

Age Hardening Wrought Al Alloys also scored highly in both performance and user experience. The material is currently used as cladding for materials and more widely in aerospace applications. These areas – especially aerospace - have similar requirements for a material for a bike frame as the key characteristic is the strength to weight ratio. For which, Age Hardening Wrought Al alloys had a value of 0.00731 for the performance index. This was in fact higher than that of Titanium Alloys. However, its rating for the SDS of Basic Vs Innovative was poor. Due to its widescale use, people do not consider it to be a cutting-edge material like they might do for CFRP. This may limit sales for the client and therefore it should not be used.

Similarly, Aluminium/Silicon Carbide Composite ranked the lowest throughout the Semantic Differential Scales. Its relatively rough appearance gives it the perception of being a cheap material. Which – compared to Titanium Alloys or CFRP – it is, costing 3.89 – 5.18 GBP/Kg. This would be beneficial to the client, however, as it would greatly reduce manufacturing costs. It did score very highly on the Basic Vs Innovative SDS, perhaps due to its longer name and the fact that it is a composite. This would potentially boost sales for the client as the customers are often drawn into the products that are considered to be cutting-edge.

Overall, MerchantPro believed that the client should use either Carbon Fibre Reinforced Polymer or a Titanium Alloy for their product. Both materials have the mechanical properties required to withstand the load cases exerted on the product. They ranked the highest in terms of the performance index of the highest tensile strength to weight ratio and scored highest within the Semantic Differential Scales. The client should decide between the two based on which factors they believe to be more important: cost or performance. If the answer is cost, they should use Titanium Alloys and if the answer is performance, they should use CFRP.

Appendices

Appendix A: Semantic Differential Scales

Table 4: Filtered Materials and Their Corresponding Number in the Semantic Differential Scales

1	2	3	4
CFRP	Age Hardening Wrought Al Alloys	Titanium Alloys	Aluminium/Silicon Carbide Composite

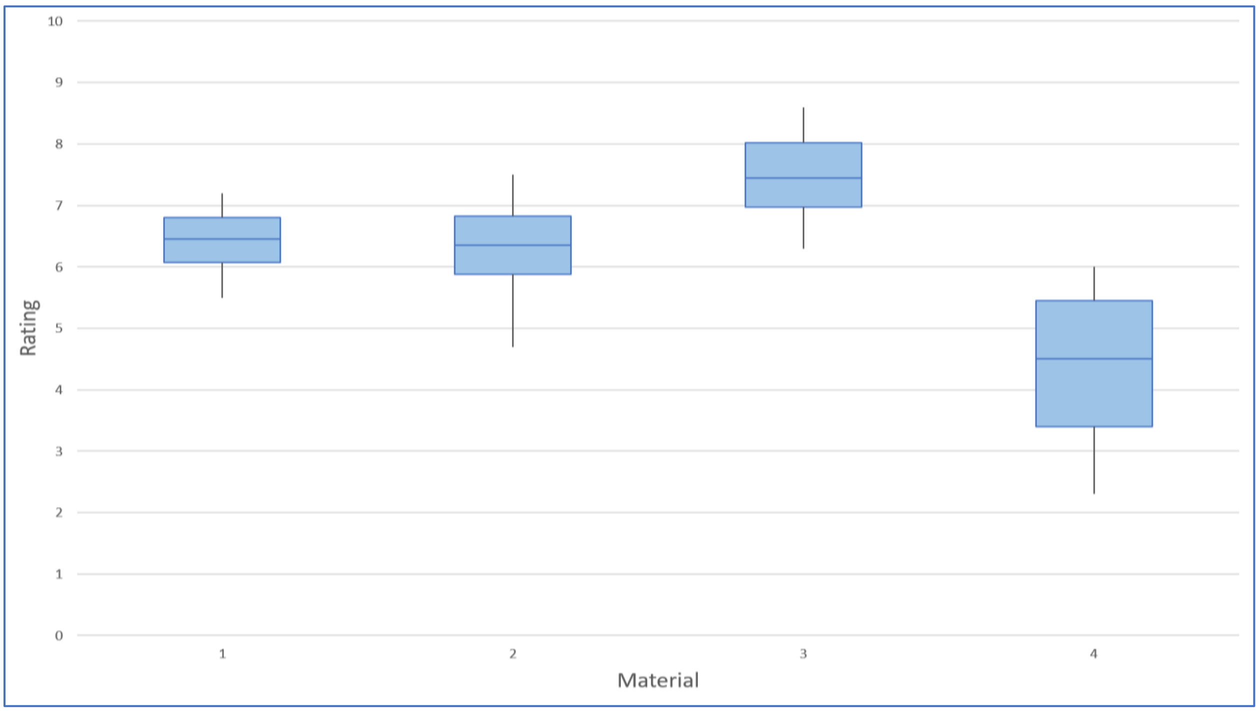

Figure 4: Cheap Vs Expensive SDS

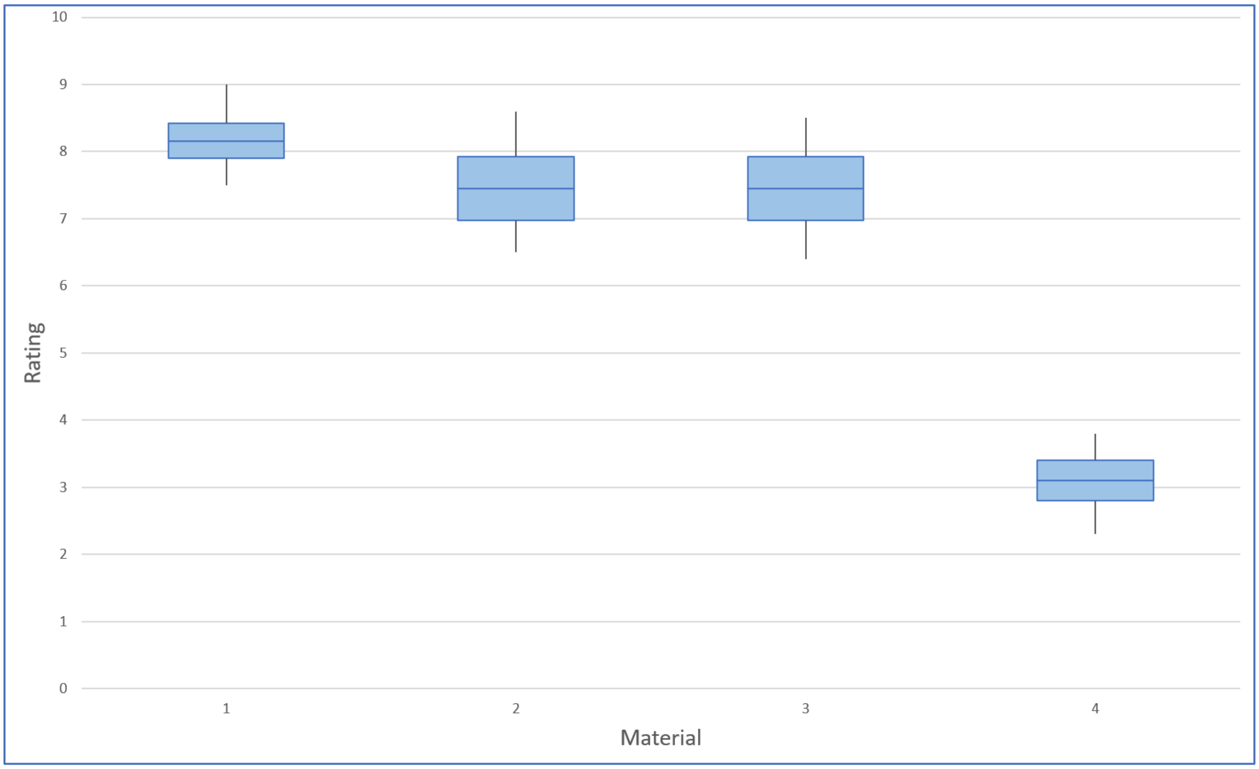

Figure 5: Rough Vs Smooth SDS

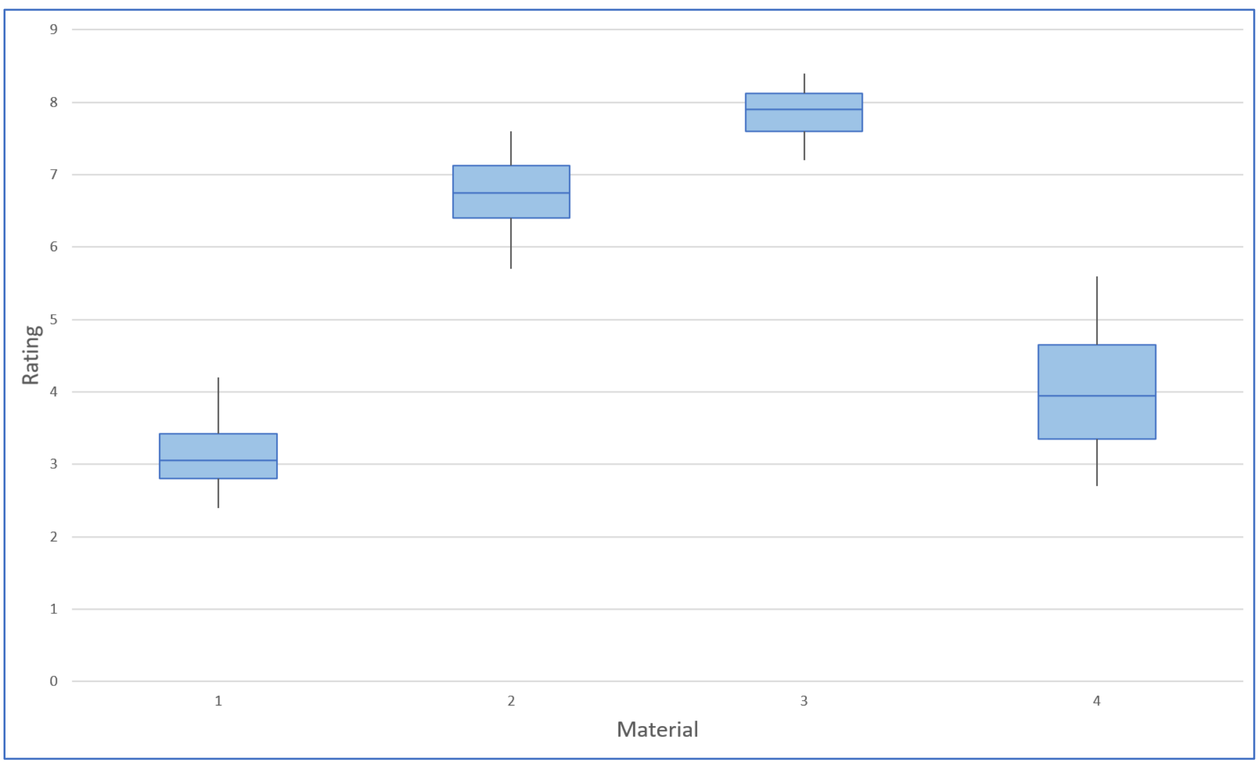

Figure 6: Warm Vs Cold SDS

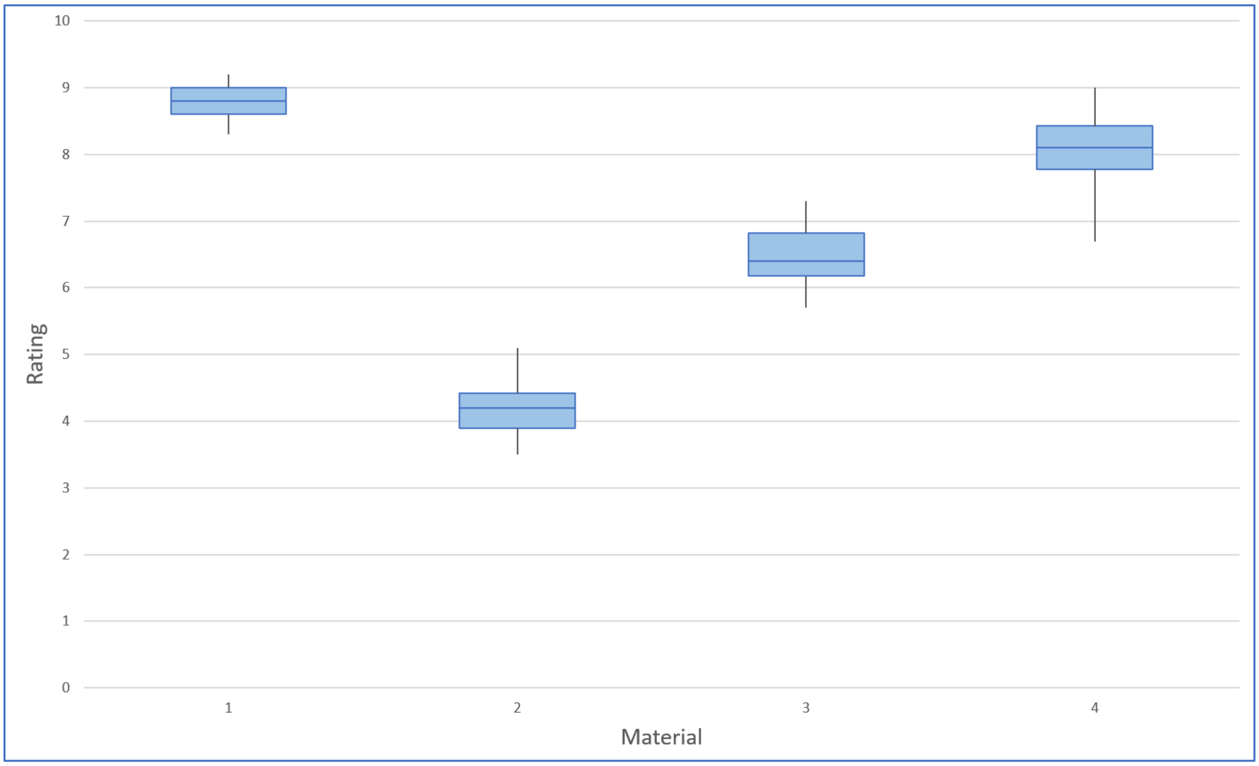

Figure 7: Basic Vs Innovative SDS

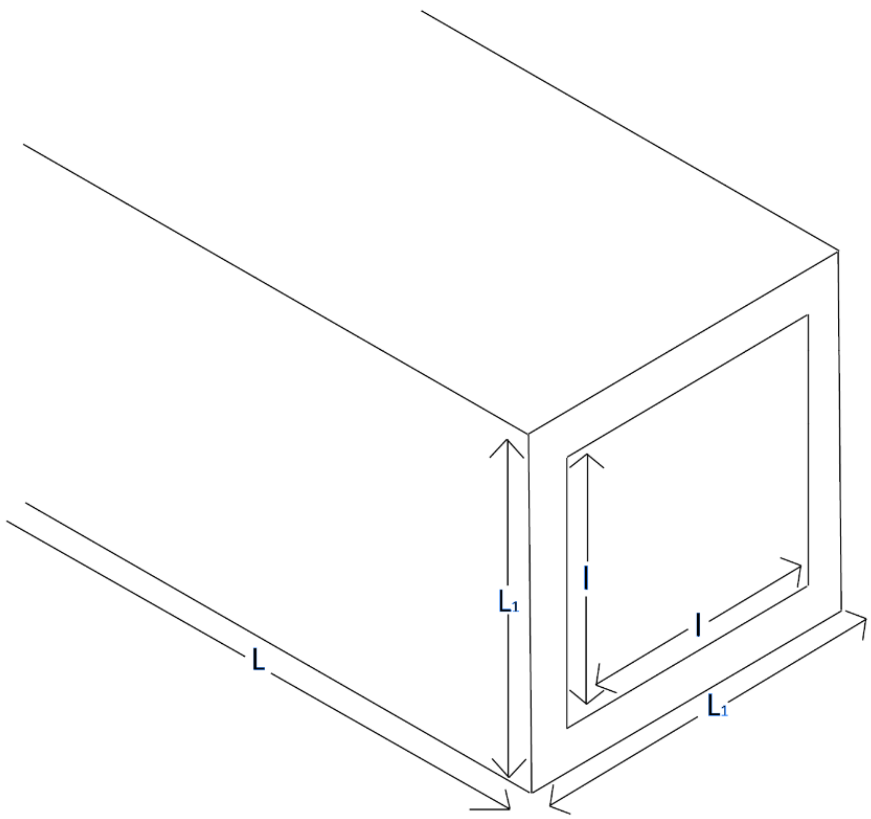

Figure 8: Square Tubing Dimension Label

Appendix B: CES Tasks

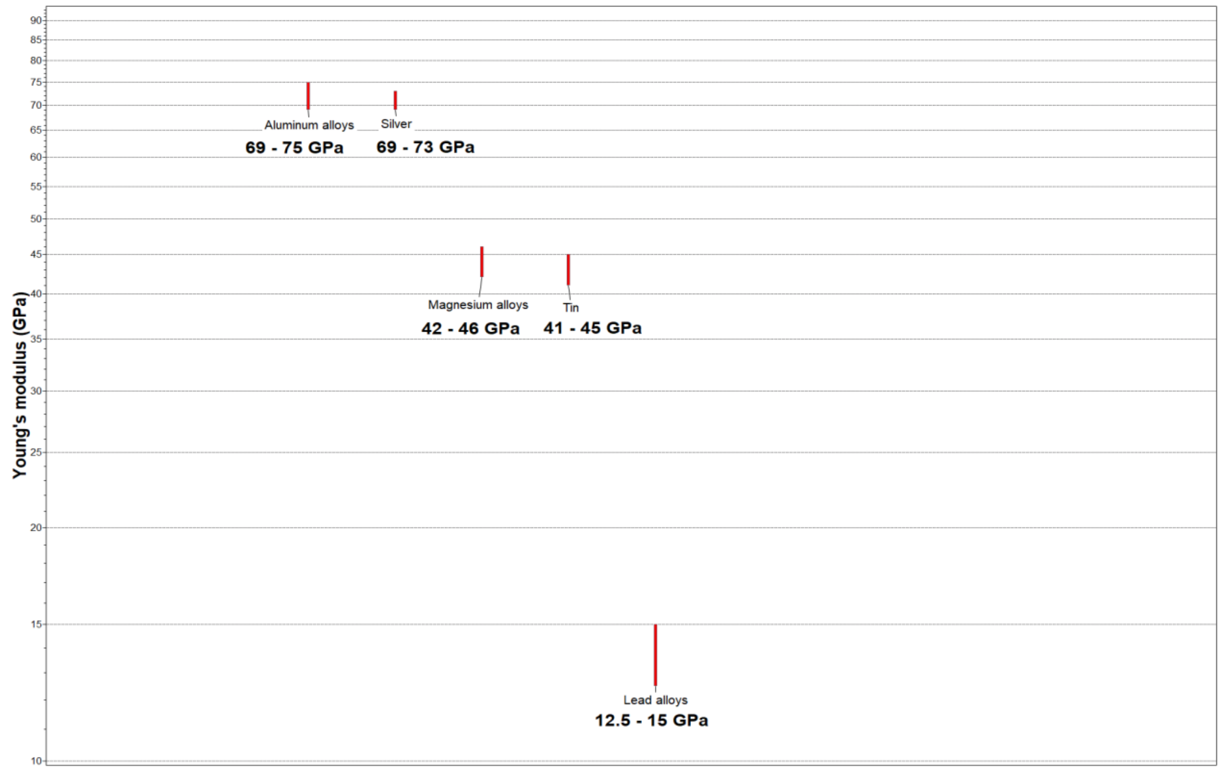

Figure 9: CES Task 1

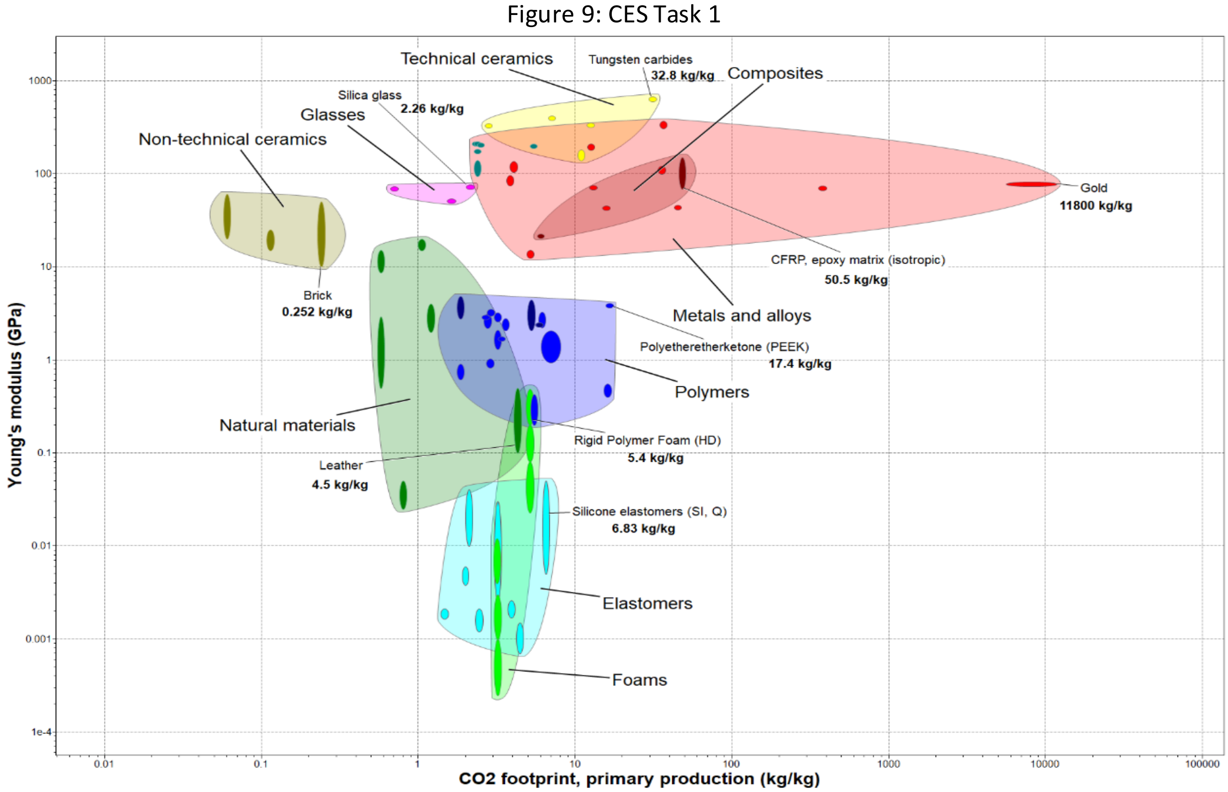

Figure 10: CES Task 2

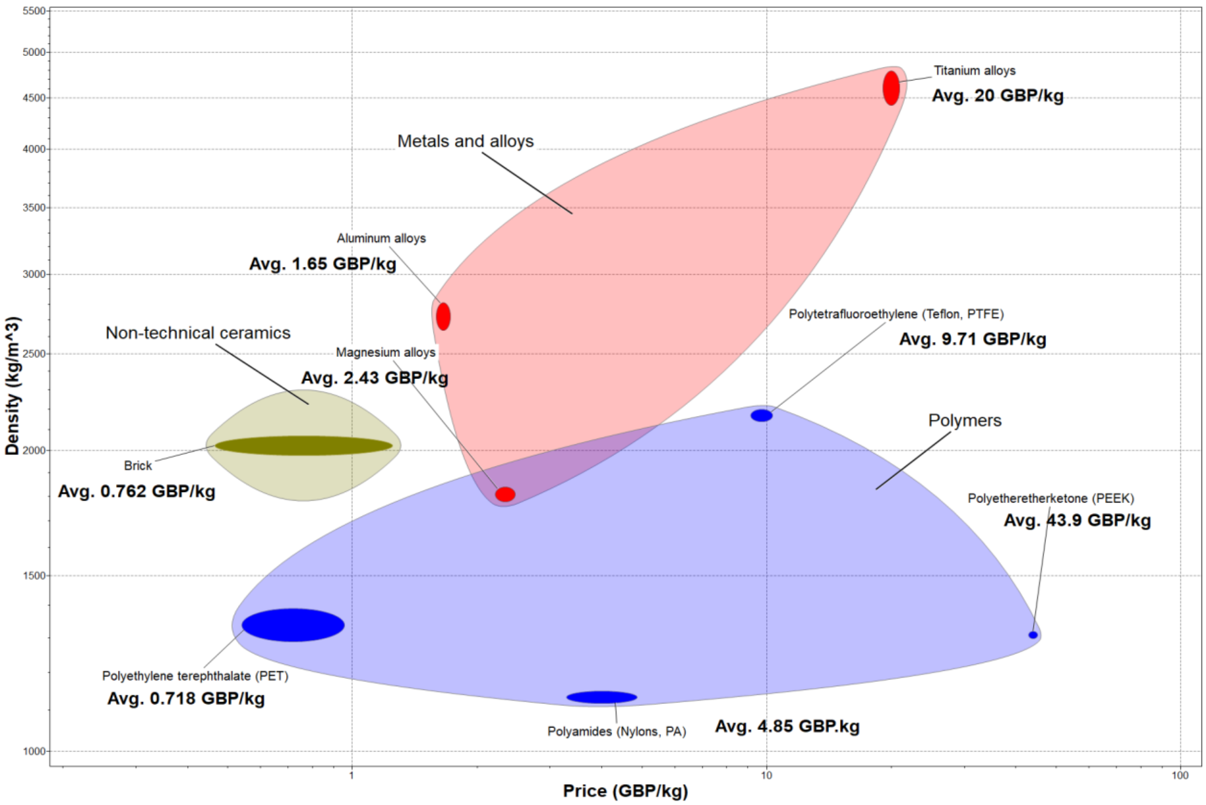

Figure 11: CES Task 3

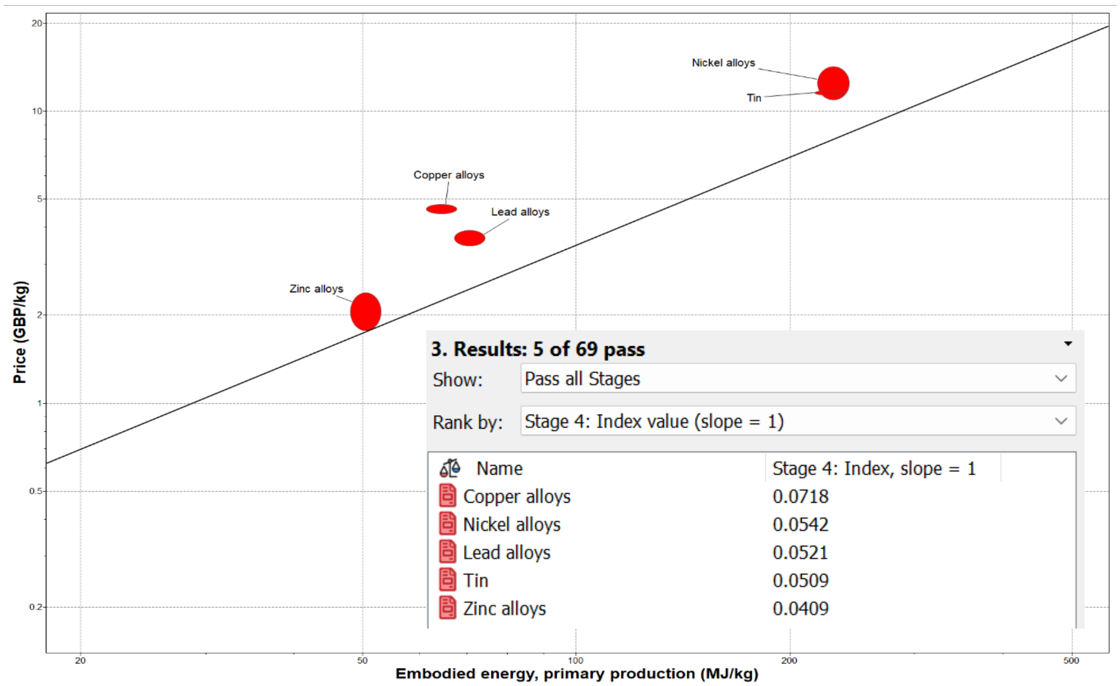

Figure 12: CES Task 4

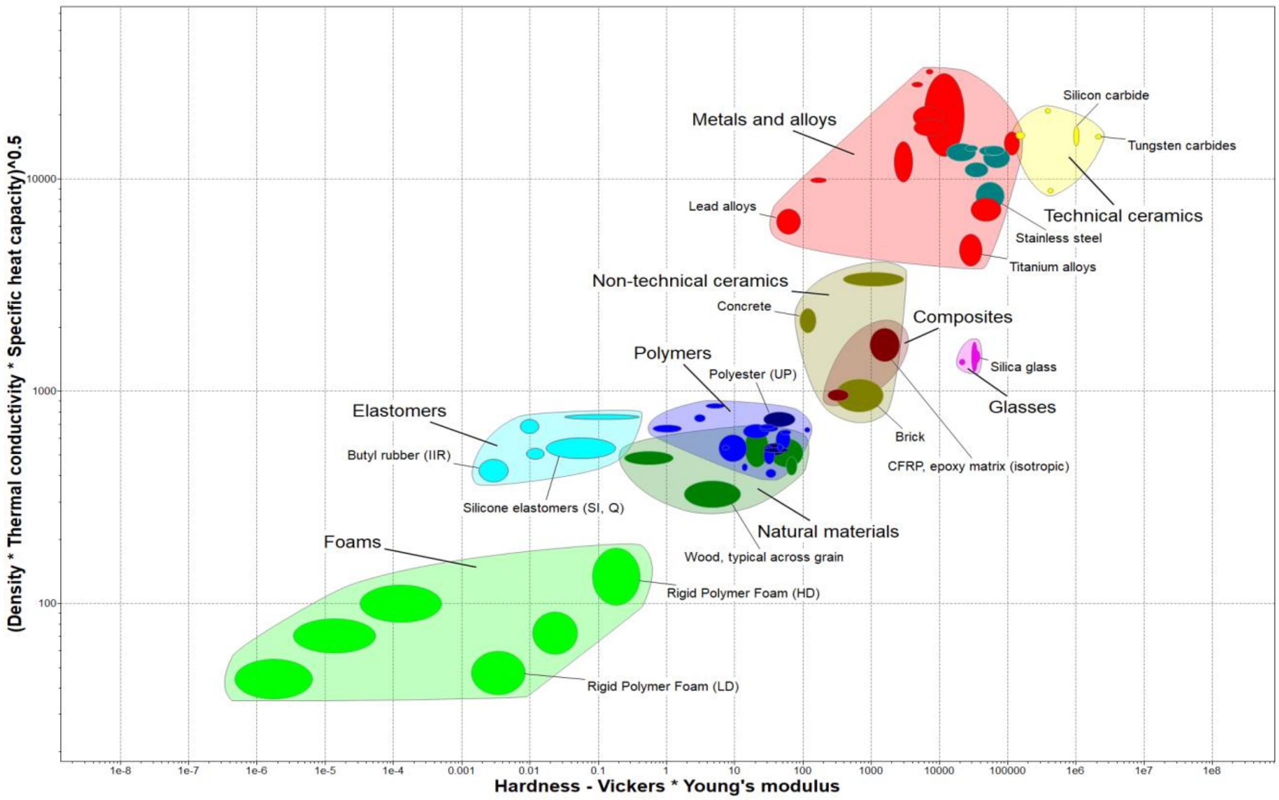

Figure 13: CES Task 5

References

1.
Bike frame materials explained [Internet]. BikeExchange. [cited 2023 Nov 29].
Available from: https://www.bikeexchange.com/blog/bike-frame-materials-explained#:~:text=Bike%20Frame%20Materials%20Explained%201%20Carbon%20Fiber%20Carbon

2.
design - Standard forces on a bike frame [Internet]. Bicycles Stack Exchange. [cited 2023 Nov 29].
Available from: https://bicycles.stackexchange.com/questions/74587/standard-forces-on-a-bike-frame

3.
Satrijo D, Kurdi O, Wijaya S. Static Linear Stress Analysis of Road Bike Frame Design Using Finite Element Method [Internet]. [cited 2023 Nov 29].
Available from: https://www.atlantis-press.com/article/125969740.pdf

4.
Strength of Materials [Internet]. www.slideshare.net. 2017 [cited 2023 Nov 29].
Available from: https://www.slideshare.net/HurumaPeter/strength-of-materials-76451256

5.
Aeroad CF SLX 8 Di2 [Internet]. www.canyon.com. [cited 2023 Nov 29].
Available from: https://www.canyon.com/en-gb/road-bikes/aero-bikes/aeroad/cf-slx/aeroad-cf-slx-8-di2/3955.html?dwvar_3955_pv_rahmenfarbe=R081_P08&dwvar_3955_pv_rahmengroesse=L#productDetailModalTriggerGridContainer

6.
Strong Frames: The Final Chapter [Internet]. Strong Frames. [cited 2023 Nov 29].
Available from: https://www.strongframes.com/more/metatllurgy-seven-part-series/the-final-chapter/