Materialise

Bike Frame – Burns Corp

THE CONSULTANCY

Freddie Nicholson - [redacted] - ICL

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Technical Summary

The consultancy has been recruited by Burns Corp to research the materials for their new Bike Frame that will be launched later this year. Burns Corp are the friendly neighbourhood corporate overlords. Their products aspire to be 'excellent', industrial and make a killing profit. The bike that the bike frame will be used in is expected to be a mass market product and therefore it is critical that the consultancy finds the best solution to keep customer satisfaction high whilst keeping costs low.

The chosen material at the end of the material selection sprint performed by the consultancy was **Aluminium**. This was due to its excellent mechanical properties, cost effectiveness and experiential properties. This technical report will walk through the steps the consultancy went through to find the ideal material for the Burns Corp.

Introduction

The consultancy is a forward-thinking design engineering firm based in the Dyson School of Design Engineering, South Kensington. This report narrows down the material options set out by the consultancy for Burns Corp's new bike frame. Burns Corp describes themselves as designing towards excellency, an industrial company and seeking to find the most cost-effective solution. The consultancy will work towards these metrics within the project to find the most optimal material that matches all three criteria within the bike frame.

The consultancy analysed the technical requirements for the bike frame whilst developing figures of merit for different designs. They also worked with computer-based packages such as CES EduPack to help narrow down material selection and provide figures throughout the technical report. Semantic differential scales were also used to gather a systematic measure of how the materials would be perceived by Burns Corp's customers.

Brief

Burns Corp has stated to the consultancy that they need a selection of materials for their new bike frame with a rapid turnaround time. As Burns Corp is an international company, our bike frame will need to be suited towards many different environments. In this case, it makes sense to focus on a road bike style frame as this will cover the majority of Burns Corp's client base. They are also keen for the product to meet all safety regulations due to the negative press around their most recent products being found to have traces of radioactive materials.

When designing the product, the consultancy narrowed down the following selection of properties that would need to be adhered to:

General Properties

- The bike will need to be durable (corrosion and reaction resistance) as it will be operating in many countries in varying environmental conditions.
- The bike frame will need to have a killing profit and therefore the Price of the material (GBP/kg) is a key metric.

Mechanical Properties

- The bike frame will need to be stiff to provide 'excellent' ride feel and quality (1) for the demanding customer. This means the Young's Modulus (GPa) of the material will need to be high.
- The bike frame will also need to have a high level of yield strength (MPa).
- Bike frame should be ductile allowing it to deform more without reaching the failure point.

- The weight (Kg) of the frame is also an important consideration, lighter materials tend to be more expensive but make the bike easier to ride.
- The bike will also be up against rainwater which is a fresh (no saltwater). Therefore, the bike will need to be corrosion resistant to an extent at which it can withstand moderate amounts of freshwater exposure.
- The environment our target road bike will be under will generally have a temperature range within -20 °C and 40 °C in a standard commuting environment and the material will need to operate within these temperatures.

Sensorial Properties

- The bike will need to look ‘excellent’ to the eye. A sleek material with a premium finish will give this aesthetic.
- The frame should not be audible (creaking and squeaking) when in use and this can be achieved by following the mechanical properties set out above.

Background Research

Bike Frame Initial Research

Bike frames often follow the standard ‘diamond’ frame for their structure. It consists of two triangles with the larger one consisting of a series of tubes and the smaller one being made of up two rear ‘forks’. This is the style of frame that the consultancy will be basing the bike frame material choices on.

During usage of the bike there are four primary locations from the rider that experience a force, the pedals, rear, seat and handlebars. This is shown in Figure 1. The URES scale in this figure indicates the degree of deflection experienced by the bike frame when the forces are applied by the rider. The simulation shows that the corners of the frame experience the most load from the cyclist.

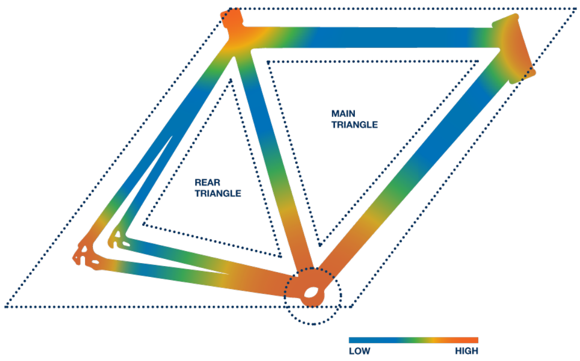

Figure 1 – Static Analysis of a Bike Frame (2)

A technique that is used to improve the mechanical properties of the bike frame to suit this deflection pattern caused by the rider is Frame Butting (2). This means putting more material wherever the bike experiences more stress. It is still made from the same material. This can be more cost effective which is ideal for our client.

Figure 2 – Four different types of Frame Butting (2).

Current Bike Frame Materials

The consultancy set out to investigate materials currently used within the field of bike frame manufacture.

Table 1 – Materials (3) currently used within bike frames; data sourced from CES EduPack.

	Price (GBP/kg)	Young's Modulus (GPa)	Yield Strength (MPa)	Durability water (fresh/salt)	CO^2 Footprint (kg/kg)	Density (kg / m^3)
Steel (medium carbon)	0.524 – 0.552	200 – 200	376 - 929	Acceptable / Limited Use	2.26 – 2.49	7.8e3
Aluminium	1.59 – 1.72	69 - 75	109 - 439	Excellent / Acceptable	12.4 – 13.7	2.6e3-2.8e3
Titanium	19.1 – 20.9	100 - 120	470 – 1.09e3	Excellent / Excellent	33.9 – 37.4	4.4e3 – 4.8e3
Carbon Fibre	28.6 – 31.8	69 - 150	550 – 1.05e3	Excellent / Excellent	45.8 – 50.5	1.5e3 – 1.6e3
Magnesium	2.22 – 2.46	42 - 46	109 - 216	Excellent / Excellent	42.8 – 47.1	1.78e3 – 1.84e3
Bamboo	1.01 – 1.51	15.1 – 19.9	35.8 – 44.1	Limited Use / Limited Use	1 – 1.11	602 - 797

The most common material used is a medium carbon steel commonly referred to as Chromoly steel. This is due to its affordable price and reasonable mechanical properties that allow it to be used within commuter bikes. Alloys are generally used as they are more performant than their pure counterparts. More performant examples include Carbon Fibre (CFRP) and Titanium which have significantly better mechanical properties allowing for a smoother and more stable ride but are almost 40x the price of Chromoly steel. There are also more interesting examples such as Bamboo bikes, but these may not be practical for the world dominating bike frame that Burns Corp desires. The CO^2 footprint of these more expensive materials is generally higher however the client has specified this is not a priority.

Discussion

Quantitative Constraints

Cost

To consider the pricing of the bike for Burns Corp we considered their key values of putting profit at the centre of their operations. Looking at the currently used materials within bike frames above in Table 1. We can see that price ranges from 0.524 (Medium Carbon Steel) – 31.8 GBP/kg (CFRP). Therefore, a reasonable absolute maximum price for the material should be 31.8 GBP/Kg.

Stiffness (Young's Modulus)

To find the minimum stiffness of the bike we use the following equation (derivation below in performance index)

$$\delta = \frac{WL^3}{12E\pi r^4}$$

We rearrange to make E, the Young's modulus, the subject.

$$E = \frac{WL^3}{12\pi\delta r^4}$$

We then need to estimate some of the parameters for the maximum load the bike should undergo. Generally, a safety factor of 2 should be sufficient. Assuming a user will generally never be over 350kg for a standard road bike we can determine the maximum weight to be 700kg. The deflection should never be greater than 1mm and the radius of an average bike frame is approximately 4cm. We can assume the frame is about 1m in total length. Substituting these values into the equations returns the following result for the minimum value for the Young's modulus:

$$E = \frac{WL^3}{12\delta r^4} = \frac{700 \times 1^3}{12\pi \times (1.0 \times 10{-}3) \times (4.0 \times 10^{-2})^4} = 7.25 \times 10^9\, Pa$$

Density

Using the data above around the cylindrical rod and assuming a road bike frame should have a maximum weight of twice the weight of an average bike frame (1.5kg * 2 = 3kg) (4). We can calculate the minimum density.

$$V = \pi r^2 h$$
$$Let\, h = 1\,m, r = 4 \times 10^{-2}\,m$$
$$V = \pi(4 \times 10^{-2})^2 \times 1 = 5.03 \times 10^{-3}$$
$$\rho = \frac{m}{v} \therefore \rho \geq \frac{3}{5.03 \times 10^{-3}}, \rho \geq 596\, kg\, m^{-3}$$

Initial Ashby Plot

To set out a set of candidate materials for the bike frame. CES EduPack was used to generate an Ashby plot using the below performance index parameters. The result was a log-log plot shown below.

Several material groups were mapped including Foams, Polymers, Metals and Alloys, Natural Materials, and ceramics. To help narrow down the options, the consultancy set out to calculate the performance index and limits.

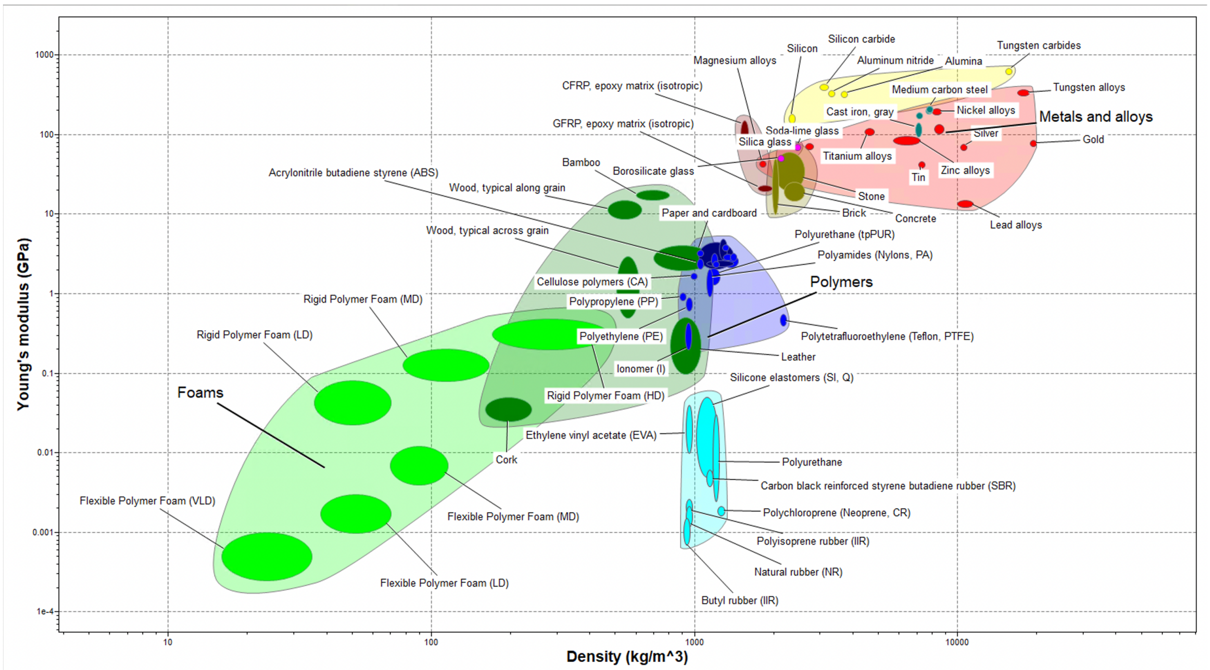

Figure 3: Ashby plot log-log of Young's modulus vs density.

Performance Index

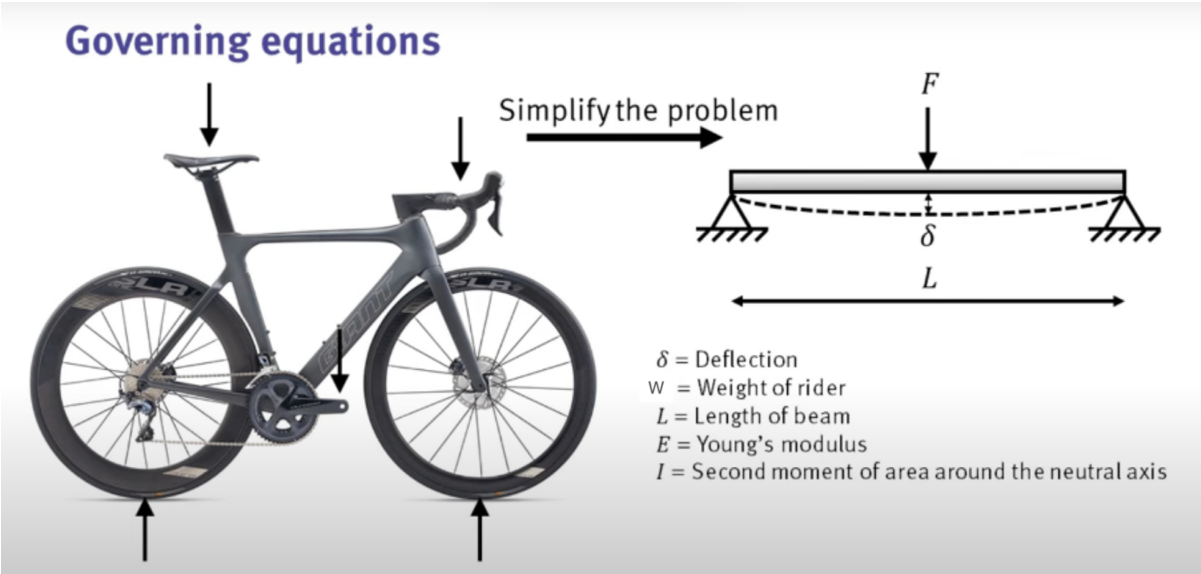

Figure 4: Simplification of bike forces into a cylindrical rod (5)

First, we find the mass of a cylindrical rod:

$$m = \pi r^2 L \rho$$

We then rearrange the first equation to find the radius.

$$r = \sqrt{\frac{m}{\pi L \rho}}$$

Next, retrieve deflection equation for beams bent about principal axis from Databook (6).

$$\delta = \frac{WL^3}{48EI}$$

Get the equation for the general moment of inertia of a circle.

$$I = \frac{\pi r^4}{4}$$

Substitute the general moment of inertia of circle equation into the deflection beam equation.

$$\delta = \frac{WL^3}{12E\pi r^4}$$

Substitute in the radius given by the rearrangement of the mass of the cylindrical rod into the deflection beam equation with general moment of inertia of a circle.

$$\delta = \frac{WL^3}{12E\pi(\frac{m}{\pi L\rho})^4}$$

$$\delta = \frac{WL^5\pi\rho^2}{12Em^2}$$

We can then split the equation into geometric parameters and material properties to work out the performance index. In this case we want a small mass and arrange to get the performance index to reflect this accordingly.

$$m = \left(\frac{WL^5\pi}{12\delta}\right)^{\frac{1}{2}} \frac{\rho}{\sqrt{E}}$$

$$P = \frac{E^{\frac{1}{2}}}{\rho}$$

As we are plotting an Ashby plot, we take logs of the exponential equation and rearrange into the form y=mx+c.

$$\log E = 2 \log \rho + 2 \log P$$

Final Ashby Plot

From this equation for the performance index, we plot a log-log Ashby plot with Young's modulus on the y axis and density on the x axis. The gradient of the performance index line will be 2 (due to y=mx+c). As calculated beforehand the minimum material stiffness required to avoid deflection under load would be 7.25 GPa which is marked on the graph as a straight line. The density minimum is also added as a straight line.

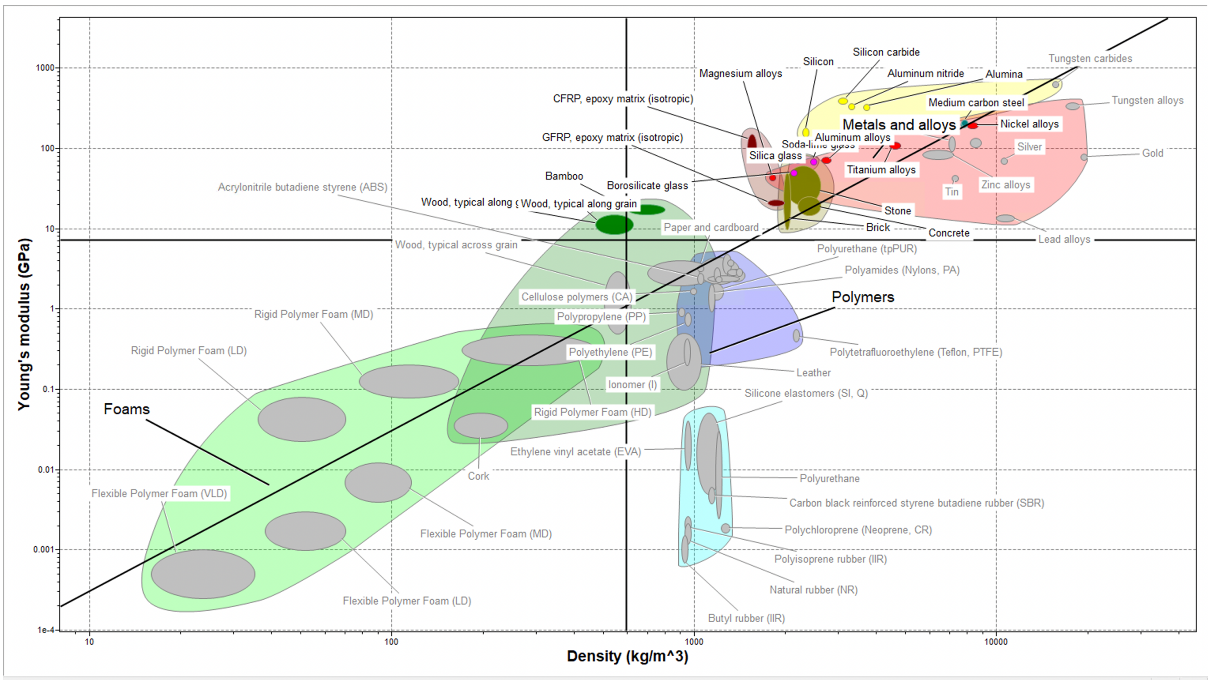

Figure 5: Ashby plot log-log of Young's modulus vs density with performance index, Young's modulus and density limits.

The process of narrowing down the materials using the limits defined above found the following materials to be shortlisted:

- Natural Materials
  - Wood
  - Bamboo
- Metals and Alloys
  - Titanium alloys
  - Medium carbon steel
  - Magnesium alloys
  - Aluminium alloys
- Composites
  - CFRP

The materials from non-technical ceramics and technical ceramics were not included as they are not suitable for the application as they have low toughness and very brittle. A bike would be under strain in several positions as shown by Figure 1 and therefore we must eliminate them from our decision making.

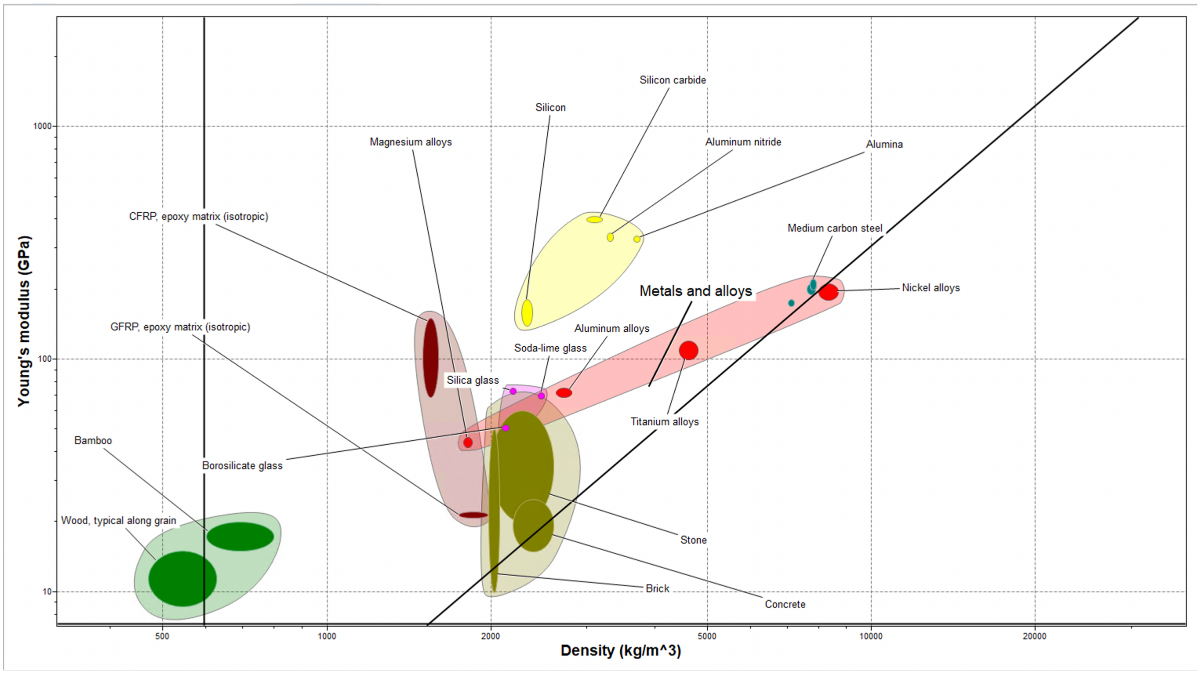

Figure 6: Ashby plot log-log of Young's modulus vs density with performance index, Young's modulus and density limits (zoomed in).

Using the above Ashby Plot, we can see that the following materials would be strong contenders for the bike frame:

- Titanium alloys
- Aluminium alloys
- CFRP
- Wood
- Bamboo

This is due to them having a high young's modulus and suitable density to undergo the large amount of strain the bike will be put under. Woods and bamboo were included due to their unique aesthetic and potential for innovation.

Semantic differential scales

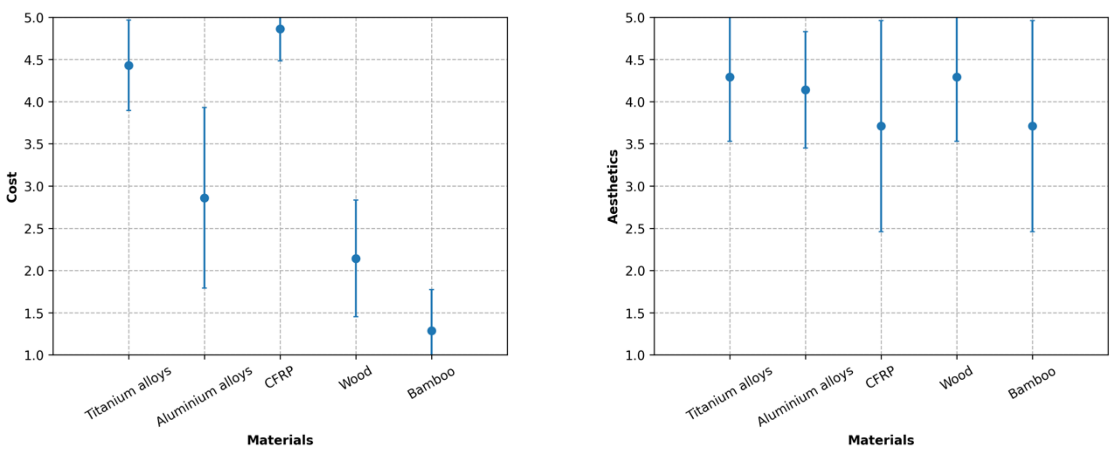

Figure 7: Semantic differential scales generated for selection of final shortlisted materials using 7 people's opinions from a survey. (7) The scales were generated with a script. (8)

This survey was run to the 'feels-like' experiential properties of the materials selected. The optimal survey results should have a high score for aesthetics (looks great) and a low score for cost (low cost). The general range of scores for Aesthetics was consistent amongst the materials. However, wood and titanium generally scored higher. For the cost of the material, Wood and Bamboo were leaders with aluminium being the only metal that seemed affordable for the users.

Final Selection

Table 2 – Materials selected based on materials analysis using Ashby plots, performance index, limits and SDS results; data sourced from CES EduPack.

	Price (GBP/kg)	**Young's Modulus (GPa)**	**Yield Strength (MPa)**	**Durability water (fresh/salt)**	**CO^2 Footprint (kg/kg)**	**Density (kg / m^3)**	**Performance Index ($P = \frac{E^{\frac{1}{2}}}{\rho}$)**
Steel (medium carbon)	0.524 – 0.552	200 – 200	376 - 929	Acceptable / Limited Use	2.26 – 2.49	7.8e3	1.8e-3
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Bamboo	1.01 – 1.51	15.1 – 19.9	35.8 – 44.1	Limited Use / Limited Use	1 – 1.11	602 - 797	5.6e-3

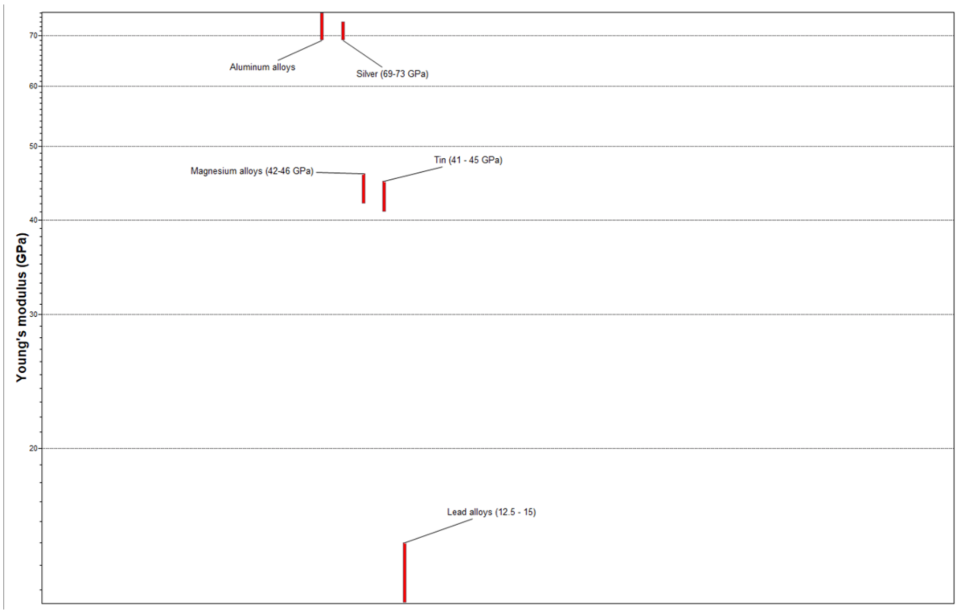
Conclusion

The final material the consultancy decided for the new Burns Corp bike frame was **Aluminium**. This is due to its 'excellent' material properties. The price of aluminium (max 1.79 GBP/kg) is significantly below the benchmark (31.8 GBP/Kg). It also has an acceptable level of corrosion resistance for a road bike which will be used in conditions with rain (fresh) water. Although it's manufacturing costs are high and a large amount of electrical energy will be required to produce it, this is ideal for Burns Corp as can use their top-of-the-line power nuclear power station. The Young's modulus of the material whilst not as high as titanium is almost on par with the much more expensive carbon fibre and will be suited to the tough conditions the bike will be placed under. Aluminium is also very readily available as it is the most abundant metal making up about 8.3% of the world's crust. (9) The CO^2 footprint is significantly greater than other materials, but this was not a priority for Burns Corp. The yield strength of the material is average and suitable for the application to prevent the bike undergoing plastic deformation with use. SDS results rated aluminium positively in comparison to Wood and Bamboo with most users saying it looked great. The performance index of the material (3.1e-3) is also good in comparison to the other final contenders. Whilst Bamboo has a higher performance index (5.6e-3), the other characteristics stated above make Aluminium the clear best fit choice for Burns Corp's new bike frame.

Appendices

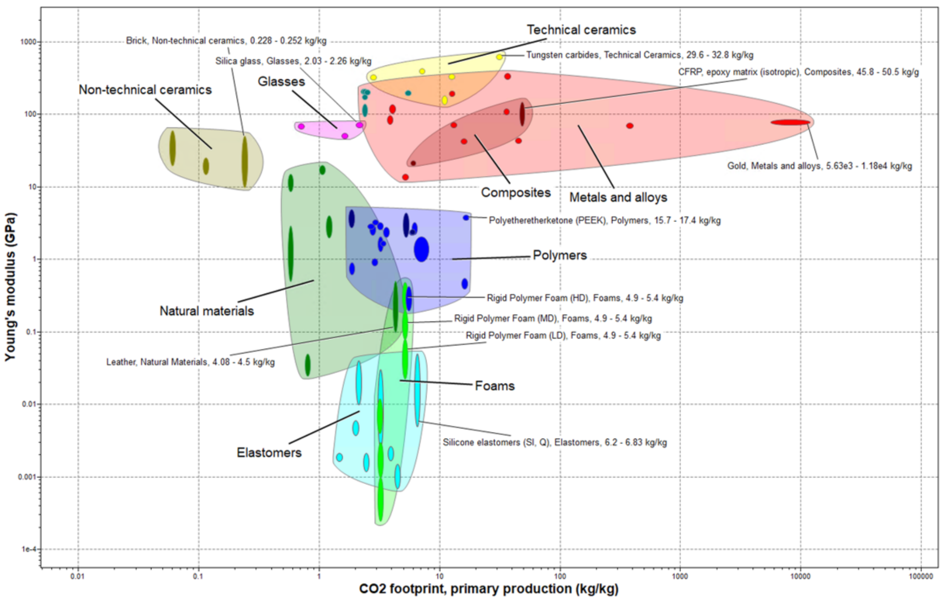
CES EduPack Tasks

Task 1



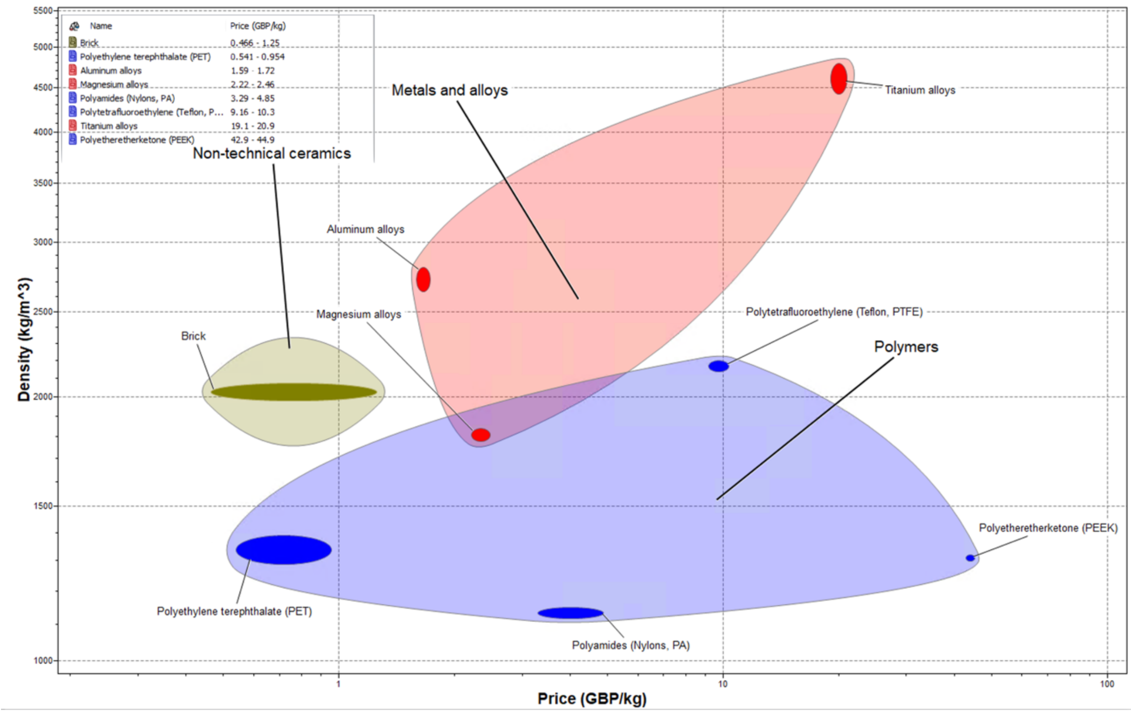
Level 1 metals, alloys, polymers and elastomers Young's modulus (GPa) (5-70GPa only).

Task 2



Level 1 materials Young's modulus (GPa) vs CO_2 footprint (kg/kg). Labels have CO_2 footprint (Kg/Kg).

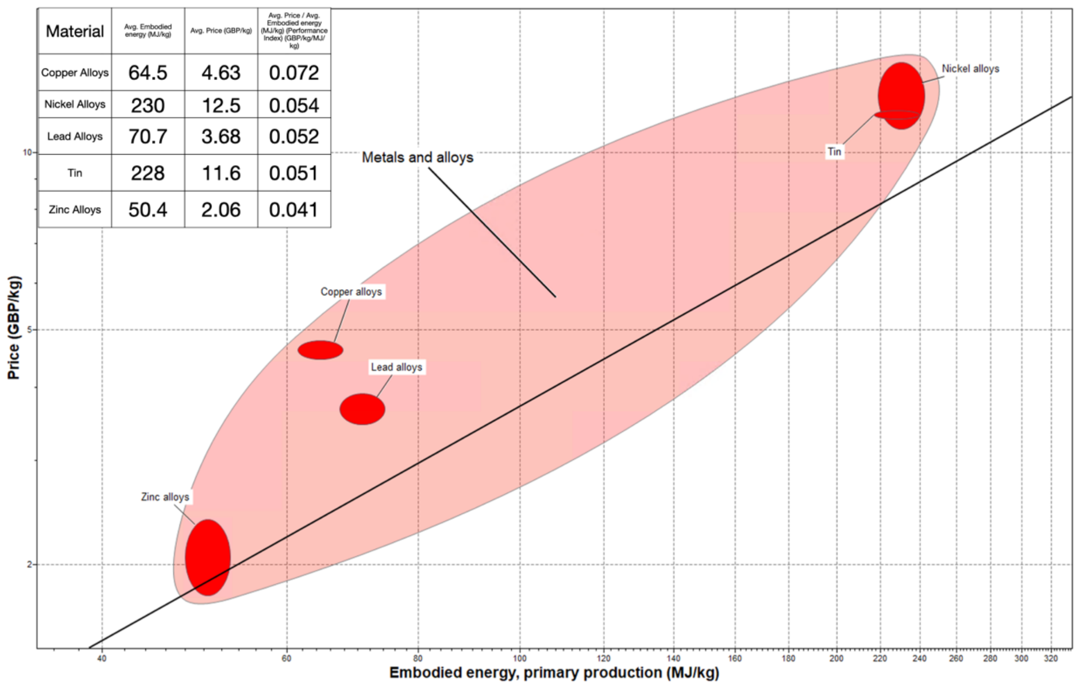
Task 3



Name	Price (GBP/kg)
Brick	0.466 - 1.25
Polyethylene terephthalate (PET)	0.541 - 0.954
Aluminum alloys	1.59 - 1.72
Magnesium alloys	2.22 - 2.46
Polyamides (Nylons, PA)	3.29 - 4.85
Polytetrafluoroethylene (Teflon, P...	9.16 - 10.3
Titanium alloys	19.1 - 20.9
Polyetheretherketone (PEEK)	42.9 - 44.9

Level 1 materials Density (kg/m^3) vs Price (GBP/kg) (only density of 500-5000 kg/m^3, cost between 0.5-50 £/kg, have a Young's modulus <100 GPa and a melting temperature > 200°C) with pricing table.

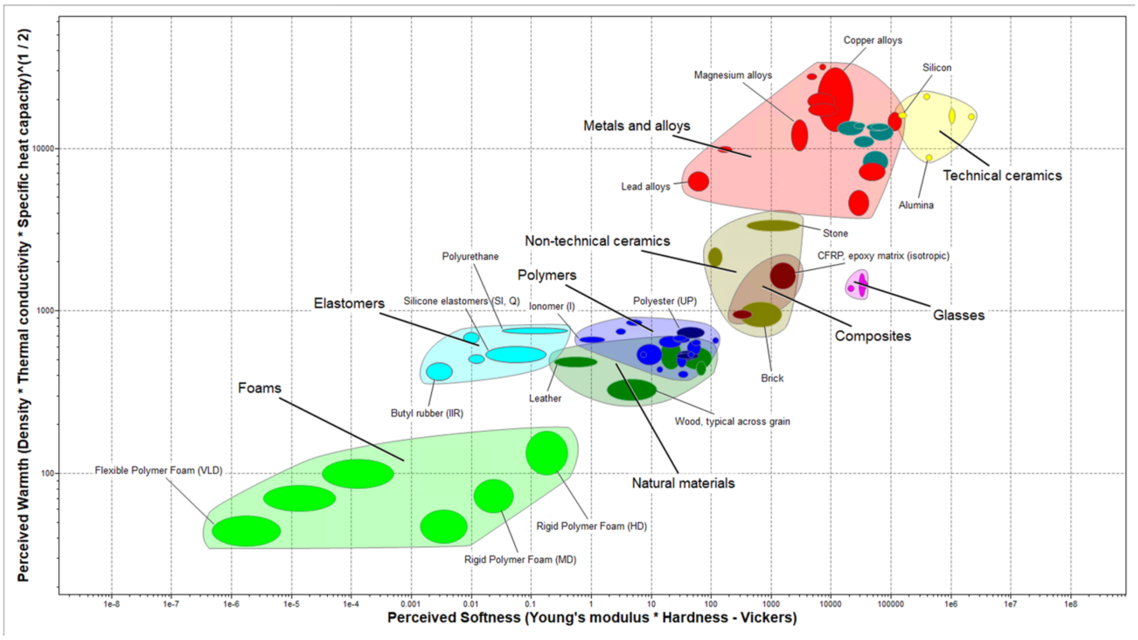
Task 4



Material	Avg. Embodied energy (MJ/kg)	Avg. Price (GBP/kg)	Avg. Price / Avg. Embodied energy (MJ/kg) (Performance Index) (GBP/kg/MJ/kg)
Copper Alloys	64.5	4.63	0.072
Nickel Alloys	230	12.5	0.054
Lead Alloys	70.7	3.68	0.052
Tin	228	11.6	0.051
Zinc Alloys	50.4	2.06	0.041

Level 1 electrical conductors (good and poor) Price (GBP/kg) vs Embodied energy (MJ/kg) with selection line gradient 1 above Zinc alloys (only Tensile strength > 10MPa and material must be able to undergo casting).

Task 5



Level 1 materials Perceived warmth ($\sqrt{\rho\lambda C_p}$) vs Perceived softness ($S = EH$).

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