MATERIALISE REPORT

A CUTTING-EDGE GOLF CLUB FOR FRINK LABS

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1 Technical summary

Carbon Fibre Reinforced Plastic (CFRP) was found to be the most suitable material for the shaft of a golf club based on its general, mechanical, and experimental properties and the stakeholder's opinions on how cutting-edge the material is. It is the closest match to the Frink Labs company values while still being sufficiently performant to be used in the shaft of a golf club.

These findings were established by first researching thoroughly the properties, use and currently used materials of a golf club. A technical brief was developed based on the research findings to summarise the problem. Then, a three-stage selection process was conducted which consisted of setting minimum or maximum limits to the relevant properties of materials to get an initial list of suitable materials. Then through the use of a performance index only the highest performing materials from the initial candidates were chosen. Lastly, a semantic differential scale was used to determine which of the final candidates matched the values of Frink Labs the most.

2 Introduction

KWD Consultants is a London based consultancy company, specialising in material selection for consumer products. The following report describes and explains the process undertaken to choose a material for a new golf club.

The client, Frink Labs, has specified that the materials for the golf club must be chosen in accordance with their company values, which prides itself in using the most cutting-edge materials and in their flagship Vibranium alloy. Although the company values are a priority, they will need to be achieved without compromising the usability, appearance, cost, and performance of the product.

3 Background

3.1 History

Golf clubs have evolved over hundreds of years: starting off as a wooden stick in the roman times, through being a combination of wood and iron, and later of steel and iron. Currently, most golf clubs consist of a high-tech composite shaft and a computer designed head. In turn, the head is made up of a foam filling inside and a cast metal outside layer. (1) While the materials used have changed massively, the basic principle of the golf swing has stayed the same; it is a pendulum which collides with a ball and makes it travel. (2)

3.2 Club Types

There are five main types of golf clubs, each with its own size, shape, and purpose in the game. These include Woods, Irons, Hybrids, Wedges and Putters. (3) During any game, the golfer is permitted to carry a set of 14 clubs, with no requirements regarding the make-up of this number (4). Below is a table (Table 1) which briefly describes each type, its purpose, and the materials it uses for the head and the shaft.

Club Type	Use
Wood	longest shots, fastest swing (3)
Iron	shots from the fairway i.e., initial shots (3)
Hybrid	combination of the iron and wood clubs (3)

Wedge	short approach into greens, getting out of sand pits (3)
Putter	used for the very last shot or for knocking the ball into the hole (3)

Table 1 – Types of golf clubs

There is a large range of golf club types, each with varying mass and size. Despite this, the golf club shaft can be modelled as a rod in all cases, as is explained below.

3.3 Forces

The golf club shaft was simplified to be modelled as a uniform rod. The diagram in Figure 1 shows how this can be visually represented, alongside relevant equations for the end deflection due to the force exerted by the ball, $W$and the bending moment exerted by the ball, M.

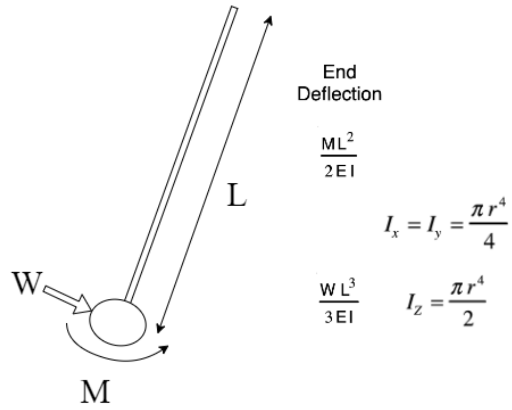


Figure 1 – Golf club model

The peak force between the club and the ball during a swing can reach up to $9000\ Newtons$ during the $0.005\ second$ collision. (5)

3.4 Material Properties

In Tables 3 and 4, the material properties which will be relevant when determining the material for a golf club have been discussed.

3.4.1 Quantitative properties

Type of property	Property	Units	Description
General	Price	$GBP\ kg^{-1}$	The chosen material price must be feasible to make on a commercial scale.
	Density	$kg\ m^{-3}$	Density determines the mass per volume and will determine the usability and portability of the club.
Mechanical	Modulus of Elasticity	GPa	Young's Modulus should be maximised to minimise the flex when hitting the ball.
	Yield Strength (Elastic Limit)	MPa	The yield point must be maximised to ensure the club does not deform.
	Fracture toughness	$MPa\ m^{\frac{1}{2}}$	This metric will need to be maximised as the club will need to absorb a lot of energy at impact.
Experimental	Perceived Warmth	$kg\ m^{\frac{1}{2}}\ K^{-1} s^{-\frac{5}{2}}$	The perceived warmth can be useful for the handle of the club.

Table 2 – Relevant quantitative properties and their descriptions

3.4.2 Qualitative properties

These properties are all subjective and can be assessed by conducting a semantic differential scale survey with the project stakeholders.

Property pair	Description
Boring - Innovative	The material must match the innovative company values.
Common - Exclusive	A cutting-edge material will be exclusive.
Cheap - Expensive	The appearance of an innovative material will be expensive.
Nostalgic - Futuristic	The material must feel futuristic.
Clumsy - Elegant	A cutting-edge material must be elegant.

Table 3 – Relevant qualitative property pairs, with the desirable properties on the right

3.5 Currently Used Materials

Using CES EduPack a table with the values of the quantitative properties of currently used materials has been generated.

Material	Price $GBP\ kg^{-1}$	Density $kg\ m^{-3}$	Modulus of Elasticity GPa	Yield Strength MPa	Fracture toughness $MPa\ m^{\frac{1}{2}}$	Perceived Warmth $kg\ m^{\frac{1}{2}}\ K^{-1}s^{-\frac{5}{2}}$	Used for
Aluminium alloys	$1.59 - 1.72$	$2.64 \times 10^3 - 2.81 \times 10^3$	$69 - 75$	$109 - 439$	$23 - 38$	$1.75 \times 10^4 - 2.2 \times 10^4$	Shafts
Stainless steel	$2.12 - 2.27$	$7.61 \times 10^3 - 7.87 \times 10^3$	$190 - 210$	$257 - 1.14 \times 10^3$	$57 - 137$	$7.19 \times 10^3 - 9.63 \times 10^3$	Shafts, Heads
Titanium alloys	$19.1 - 20.9$	$4.43 \times 10^3 - 4.79 \times 10^3$	$100 - 120$	$470 - 1.09 \times 10^3$	$50 - 84.1$	$3.9 \times 10^3 - 5.5 \times 10^3$	Shafts, Heads
Tungsten alloys	$46.6 - 51.6$	$1.69 \times 10^4 - 1.86 \times 10^4$	$310 - 370$	$490 - 1.23 \times 10^3$	$120 - 150$	$1.3 \times 10^4 - 1.67 \times 10^4$	Heads
CFRP	$28.6 - 31.8$	$1.5 \times 10^3 - 1.6 \times 10^3$	$69 - 150$	$550 - 1.05$	$6.12 - 20$	$1.38 \times 10^3 - 1.98 \times 10^3$	Shafts

Table 4 – Currently used materials for golf club shafts and heads and their relevant properties (1)

In the table above, the Perceived Warmth, Q was calculated using the following formula: $Q = \sqrt{\rho \lambda C}$ where ρ is the material density, λ is the thermal conductivity, and C is the specific heat capacity. The values above have created a baseline to get an idea on what the values in the selection process should be.

3.6 Size Rules

Professional golf has very strictly defined rules on the size of the clubs. The maximum size for the head of a club is $7.1\ cm$ in height and $12.7\ cm$ in width. Additionally, the volume of the head must not exceed $460\ cm^3$. (2)

Dimensions of the shaft are also strictly regulated. The minimum length allowed is $45.72\ cm$ with the maximum being $121.92\ cm$. (6) The diameter is not regulated; however the typical dimensions range from $0.9\ cm$ to $1.5\ cm$. (7) Similarly, the mass of the shaft is not regulated, but on average the mass of a club is around $0.45\ kg$. Additionally, it is crucial that the shaft is not too light as this will cause the club to be hard to aim with. (8)

The golf ball must also conform to rules. Its diameter must be greater than or equal to $42.67\ mm$ and it must not be heavier than $49.93\ g$. (9)

These dimensions needed to be considered when choosing the material for the golf club; the material chosen had to have the desired properties without exceeding the allowed mass or volume.

4 Technical Brief

The aim of this report is to find a material which mechanical properties are largely similar to the currently existing materials in the market in use for a golf club. This can be done using a performance index and an Ashby Plot. The main differentiating factor are the stakeholder views which, when measured, can indicate what materials are deemed to be “cutting-edge”. Both of these factors must be achieved while also ensuring that the chosen material’s price makes it feasible to be produced. Lastly, the material chosen must allow for the mass of the shaft must be kept within the currently accepted range and for the size of the product to fit within the official regulations.

5 Discussion

In this section, the process of selecting the optimal material has been described. The discussion was focused on choosing a material for the shaft of the club only.

5.1 Metrics of Interest

5.1.1 General Properties

5.1.1.1 Price ($\boldsymbol{GBP\ kg^{-1}}$)

As shown by the research carried out in the background section of the report, the most expensive material currently in use for the shaft of the golf club is CFRP (Carbon Fibre Reinforced Plastic). Its price falls in the range of 28.6 – $31.8\ GBP\ kg^{-1}$. A new golf club while being made of cutting-edge materials, must be competitive with the existing solutions on the market; hence the price limit was set to $32\ GBP\ kg^{-1}$.

5.1.1.2 Density ($\boldsymbol{kg\ m^{-3}}$)

It was given that the shaft of the golf club usually has a diameter, d between $0.9\ cm$ and $1.5\ cm$, and has an allowed length, l between $45.72\ cm$ and $121.92\ cm$. From this the mean volume, $\bar{V}$ of a golf club shaft was calculated using the following formula:

$$\bar{V} = \frac{\pi \bar{d}^2}{4} \bar{l}$$

$$\bar{d} = \frac{0.9 + 1.5}{2} = 1.2\ cm \qquad \bar{l} = \frac{45.72 + 121.92}{2} = 83.82\ cm$$

$$\bar{V} = \frac{\pi \times 1.2^2}{4} \times 83.82 = 94.79\ cm^3 \sim 9.5 \times 10^{-5}\ m^3$$

It was given that the mass of a whole golf club is 0.45 kg. We can assume that the shaft makes up 20% of a golf club. This produces a value of $\sim 0.1 kg$ for the mass of the golf club shaft, m. In turn, the density of an average golf club, ρ was calculated using the formula $\rho = \frac{m}{\bar{V}}$.

$$\rho = \frac{0.1}{9.5 \times 10^{-5}} = 1.05 \times 10^3\ kg\ m^{-3}$$

This value was taken as the minimum density so that the golf club shaft will fit within the currently adopted size and mass constraints.

5.1.2 Mechanical Properties

5.1.2.1 Modulus of Elasticity $(\boldsymbol{GPa})$

The Youngs Modulus is a crucial metric as the shaft must be stiff to avoid any potential flex as much as possible. The materials currently in use have a modulus between 69 and $370\ GPa$. Therefore, the minimum Young Modulus was chosen to be $70\ GPa$.

5.1.2.2 Yield Strength $(\boldsymbol{MPa})$

This metric determines the point at which plastic deformation occurs. Any plastic deformation would deem the golf club unusable, therefore the yield point of the club must be maximised. Aluminium and stainless steel have the lowest yield strength and are outliers when compared with the other currently used materials. Therefore, the next lowest value was chosen of $470\ MPa$. This was the value of Titanium.

5.1.2.3 Fracture toughness ($\boldsymbol{MPa\ m^{\frac{1}{2}}}$*)*

This is the ability of a material to absorb energy until fracture. As shown in background research, during the impact between the ball and the club, the force can between the two objects can reach up to $9000N$. This means that the club must have a high fracture strength. The minimum value was chosen to be $6.12\ MPa\ m^{\frac{1}{2}}$.

5.1.3 Experimental Properties

5.1.3.1 Perceived Warmth ($\boldsymbol{kg\ m^{\frac{1}{2}}\ K^{-1}s^{-\frac{5}{2}}}$*)*

The perceived warmth will ideally be low, to create a comfortable experience when handling the club. The maximum desired value is $1 \times 10^4\ kg\ m^{\frac{1}{2}}\ K^{-1}s^{-\frac{5}{2}}$.

5.2 Initial Selection

After applying the filters, a list of nine materials which fulfil all the above requirements was created. An Ashby Plot was plotted to illustrate the relationship between density and Young's Modulus of the materials.

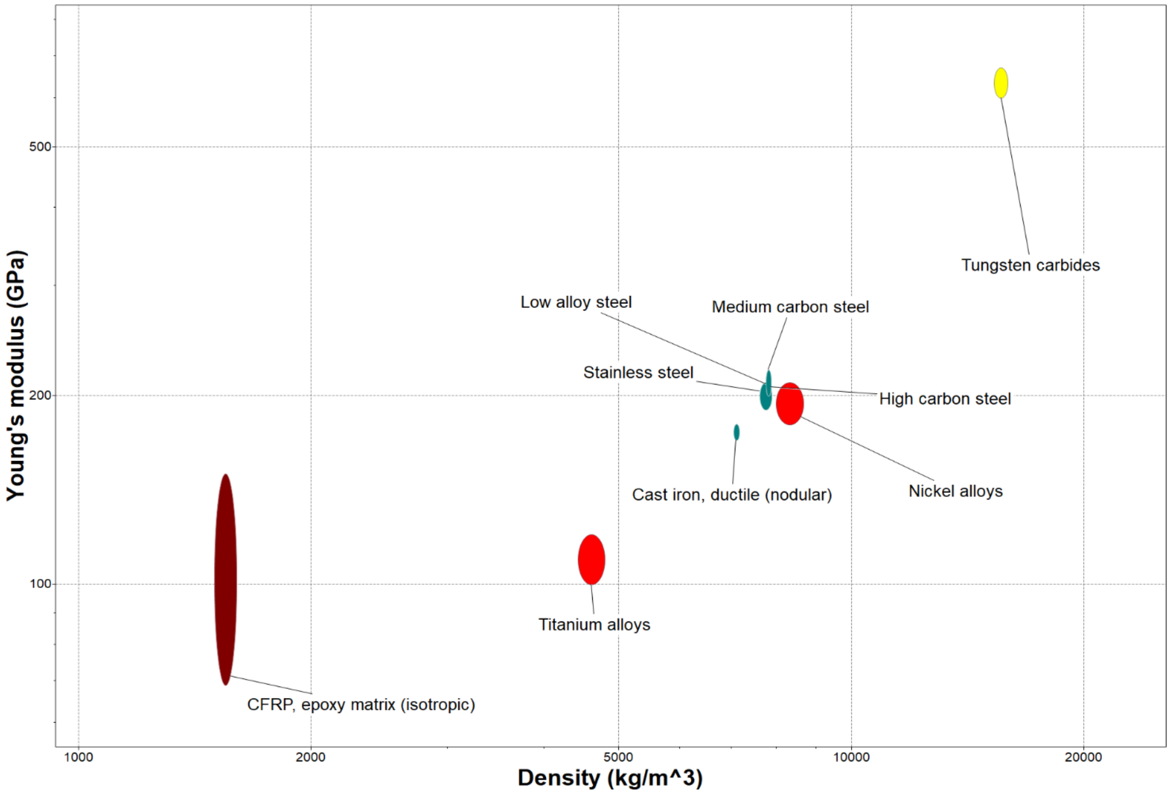


Figure 2 - Initial Ashby Plot of Young's Modulus and Density

5.3 Performance Index

In order to down select further, a performance index was established. This was done using the following method:

First, as was established in the background research section, the shaft of the golf club was modelled as a uniform beam with a weight being applied to one end of it. The deflection of such rod, δ can be found using the following formula:

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

where: W is the Weight applied to the end of the beam, L is the length of the beam, E is the Young's Modulus of the beam and I is the second moment of area about neutral axis.

In turn, I can be defined as follows:

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

where r is the radius of the rod.

Substituting the two above equations together we get:

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

The mass, m of the rod can be expressed as:

$$m = \pi r^2 L\rho \qquad \Rightarrow \pi r^2 = \frac{m}{L\rho}$$

Substituting the above equations together to get:

$$\delta = \frac{4WL^4\rho}{3Er^2m}$$

Rearranging for m:

$$m = \frac{4WL^4\rho}{3Er^2\delta} \qquad \Rightarrow m = \frac{\rho}{E} \times \frac{4WL^4}{3r^2\delta}$$

Only the values which are the material properties of a given material are relevant in order to define a performance index. Therefore, it can be said that for given sized samples with a constant force, W applied and a constant deflection, δ:

$$m \propto \frac{\rho}{E}$$

Hence the performance index, P can be defined as:

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

As the Ashby Plot makes use of a logarithmic scale, the equation was rearranged to the following form:

$$\log P = \log E - log\rho \qquad \Rightarrow \log E = \log \rho + \log P$$

which is in the form of an equation of a straight line.

5.4 Final Ashby Plot

The plot below shows the materials chosen, based on the performance index line shown.

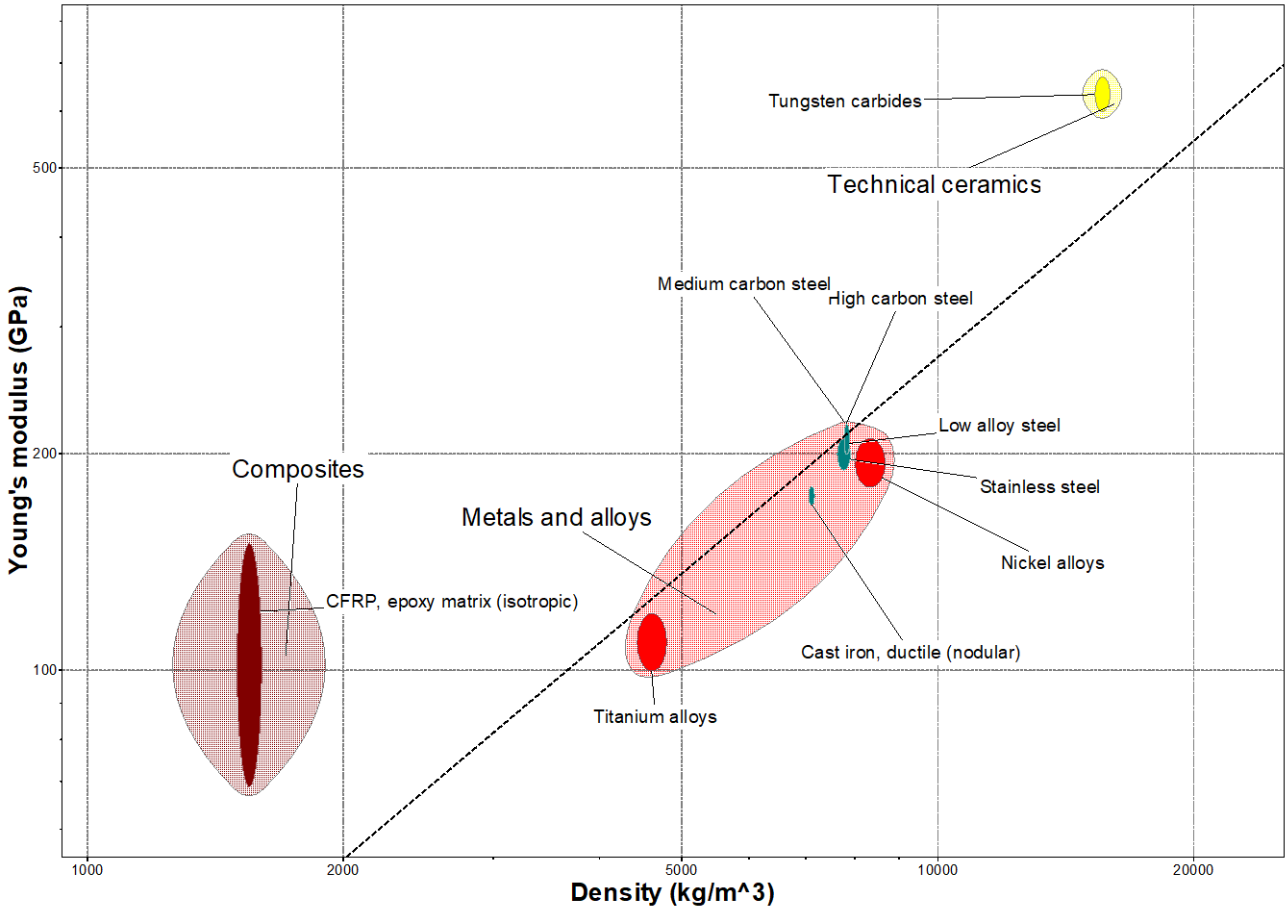


Figure 3 – Final Ashby Plot with the performance index line shown

Table 5 – Four final chosen materials based on mechanical properties

Material Name	Material Family
Tungsten Carbides	Technical ceramics
Medium Carbon Steel	Metals and alloys
High Carbon Steel	Metals and alloys
CFRP (Carbon Fibre Reinforced Plastic)	Composites

As can be seen in Figure 3, only a limited number (four) of materials from the previously chosen nine lay above the chosen performance index line. These are listed in Table 5.

5.5 Semantic Differential Scales (SDS)

This part of the selection process has allowed to choose the material which was deemed as most "cutting-edge" from the four materials which have satisfied the mechanical properties requirements. The pairs of adjectives which were identified in the Background section have been used to perform this differentiation. The participants were presented with the name and a picture of each material. Then they were asked to rate each material from 1 to 10 for each property pair, with 1 being the least desirable adjective (e.g. cheap) and 10 being the most desirable adjective (e.g. expensive). In Table 6 a summary of the findings can be found.

Desirable property	Material with the highest rating
Innovative	CFRP (Carbon Fibre Reinforced Plastic)
Exclusive	CFRP (Carbon Fibre Reinforced Plastic)
Expensive	Tungsten Carbides
Futuristic	CFRP (Carbon Fibre Reinforced Plastic)
Elegant	Tungsten Carbides

Table 6 – Materials with highest semantic rating for each property pair

As shown in the table above, Carbon Fibre Reinforced Plastic has scored the highest in most categories in the SDS analysis. This means that CFRP can be concluded to be the most cutting-edge material out of the four tested materials.

6 Conclusion

The insight gained from background research conducted has allowed to set clear mechanical property performance limits which were used in the first stage of the selection process. This stage has narrowed down the number of possible materials to nine. Then, a performance index was established to further reduce the number of possible materials. This has reduced the number of candidate materials to four highly performant materials with very good mechanical properties for use in a golf club. The last stage of the selection process has established Carbon Fibre Reinforced Plastic to be the most cutting-edge material out of the four final candidates, through the use of semantic differential scales.

In conclusion, thanks to the findings of these three stages of the selection process, the material chosen for the shaft of a golf club is Carbon Fibre Reinforced Plastic. Its mechanical properties fit within the currently used materials for golf club shafts, in fact it is already used in such setting. It's price, although high, fits within the limits set for feasibility, and its density allows for a shaft made from it to fit the current ranges of size and mass. Lastly, it was deemed to be the most cutting-edge material in the SDS survey, which was the last determining factor for CFRP to be the recommended material.

7 APPENDICES

7.1 APPENDIX A – LIST OF TABLES AND FIGURES

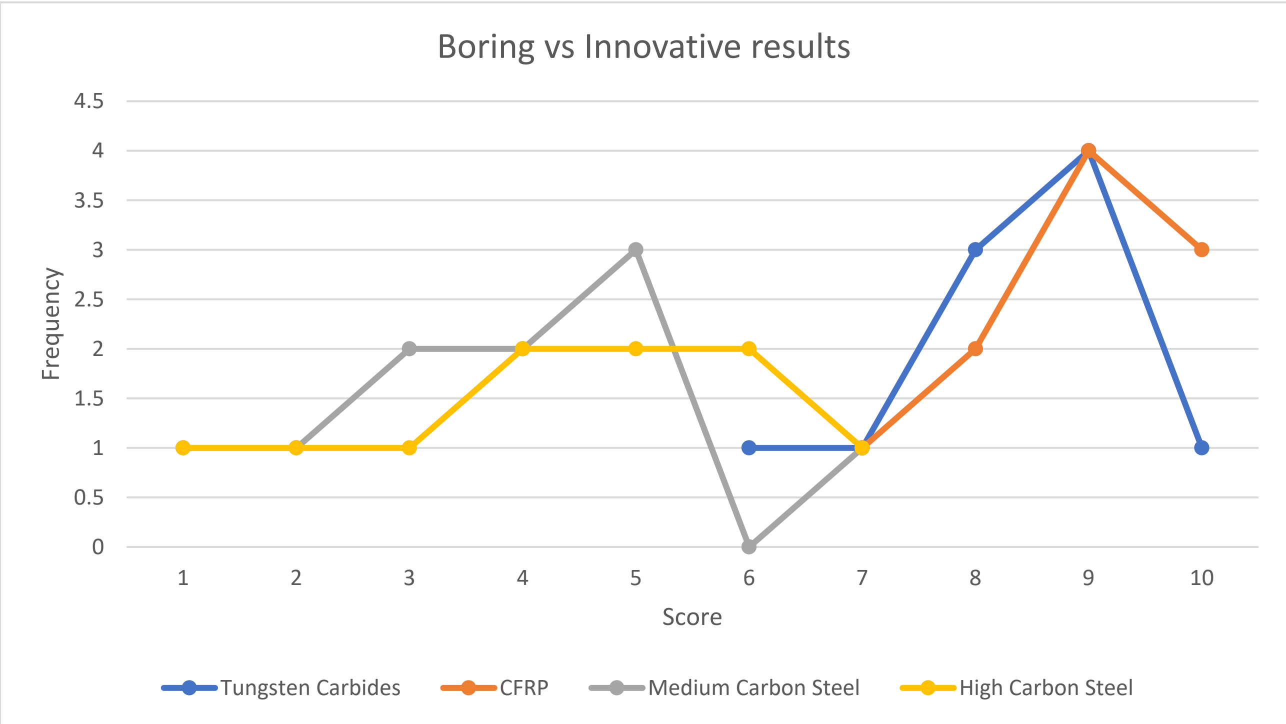
7.1.1 List of Tables

7.1.2 List of Figures

7.2 Appendix B – Semantic Differential Scales

For each property pair two graphs were created. One with the frequencies of the raw answers and one with the total score of each material. The desired property (e.g. expensive) was always rated as 10, whereas the undesired property (e.g. cheap) was always rated as 1. Therefore, the material with the highest total score in each category matches the desired property the most. In total, 10 people were asked about their views.

7.2.1.1 Boring vs. Innovative



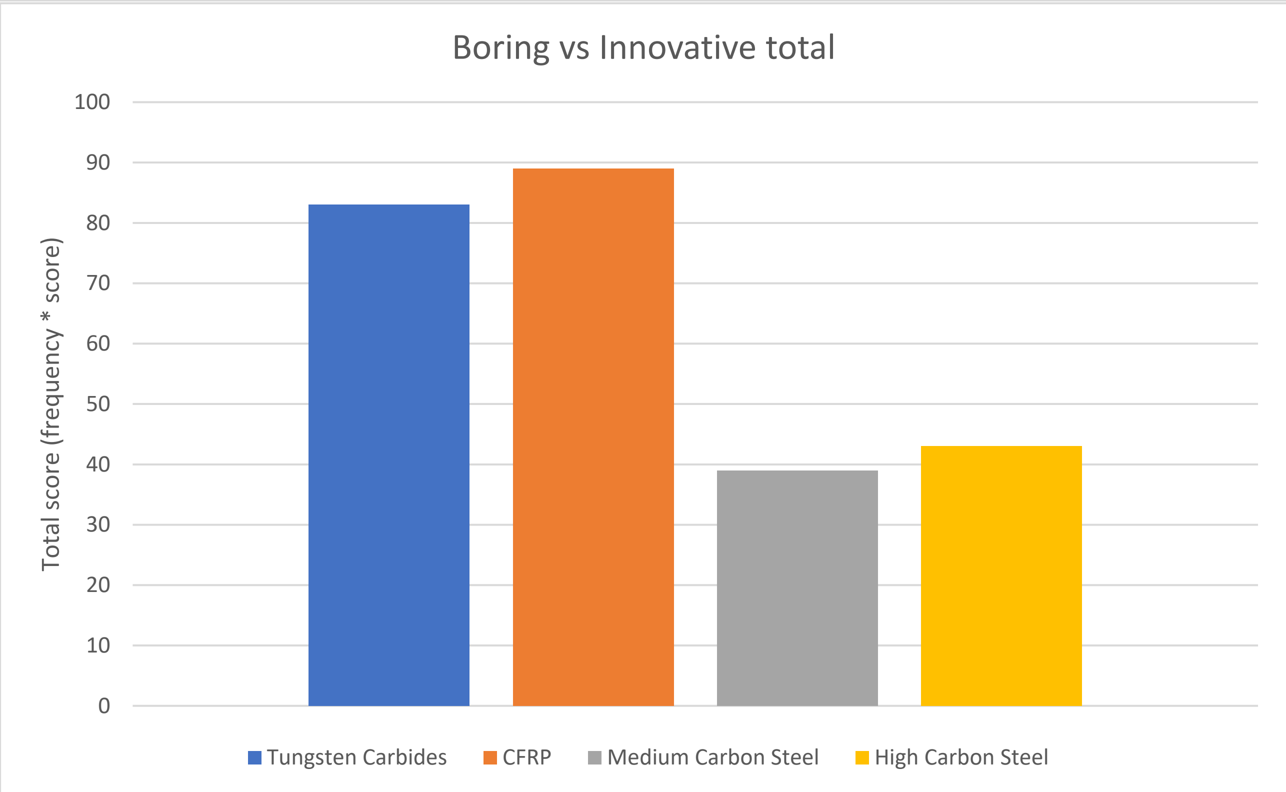
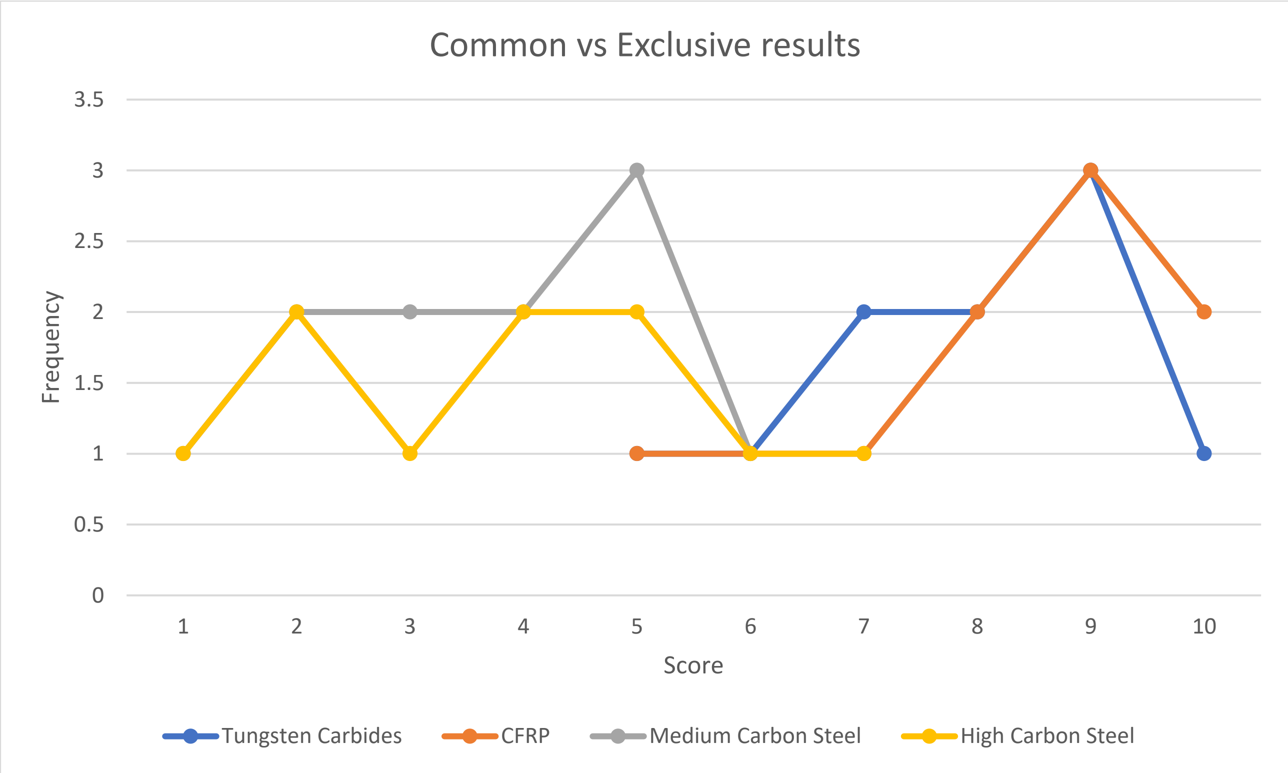


Figure 4 - Boring vs Innovative SDS

7.2.1.2 Common vs. Exclusive



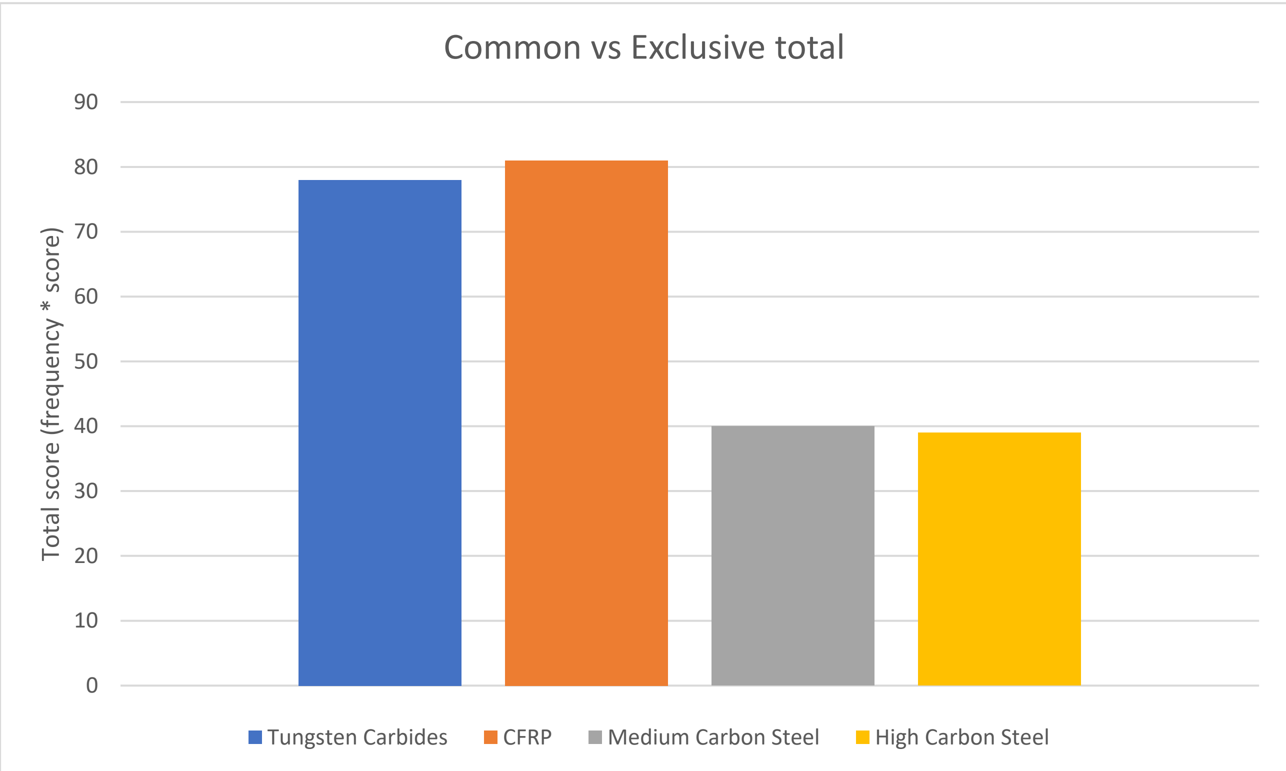
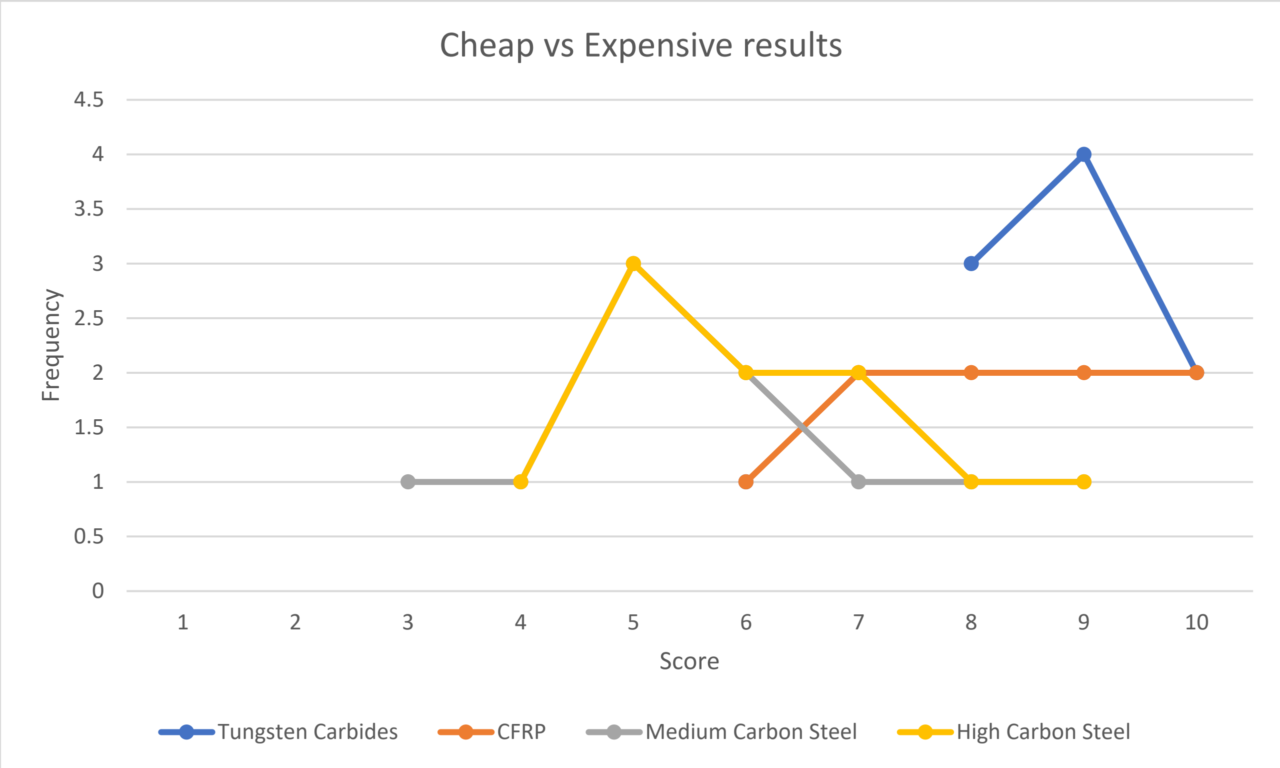


Figure 5 - Common vs Exclusive SDS

7.2.1.3 Cheap vs. Expensive



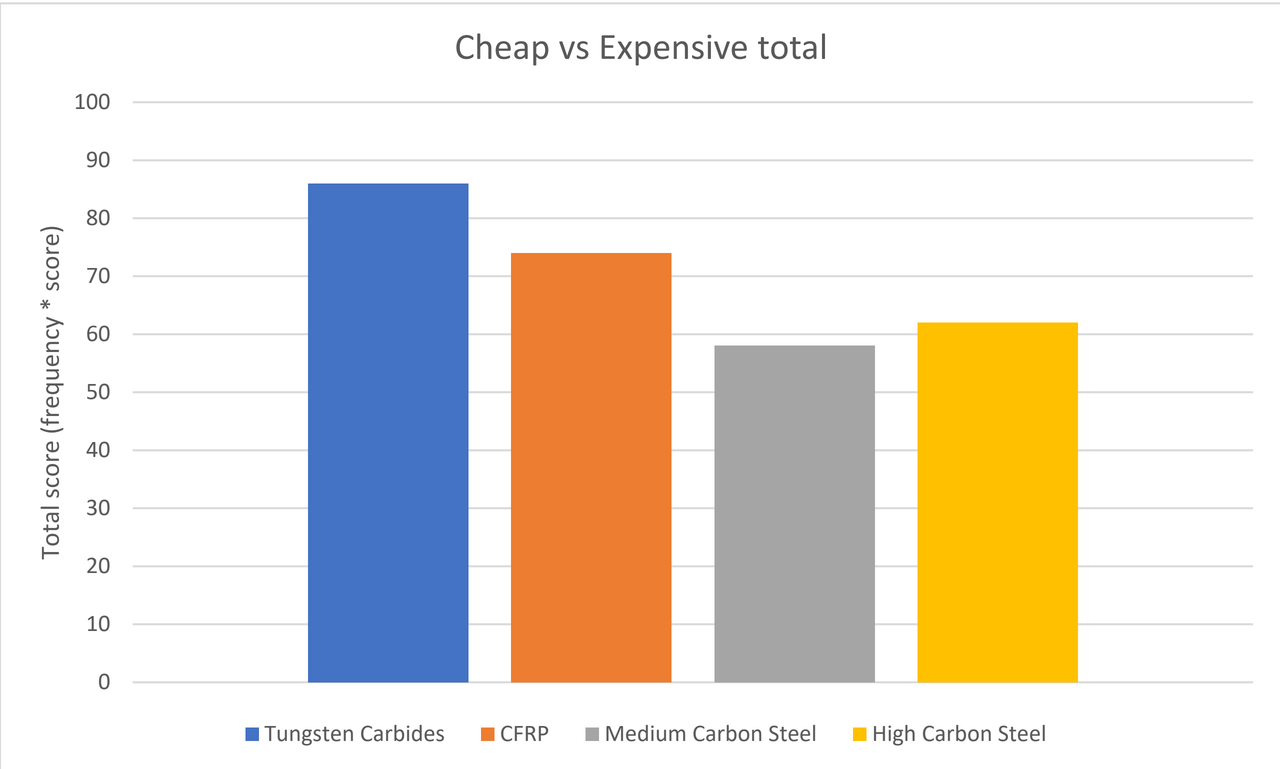
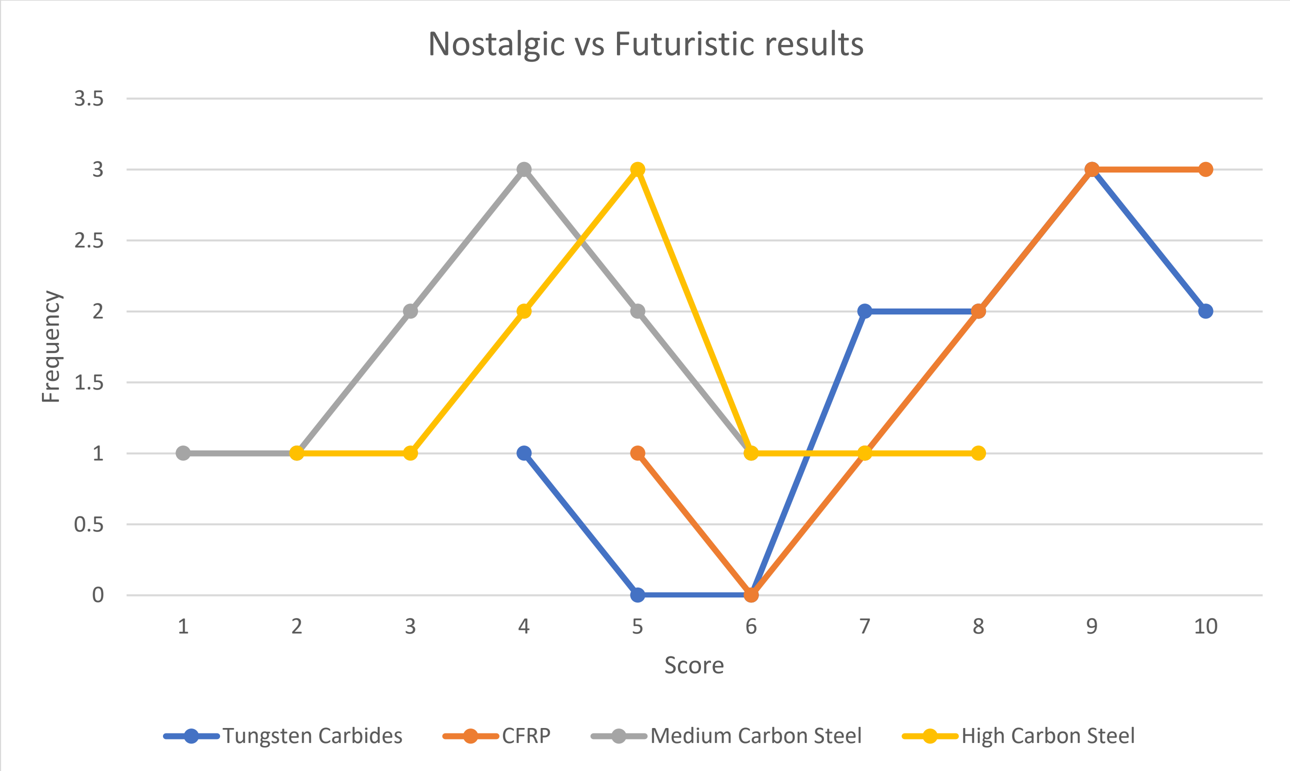


Figure 6 - Cheap vs Expensive SDS

7.2.1.4 Nostalgic vs. Futuristic



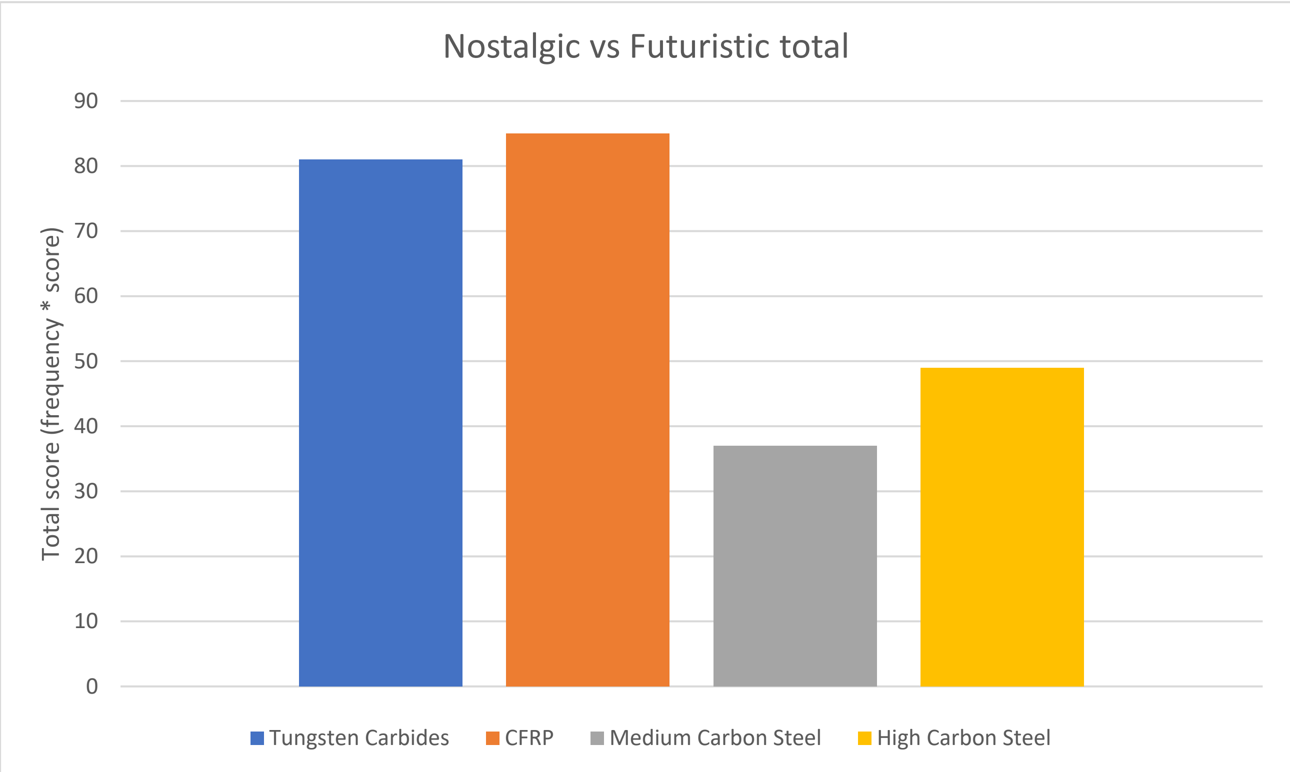
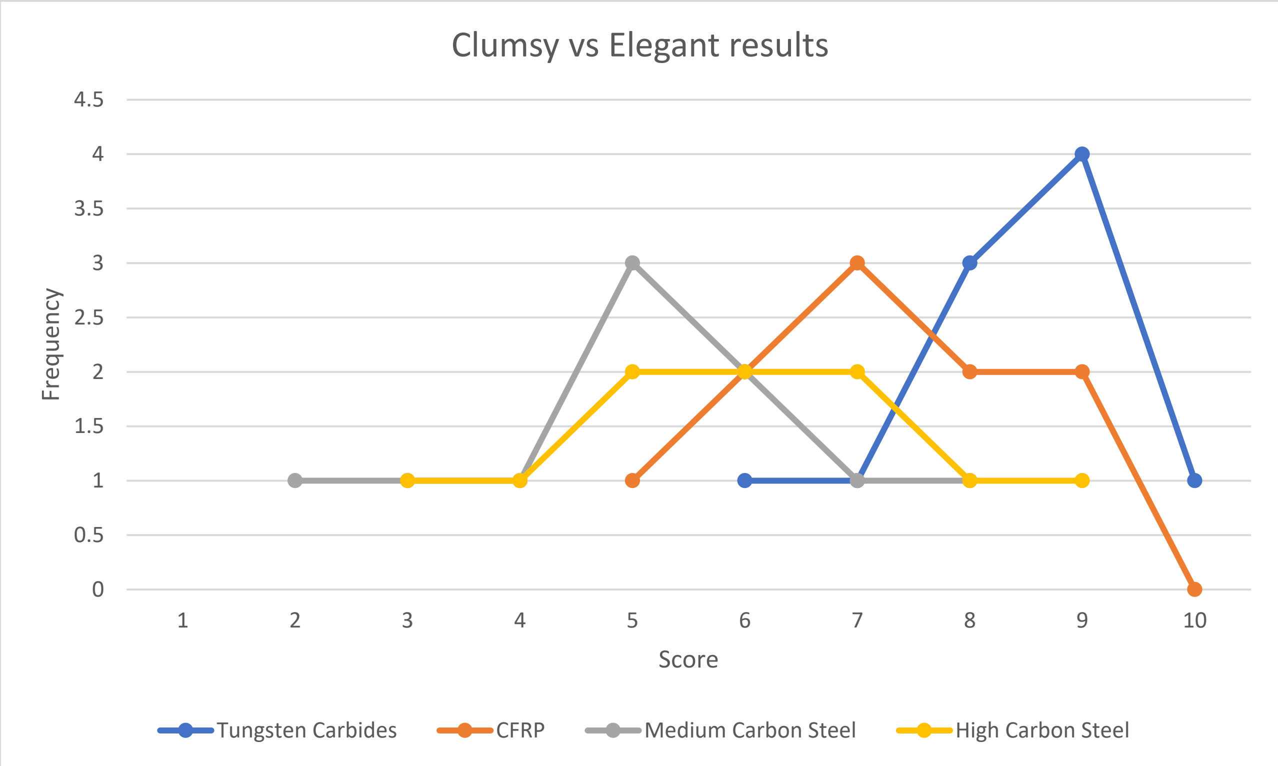


Figure 7 - Nostalgic vs Futuristic SDS

7.2.1.5 Clumsy vs. Elegant



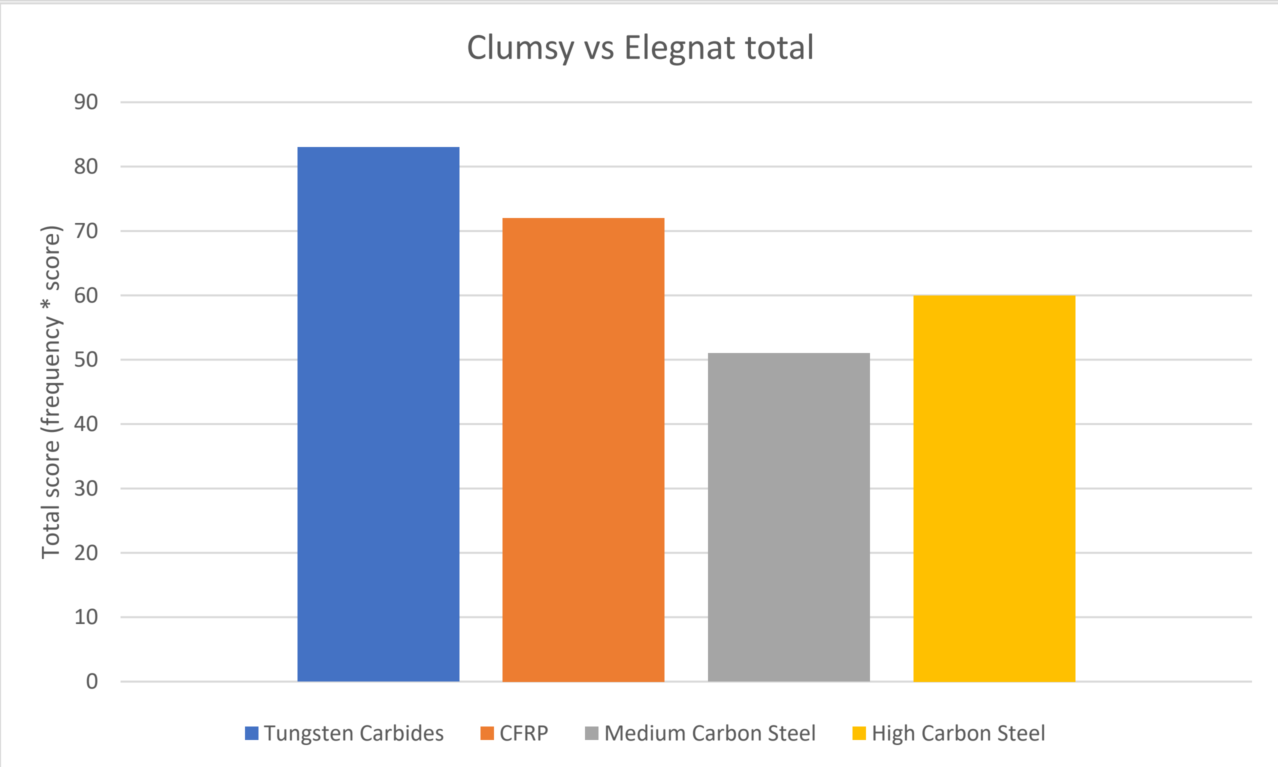


Figure 8 - Cheap vs Elegant SDS

7.3 Appendix C – CES EduPack Lab Tasks

7.3.1.1 Lab task 1

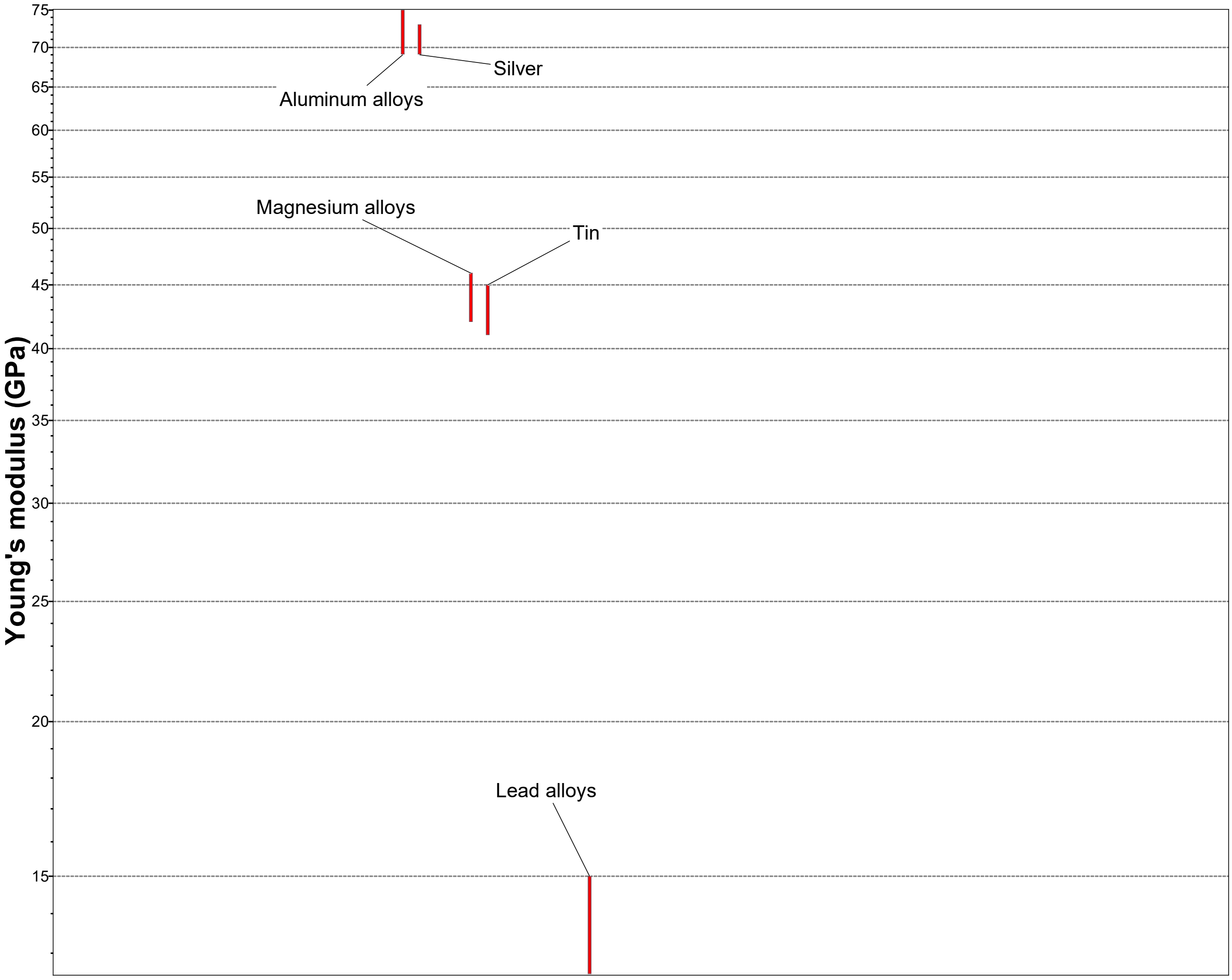


Figure 9 – a bar chart of Young's modulus showing the materials which have a Young's modulus between $5 - 70\ GPa$

Name	Young's modulus (GPa)
Lead alloys	$12.5 - 15$
Tin	$41 - 45$
Magnesium alloys	$42 - 46$
Silver	$69 - 73$
Aluminum alloys	$69 - 75$

Table 7 – the ranges of Young's modulus of the materials in Figure 9

7.3.1.2 Lab task 2

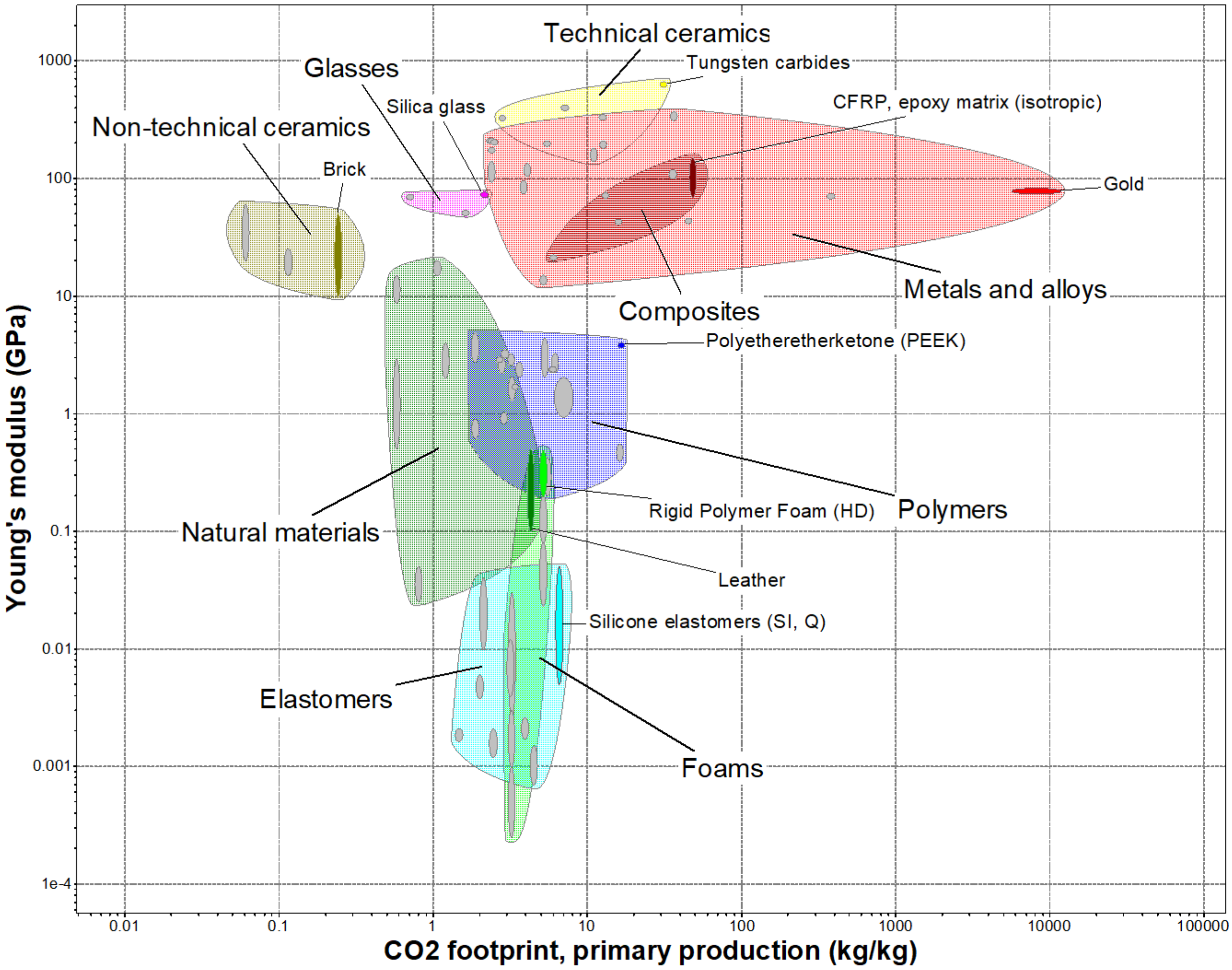


Figure 10 – an Ashby plot of Young's modulus vs CO2 footprint with material name and material families

Name	CO2 footprint primary production (kg/kg)
Brick	$0.228 - 0.252$
CFRP epoxy matrix (isotropic)	$45.8 - 50.5$
Gold	$5.63 \times 10^3 - 1.18 \times 10^4$
Leather	$4.08 - 4.5$
Polyetheretherketone (PEEK)	$15.7 - 17.4$
Rigid Polymer Foam (HD)	$4.9 - 5.4$
Silica glass	$2.03 - 2.26$
Silicone elastomers	$6.2 - 6.83$
Tungsten carbides	$29.6 - 32.8$

Table 8 – a list of materials from Figure 10 with their corresponding CO2 footprints

7.3.1.3 Lab task 3

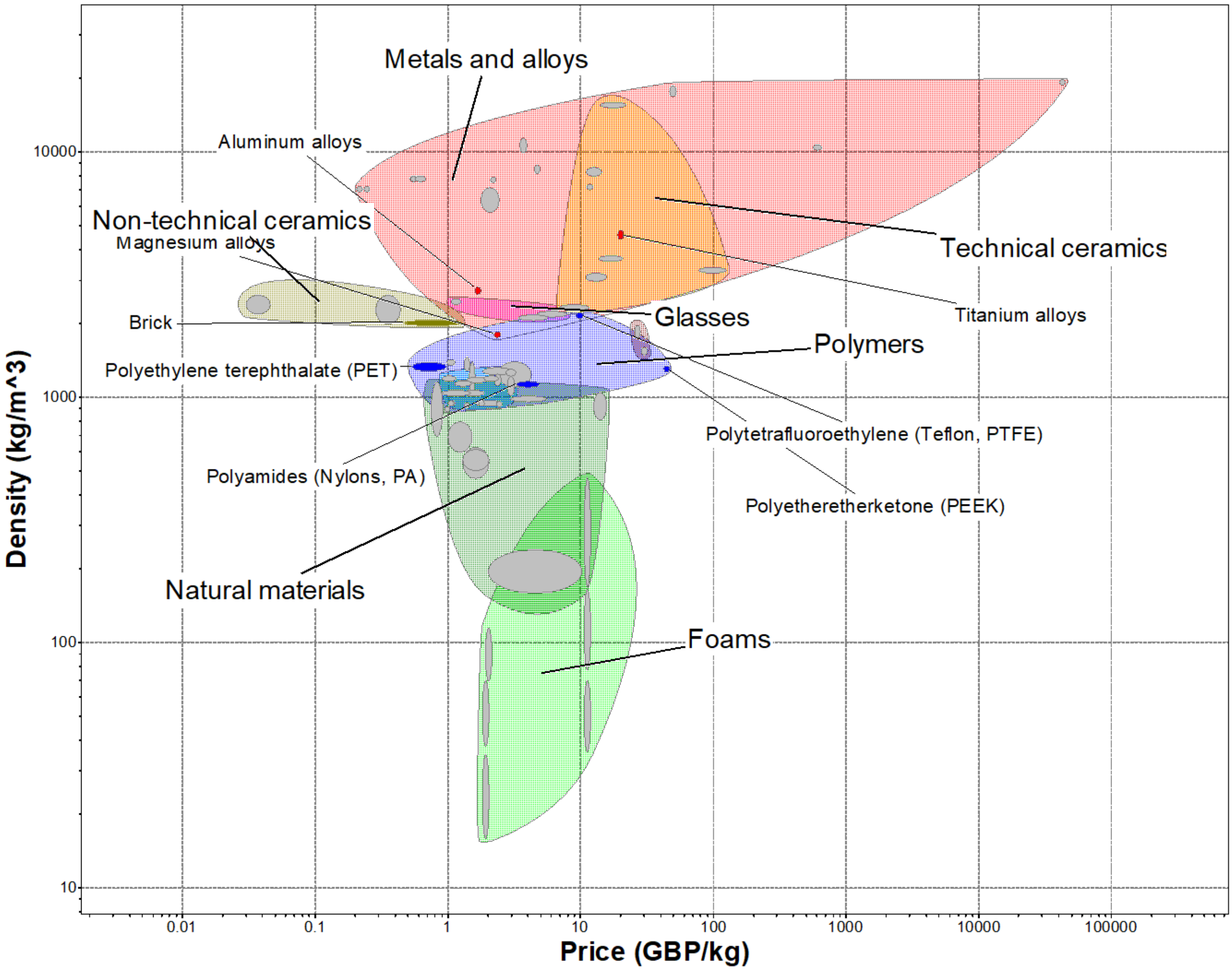


Figure 11 – an Ashby plot of density vs price of selected materials with appropriate labels

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 PTFE)	$9.16 - 10.3$
Titanium alloys	$19.1 - 20.9$
Polyetheretherketone (PEEK)	$42.9 - 44.9$

Table 9 – Materials from Figure 11 with corresponding prices

7.3.1.4 Lab task 4

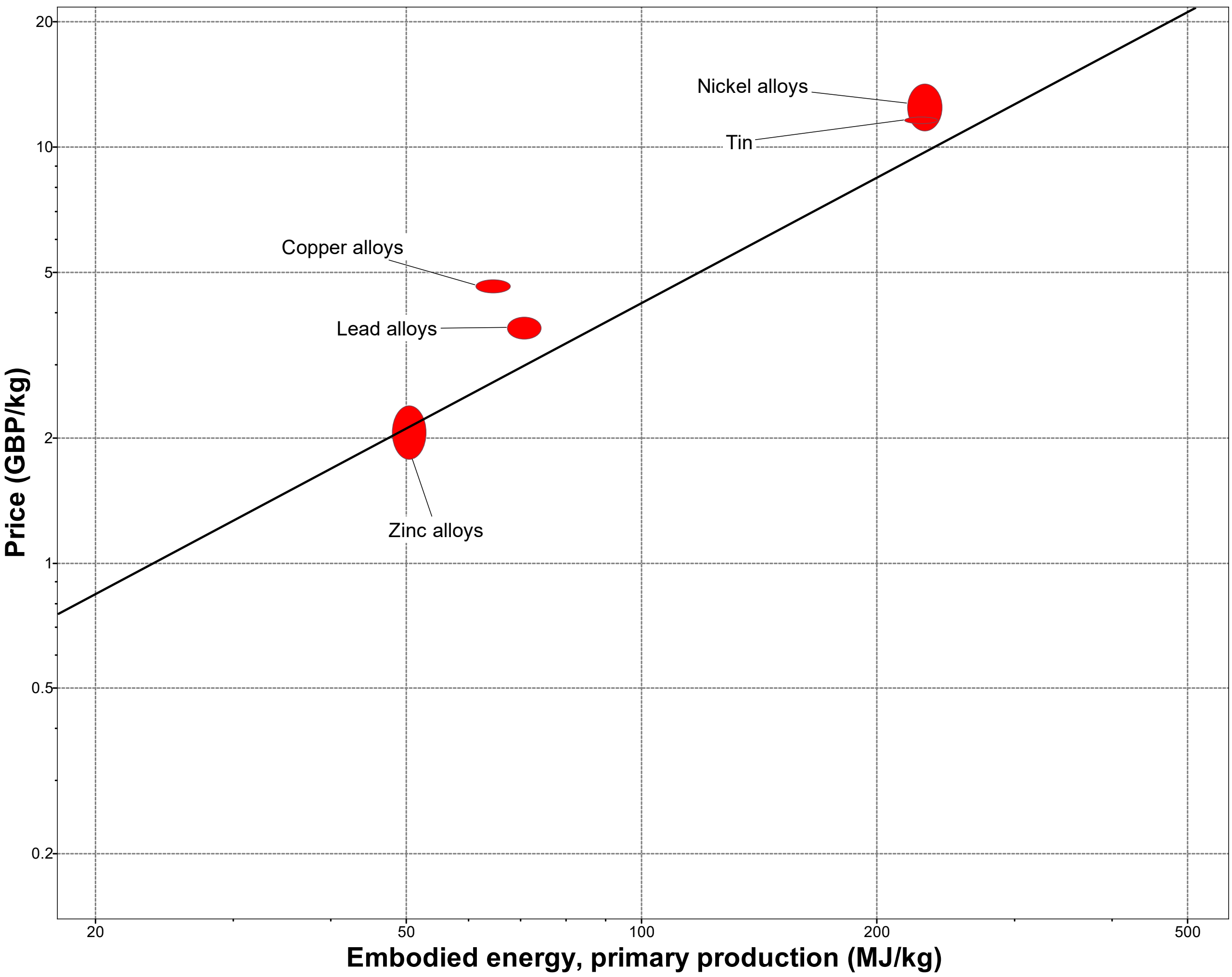


Figure 12 – an Ashby plot of Price vs Embodied energy with a selection line of gradient 1

Name	Index, $slope = 1$
Copper alloys	0.0718
Nickel alloys	0.0542
Lead alloys	0.0521
Tin	0.0509
Zinc alloys	0.0409

Table 10 – a list of materials from Figure 12 in terms of the performance index

7.3.1.5 Lab task 5

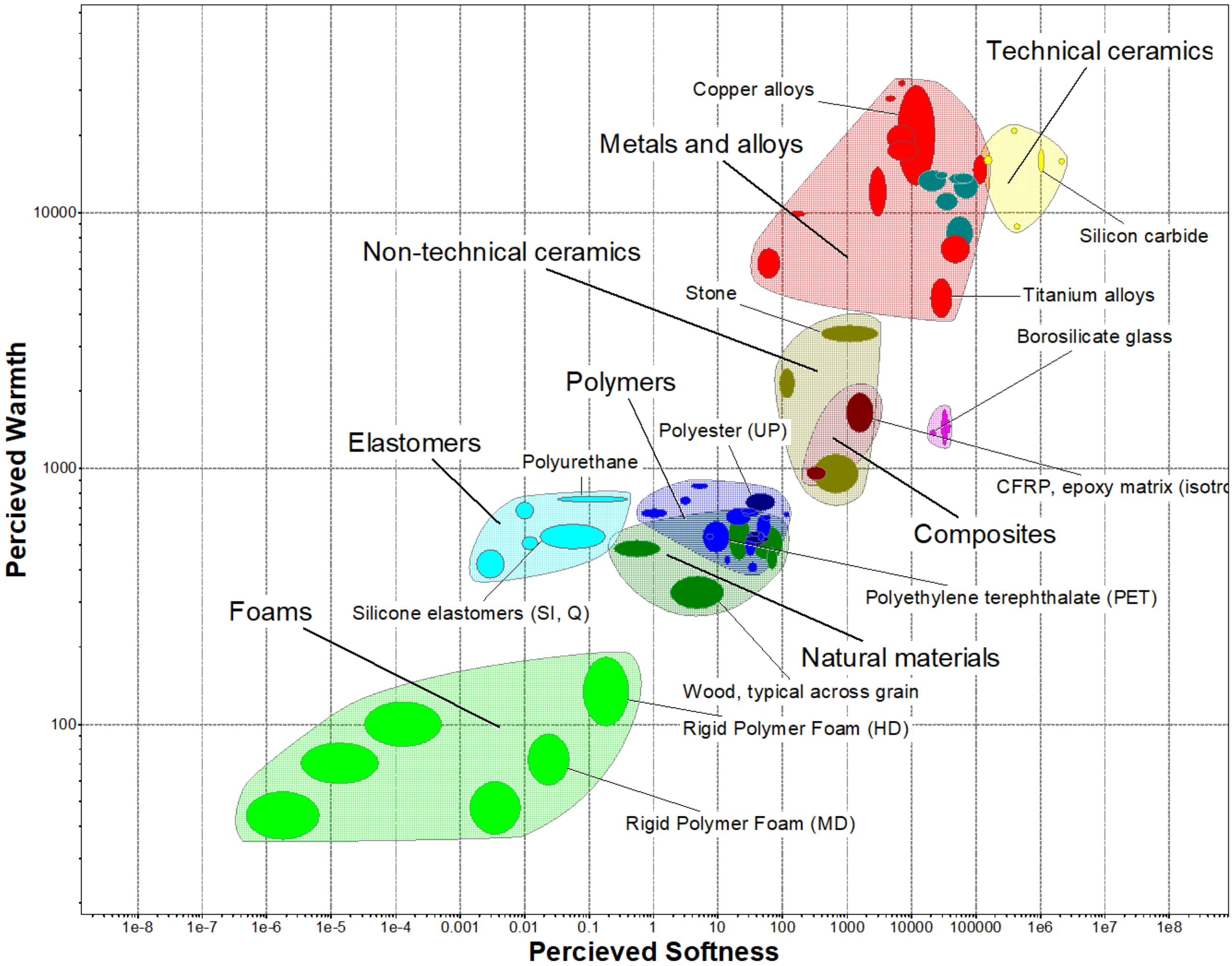


Figure 13 – an Ashby plot of the perceived warmth vs perceived softness of all level 1 materials

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