Knee Pads

Group Name: G-LOZ

Group Members: Yucong Lei, Raj Oak, Ge Zhug

Abstract

In sports and industrial workplaces men and women face different situations which can cause injury to their body. One of the protective devices to reduce the injury is Knee Pads. The purpose of the knee pads is to protect the cartilage meniscus and patella also referred to as kneecap from sudden impact which may be caused while playing sports like volleyball, cricket and others which require you to exert pressure on knees. A knee protection is required in certain sports to reduce injuries, support knee and increase performance [1].

Some of the good professional available pads are available in the range of $66 (Recoil) to $100 (Brads Self-Supporting Knee Pads 5012) and we wish to study if there is an alternative to design such equipment at a lower cost and with improved performance.

Our team is designing protective knee pads for providing comfort and protect against impact shocks experienced during sports, industrial work along with bike and motorbike accidents.

Background

Need this Design Serves

The main need that the design serves is protection against impact shocks that might be caused due to several factors like accident, professional work conditions and sports. Along with this, the design will be made keeping the comfort of the user in mind and assuming that the person has to work for longer hours wearing this knee protection equipment.

Operating Environment

The equipment is designed for professionals working in heavy industrial environment and for sportsmen considering indoor and outdoor activities. The design should be made sufficiently durable to face the harsh wear and tear, chemical contact, abrasion, weather conditions, water resistance and antibacterial. Following table indicates the operating environment for which the equipment would be designed.

Operating Environment	**Range**
Temperature	40F to 150F
Humidity (Relative)	30% to 80%
Water resistance	10,000 mm (Light rain)

Justification of the Overall Objectives

The overall objective of the design is to minimize the cost and minimize the total CO2 production. The cost can be minimized by taking into consideration the price of raw materials and vetting them against the substitute materials without compromising the functional performance. The total CO2 of the process can be minimized by taking into account the embedded energy in each material, higher the embedded energy higher is the total CO2 production associated with that material.

We have chosen to minimize cost as it is fundamental metric for any company and allows the business to keep higher margins if the raw material cost is as low as possible. Also, greenhouse gas generation is a serious issue and designers must consider this aspect while designing different equipment and products.

Overall Design Concept

The overall equipment is designed considering the various forces acting on the system and general wear and tear resulting from regular usage. We divided the knee pads into three main parts: Lace, Protective part and Shock absorber. Each part has its own application.

Protective Cover:
1. Enough stiffness: Sustain large enough impact force invariance。
2. Minimum mass: If the quality is not light enough, it will affect the comfort and athletic performance of the exercise.

Shock Absorber:
1. Impact Absorption: This material should absorb the impact of the shock caused due to accident.
2. Force Distribution: The material should distribute the force equally over the entire area.

Lace:
1. Fix the knee pads: Depending on the user, fixing the knee pads in the right place and secure.
2. Comfortable: If the strap is too tight, it will block blood circulation and interfering with the wearers movements.
3. Green material: Considering that the overall objective of the design is to minimize the cost and minimize the total CO2 production.

Illustration of the design

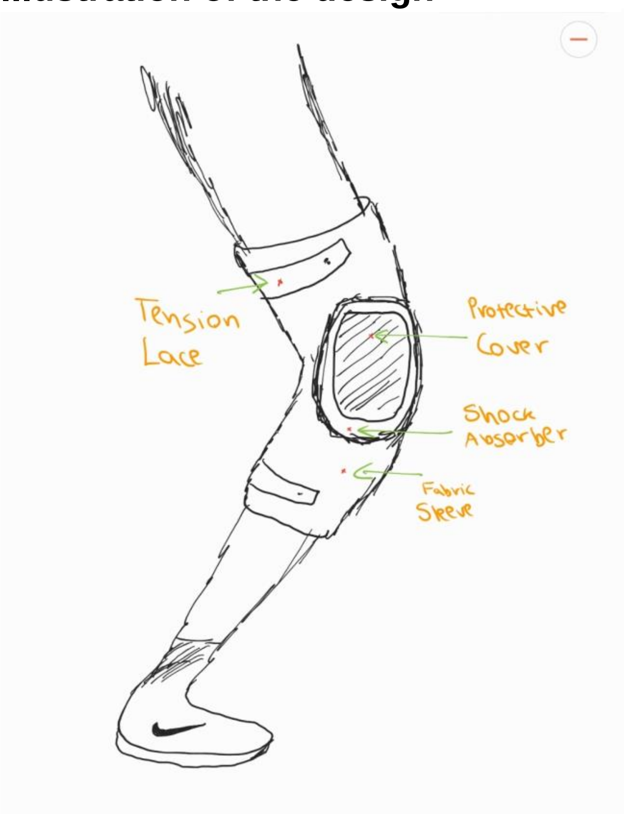


Figure a

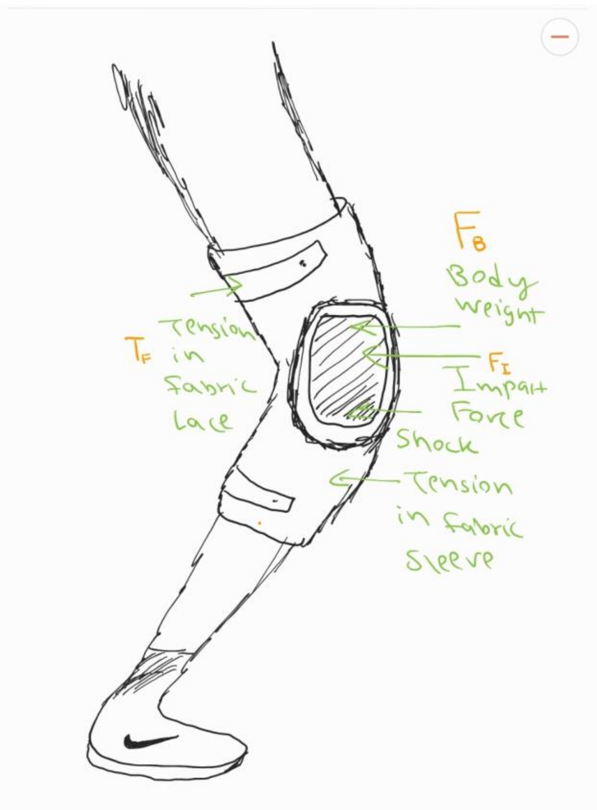


Figure b

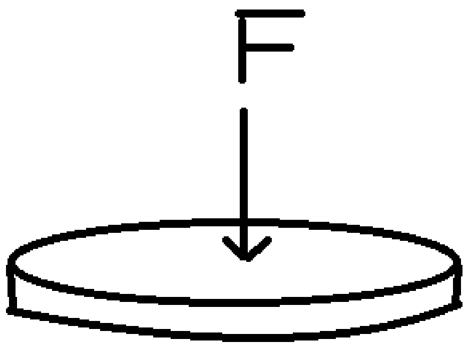
The above figure (a) represents the components visual appearance and labels. Figure (b) indicates various loads that are taken into consideration which are acting on the entire structure. The material for these components would be selected based on all these loads. Further detailed information about the load can be found in individual sections below.

Table of components

Sr. No.	**Component**	**Person Responsible**
1	Protective Cover	Lei
2	Shock Absorber	Raj Oak
3	Lace	Ge Zhu

Component 1 (Protective Cover, Yucong Lei)

Illustration of actual and simplified geometry, loads and constraints
Simplified geometric model with force in the center of the disc.



Constraints and Objectives clearly defined and explained

Function	Circular plate
Constrains	Less than plastic yield strength Radius R specified Load F specified
Objects	Minimized mass Minimized cost
Free variables	Thickness t Choice of material

Design variables listed and quantified

Design variables	
Radius R (cm)	Load F (N)
8	1000

Translation into material indices
For the plastic yield strength
(a) For mass
The mass of the plate is:

$$m = \pi R^2 t \rho$$

We can reduce the mass by reducing the cross-section, but there is a constraint: the section-area must be sufficient to carry the tensile load, requiring that:

$$\frac{F^*}{A} \leq \sigma_y$$

$$A = t \cdot R$$

Eliminating A between these two equations give

$$m \geq (F^*)(\pi R)\left(\frac{\rho}{\sigma_y}\right)$$

Thus, we can define the material index $M_1 = \frac{\sigma_y}{\rho}$

(b) For cost

$$Cost = m * C_m = (F^*)(\pi R)\left(\frac{\rho}{\sigma_y}\right)\boldsymbol{C_m}$$

Thus, we can define the material index $M_2 = \frac{\sigma_y}{\rho \boldsymbol{C_m}}$

For the requirement of the plate

(a) For mass

The mass of the plate is:

$$m = \pi R^2 t \rho$$

Where ρ is the density of material of which the protective part is made.

The deflection δ of the protective plate under impact force F is:

$$\delta = \frac{3}{4\pi}\frac{FR^2}{Et^3}(1 - v^2)(\frac{3+v}{1+v})$$

Inverting this equation for the plate:

$$t = \left(\frac{3FR^2}{4\pi E}\right)^{\frac{1}{3}} f(v)$$

Where f(v) is simply a function of v, thus it is a constant.

And then, combine these two equations:

$$m = \pi R^2 \left(\frac{3FR^2}{4\pi E}\right)^{\frac{1}{3}} (\frac{\rho}{E^{\frac{1}{3}}}) f(v)$$

Thus, we can define the material index $M_3 = \frac{E^{\frac{1}{3}}}{\boldsymbol{\rho}}$

(b)For cost

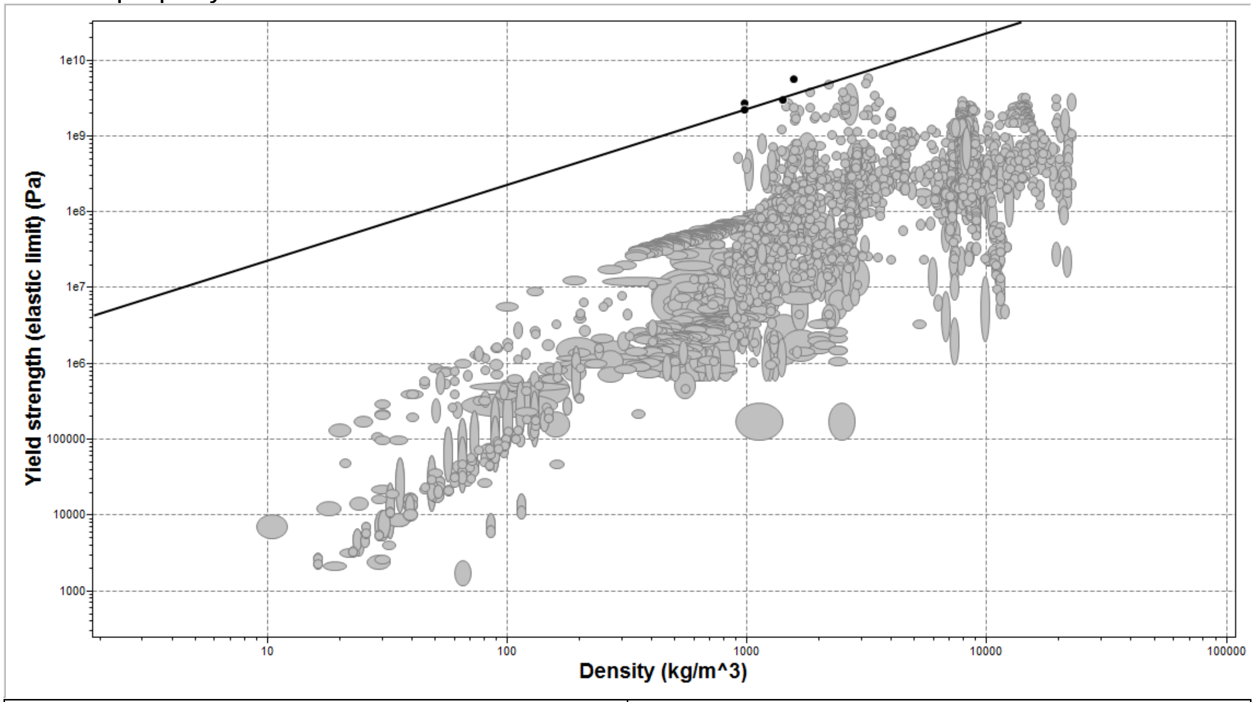
$$Cost = m * C_m = \pi R^2 \left(\frac{3Fa^2}{4\pi E}\right)^{\frac{1}{3}} (\frac{\rho}{E^{\frac{1}{3}}}) f(v)\boldsymbol{C_m}$$

Thus, we can define the material index $M_4 = \frac{E^{\frac{1}{3}}}{\rho \boldsymbol{C_m}}$

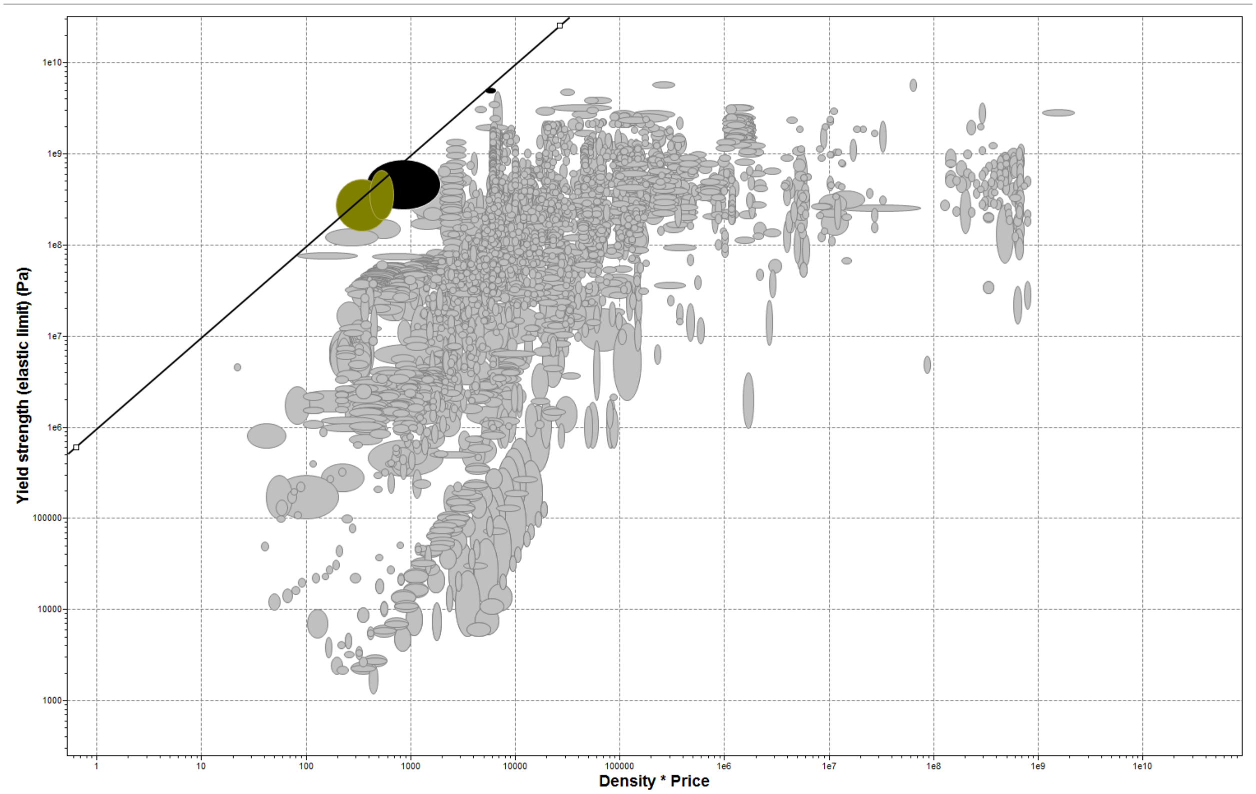
Objectives	Constrains	Performances	Indices
mass	$m = \pi R^2 t \rho$ $\frac{F^*}{A} \le \sigma_y$ $A = t \cdot R$	$m \ge (F^*)(\pi R)\left(\frac{\rho}{\sigma_y}\right)$	$M_1 = \frac{\delta_y}{\rho}$
	$m = \pi R^2 t \rho$ $\delta = \frac{3}{4\pi}\frac{FR^2}{Et^3}(1 - v^2)(\frac{3+v}{1+v})$	$m = \pi R^2 \left(\frac{3FR^2}{4\pi E}\right)^{\frac{1}{3}} (\frac{\rho}{E^{\frac{1}{3}}}) f(v)$	$M_3 = \frac{E^{\frac{1}{3}}}{\rho}$
cost	$m = \pi R^2 t \rho$ $\frac{F^*}{A} \le \sigma_y$ $A = t \cdot R$	$Cost = m * C_m$ $= (F^*)(\pi R)\left(\frac{\rho}{\sigma_y}\right) C_m$	$M_2 = \frac{\delta_y}{\rho C_m}$
	$m = \pi R^2 t \rho$ $\delta = \frac{3}{4\pi}\frac{FR^2}{Et^3}(1 - v^2)(\frac{3+v}{1+v})$	$Cost = m * C_m$ $= \pi R^2 \left(\frac{3FR^2}{4\pi E}\right)^{\frac{1}{3}} (\frac{\rho}{E^{\frac{1}{3}}}) f(v) C_m$	$M_4 = \frac{E^{\frac{1}{3}}}{\rho C_m}$

Candidate Materials List

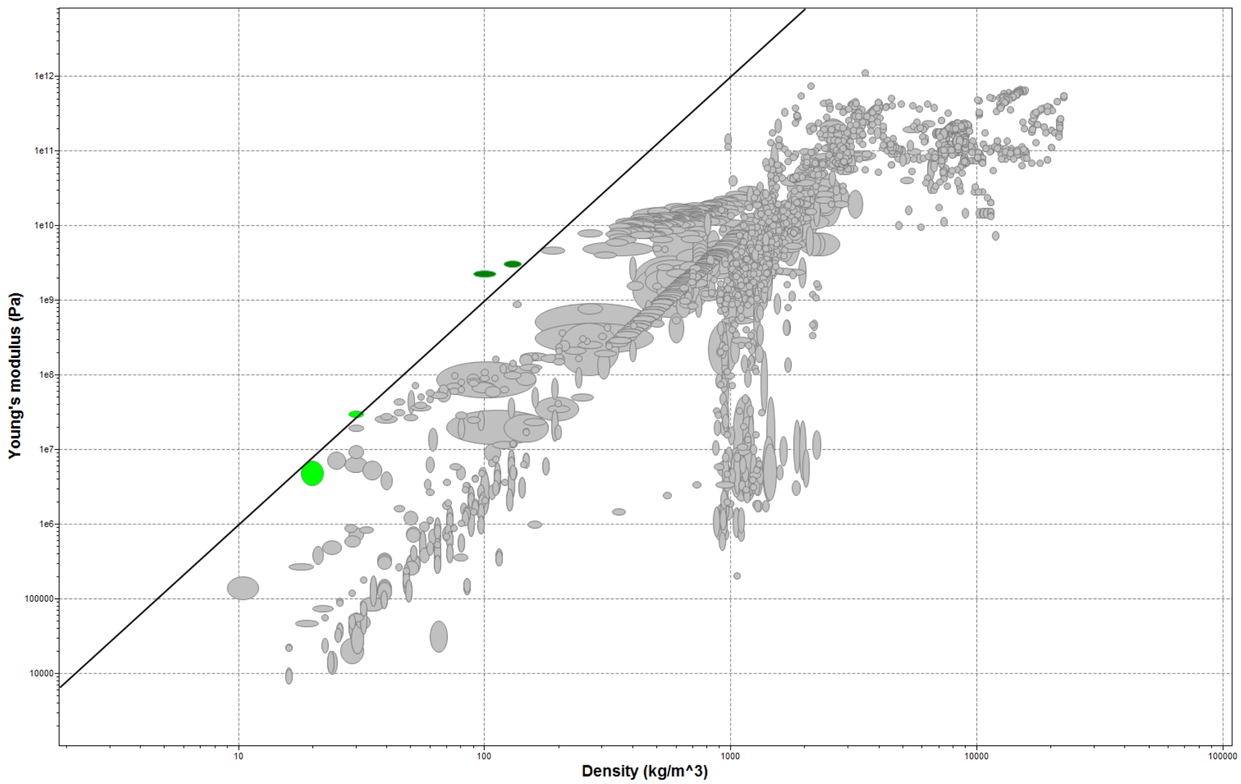
Material property charts with selection lines



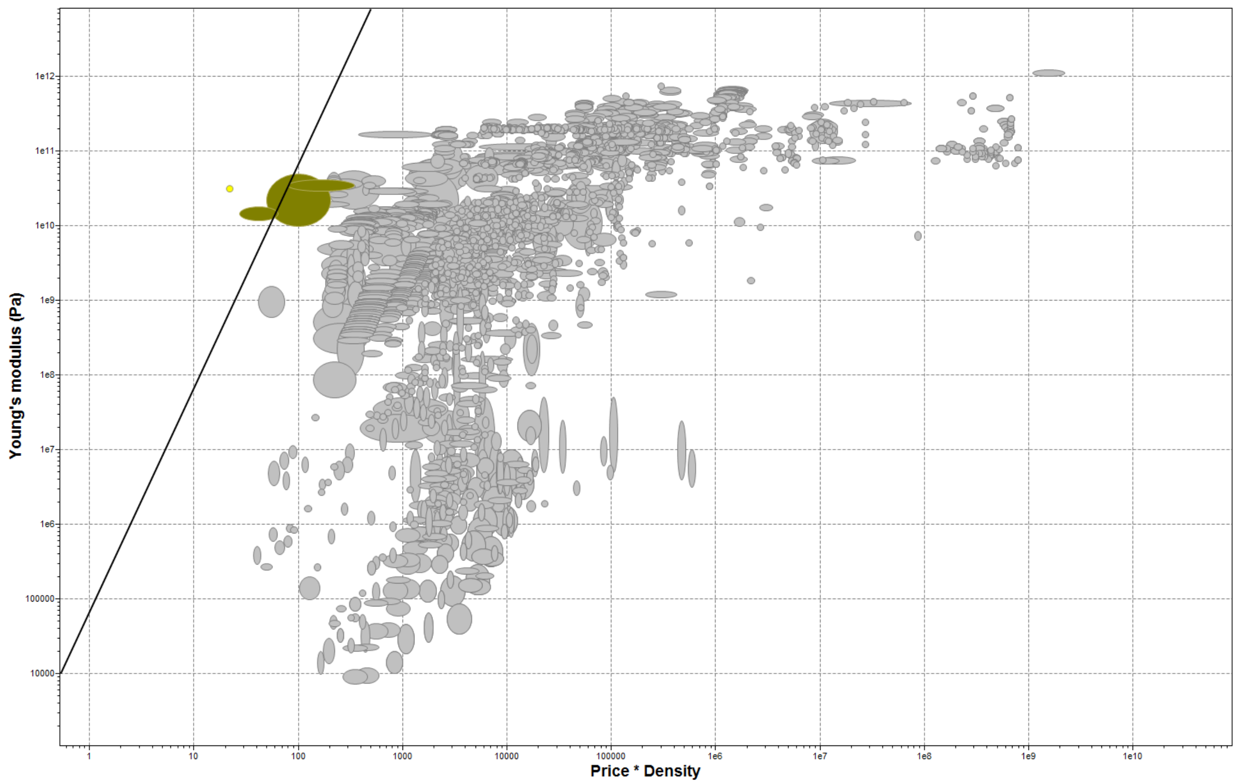
Material	Family
PBO fiber (Zylon)	Plastic (thermoset)
Polyarylate fiber (Vectran)	Plastic (thermoplastic, semi-crystalline)
Spectra 1000 polyethylene fiber	Plastic (thermoplastic, semi-crystalline)
Spectra 900 polyethylene fiber	Plastic (thermoplastic, semi-crystalline)



Material	Family
Asbestos (tremolite)	Ceramic (non-technical)
Jute fiber	Natural
Kenaf fiber	Natural
Mica (p)	Natural



Material	Family
Balsa (ochroma spp.) (0.09-0.11) (l)	Natural
Balsa (ochroma spp.) (0.12-0.14) (l)	Natural
Expanded PS foam (closed cell, 0.020)	Plastic (thermoplastic, amorphous)
PVC cross-linked foam (rigid, closed cell, DH 0.030)	Plastic (thermoplastic, amorphous)



Material	Family
Aerated concrete	Ceramic (non-technical)
Asphalt concrete	Ceramic (non-technical)
Halite (NaCl)	Ceramic (technical)
High volume fly ash concrete	Ceramic (non-technical)

Active Constraint Identification

					Free Variable					
Material	Density (kg/m^3)	Price (USD/kg)	Young's modulus (Gpa)	Yield strengh (Gpa)	T1	T2	Mass(M1)	Cost(M2)	Mass(M3)	Cost(M4)
PBO fiber (Zylon)	1560	**211**	**210000**	**5800**	0.002155	2.426448	0.067564	0.014256	76.06857	16.05047
Polyarylate fiber (Vectran)	1400	43.5	65000	3200	0.003906	7.839294	0.1099	0.004781	220.5538	9.594092
Spectra 1000 polyethylene fiber	975	143	170000	3000	0.004167	2.997377	0.08164	0.011675	58.72941	8.398306
Spectra 900 polyethylene fiber	975	143	120000	2500	0.005	4.246285	0.097968	0.014009	83.2	11.8976
Asbestos (tremolite)	3160	2.07	175000	5250	0.002381	2.911738	0.151198	0.000313	184.9051	0.382754
Jute fiber	1520	0.4	55000	530	0.023585	9.264621	0.720423	0.000288	282.9964	0.113199
Kenaf fiber	1050	0.659	47000	666	0.018769	10.84158	0.396036	0.000261	228.766	0.150757
Mica (p)	**3200**	0.651	175000	860	0.014535	2.911738	0.934698	0.000608	187.2457	0.121897
Balsa (ochroma spp.) (0.09-0.11) (l)	110	10.8	2500	6.3	1.984127	203.8217	4.386032	0.047369	450.56	4.866048
Balsa (ochroma spp.) (0.12-0.14) (l)	140	10.8	3400	10	1.25	149.8689	3.5168	0.037981	421.6471	4.553788
Expanded PS foam (closed cell, 0.020)	22	3.06	7	0.16	78.125	72793.45	34.54	0.105692	32182.86	98.47954
PVC cross-linked foam (rigid, closed cell, DH 0.030)	32	16.9	32	0.32	39.0625	15923.57	25.12	0.424528	10240	173.056
Aerated concrete	900	0.08	18000	1.1	11.36364	28.30856	205.5273	0.016442	512	0.04096
Asphalt concrete	2800	0.08	50000	0.3	41.66667	10.19108	2344.533	0.187563	573.44	0.045875
Halite (NaCl)	2210	0.01	32800	5	2.5	15.53519	111.0304	0.00111	689.9512	0.0069
High volume fly ash concrete	2200	0.17	41000	2.5	5	12.42815	221.056	0.03758	549.4634	0.093409

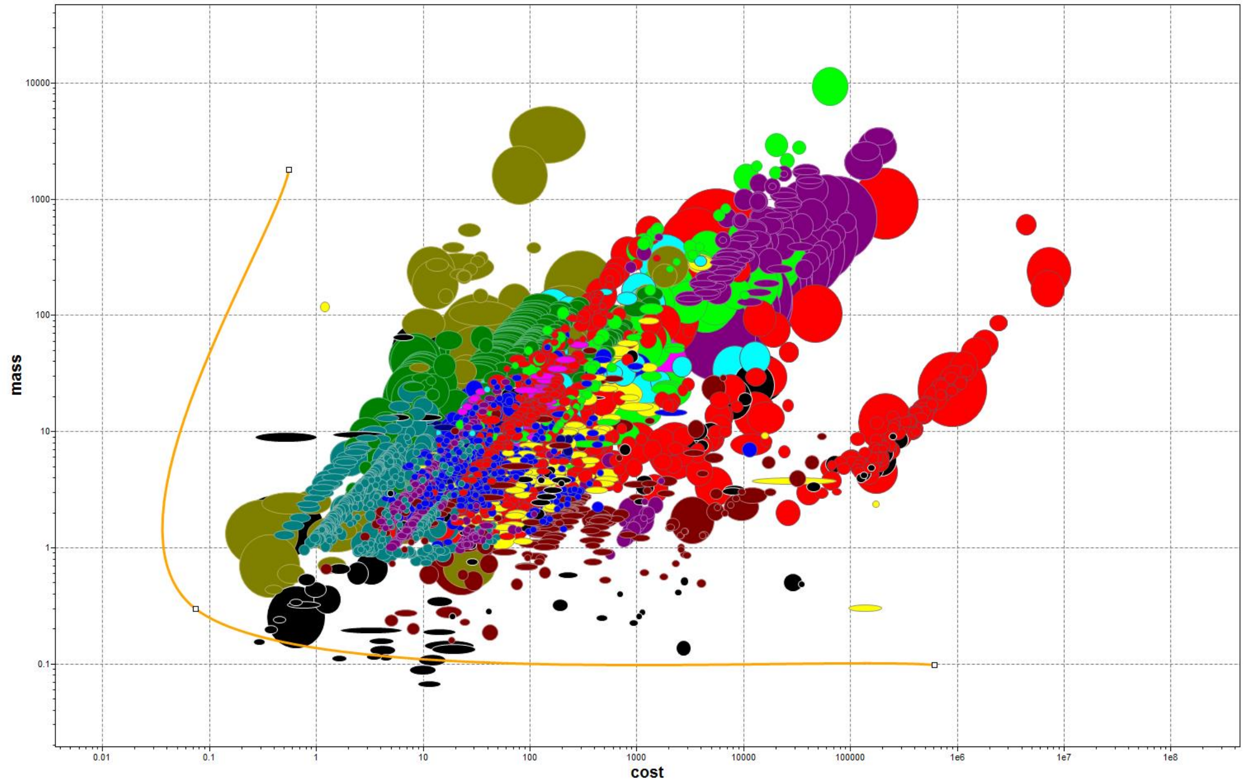
Ranking
Sort candidate materials, best to worst, for each objective

Material	rank(M1)	rank(M2)	rank(M3)	rank(M4)
PBO fiber (Zylon)	1	9	2	14
Polyarylate fiber (Vectran)	4	6	6	12
Spectra 1000 polyethylene fiber	2	7	1	11
Spectra 900 polyethylene fiber	3	8	3	13
Asbestos (tremolite)	5	3	4	8
Jute fiber	7	2	8	5
Kenaf fiber	6	1	7	7
Mica (p)	8	4	5	6
Balsa (ochroma spp.) (0.09-0.11) (l)	10	13	10	10
Balsa (ochroma spp.) (0.12-0.14) (l)	9	12	9	9
Expanded PS foam (closed cell, 0.020)	12	14	16	15
PVC cross-linked foam (rigid, closed cell, DH 0.030)	11	16	15	16
Aerated concrete	14	10	11	2
Asphalt concrete	16	15	13	3
Halite (NaCl)	13	5	14	1
High volume fly ash concrete	15	11	12	4

Identify strong, intermediate, and weak materials across all objectives

Strong material	Intermediate material	Weak material
PBO fiber (Zylon)	Asbestos (tremolite)	Asphalt concrete
Spectra 1000 polyethylene fiber	Polyarylate fiber (Vectran)	High volume fly ash concrete
Spectra 900 polyethylene fiber	Kenaf fiber	Aerated concrete

Trade-off Plots



Documentation

Considering the comfort and flexibility of wearing knee pads, the thickness of the protective part should not exceed 10mm. We have the following materials to choose from:

Material	T1	T2
PBO fiber (Zylon)	0.002155	2.426448
Polyarylate fiber (Vectran)	0.003906	7.839294
Spectra 1000 polyethylene fiber	0.004167	2.997377
Spectra 900 polyethylene fiber	0.005	4.246285
Asbestos (tremolite)	0.002381	2.911738
Jute fiber	0.023585	9.264621
Mica (p)	0.014535	2.911738

Then consider the price factor. Under the condition that the intensity requirements are met, the lower the cost, the better the economic benefits. According to the rank of the cost, Jute fiber and Asbestos (tremolite) will be the best choice.

Discussion of final materials selections

Jute is a long, soft, shiny vegetable fiber made from plates in the genus Corchorus, family Malvaceae. Jute is one of the cheapest natural fibers and is second only to cotton in amount produced and variety of uses. It can be spun into coarse, strong threads. It is a strong, durable, colored and lightfast fiber. Its UV protection, sound insulation and thermal insulation, low thermal conductivity and antistatic properties make it a good choice. Moreover, fabrics made from jute fibers are carbon dioxide neutral and naturally decomposable.

Component 2 (Shock Absorber, Raj Oak)

Illustration of actual and simplified geometry, loads and constraints

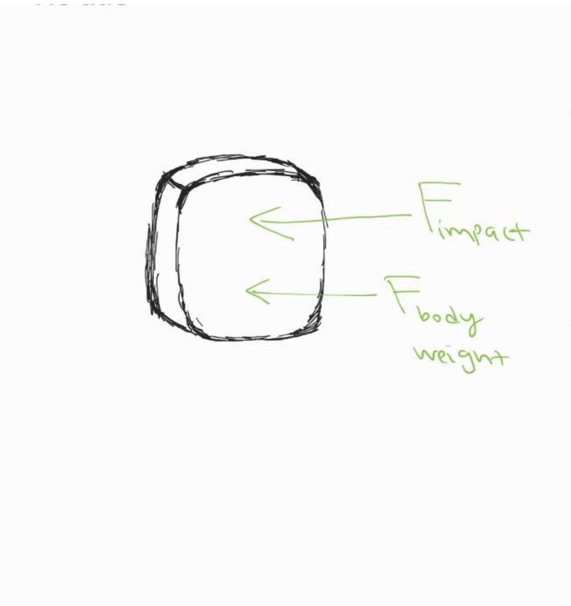


Figure 2.1

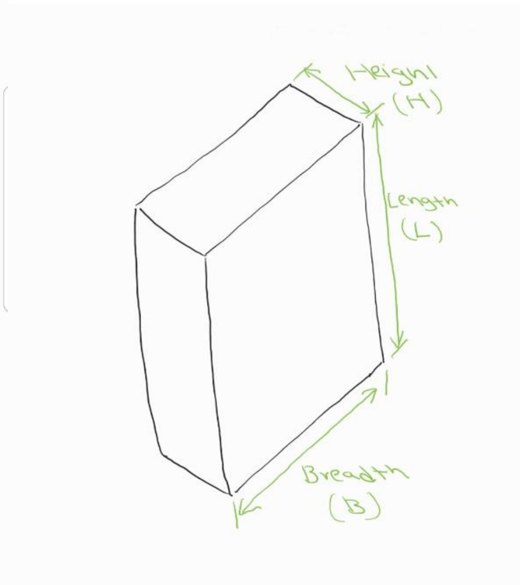


Figure 2.2

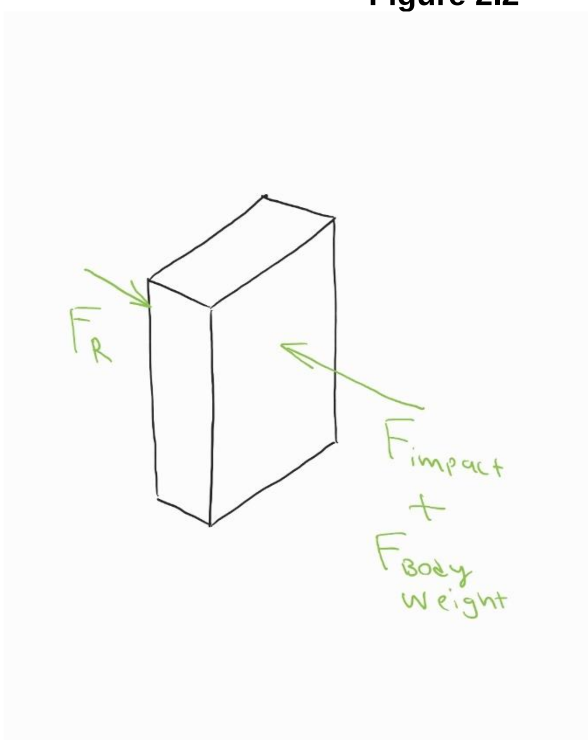


Figure 2.3

Figure 2.1 depicts the visual representation of actual component, figure 2.2 illustrates the geometry of the component in a simplified format. Figure 2.3 shows the free body diagram with the reactive force component. This reactive force component is generated due to reaction from the knee joint in response to the force generated due to the body weight while leaning on knee pads or the impact force caused due to knee pad hit with a hard surface.

Constraints and Objectives clearly defined and explained

Objectives	**Description**
Obj 1	Minimize the mass of the design
Obj 2	Minimize the cost of the design

Constraints	**Description**
Const 1	Should not fail under load (Stiffness equation)
Const 2	Should not fracture under load (Fracture equation)

Design variables listed and quantified

Sr. No.	**Design Variable**	**Quantification (Metric units)**
1	Length of the pad	0.1 m
2	Breadth of the pad	0.1 m
3	Design Load Limit	2.7 kN
4	Assumed crack length	0.001m
5	Value of constant C1 (Fracture, Compression)	15
6	Stiffness design constraint	250 kN/m

Translation into material indices

(a) Defining the objective equation

m = (volume) x (density) = L x B x H x ρ

Here m is mass, L is length, B is breadth, H is height and ρ is density of the material

(b) Basic constraint equation

Considering bending stiffness equation

S = $\frac{C1\,E\,I}{L^3} \geq S^*$

(c) The moment of inertia = I = $\frac{bh^3}{12}$

S = $\frac{C1\,E\,b}{12}\left(\frac{h}{L}\right)^3$

(d) This can be used in equation (a)

M = bL^2 x $\left(\frac{12S}{C1b}\right)^{0.33}$ x $\frac{\rho}{E^{\frac{1}{3}}}$

(e) Partitioning the equation

Here a = $\left(\frac{12S}{C1b}\right)^{0.33}$ = functional design specifications

And b = bL^2 = geometric design specification

And c = $\frac{\rho}{E^{\frac{1}{3}}}$ = material index

If we consider minimizing the cost, the equation can be written as-

M = bL^2 x $\left(\frac{12S}{C1b}\right)^{0.33}$ x $\frac{C_m\rho}{E^{\frac{1}{3}}}$

Here $C_m = \text{Cost per unit mass}$

Considering the second constraint equation for fracture toughness [4], which is given as follows:

$$K_{1C} = \sigma\sqrt{\pi C}$$

Here K1C is the fracture toughness and C is the length of the defect or crack in the material.

For a cuboidal section:

$$\sigma = \frac{M.Y}{I}$$

Where I is moment of inertial and M is bending moment and Y is upward distance from the neutral axis.

Equation for I is given as follows:

$$I = \frac{bh^3}{12}$$

Substituting these values we can derive the equation for free variable (h)

$$h = \left(\frac{3.F.L}{K_{1C}.b}\right)^{0.5}.(\pi.C)^{0.25}$$

Substituting this equation with equation (a) we get:

$$m = (L^3.b)^{0.5}.(3.F'.(\pi.C)^{0.5})^{0.5}.\left(\frac{\rho}{\sqrt{K_{1C}}}\right)$$

The same equation for price can be written as

$$m = (L^3.b)^{0.5}.(3.F'.(\pi.C)^{0.5})^{0.5}.\left(\frac{C_m\rho}{\sqrt{K_{1C}}}\right)$$

Here C_m is the cost per kg of the specific material.

Objective equations

Objective 1- Minimize Mass (m) in Kg

m = L . b. h. p (p = density)

Objective 2 – Minimize Cost ($)

Cost ($) = L . b. h. p . C_m (C_m is cost/kg of the material)

Constraint equations

Constraint 1 – Not fail under load (Stiffness criteria)

$$S' = \frac{C_1 . E . I}{L^3}$$

Constraint 2- Not fracture (Fracture criteria)

$$K_{1C} = \sigma' . \sqrt{\pi . C}$$

Free variable

We have constrained the length(L) and the breadth(b) of the shock absorbing pad but the height is the free variable which depends upon the selection of material.

Free variable = h (in m.)

Performance equation

$$m = (L^3 . b)^{0.5} . (3 . F' . (\pi . C)^{0.5})^{0.5} . \left(\frac{\rho}{\sqrt{K_{1C}}} \right)$$

$$m = (L^3 . b)^{0.5} . (3 . F' . (\pi . C)^{0.5})^{0.5} . \left(\frac{C_m \rho}{\sqrt{K_{1C}}} \right)$$

$$\mathrm{M} = \mathrm{b} L^2 \times \left(\frac{12S}{C1b} \right)^{0.33} \times \frac{\rho}{E^{\frac{1}{3}}}$$

$$\mathrm{M} = \mathrm{b} L^2 \times \left(\frac{12S}{C1b} \right)^{0.33} \times \frac{C_m \rho}{E^{\frac{1}{3}}}$$

Material indices

Minimize:

$$M1 = \frac{E^{\frac{1}{3}}}{\rho}$$

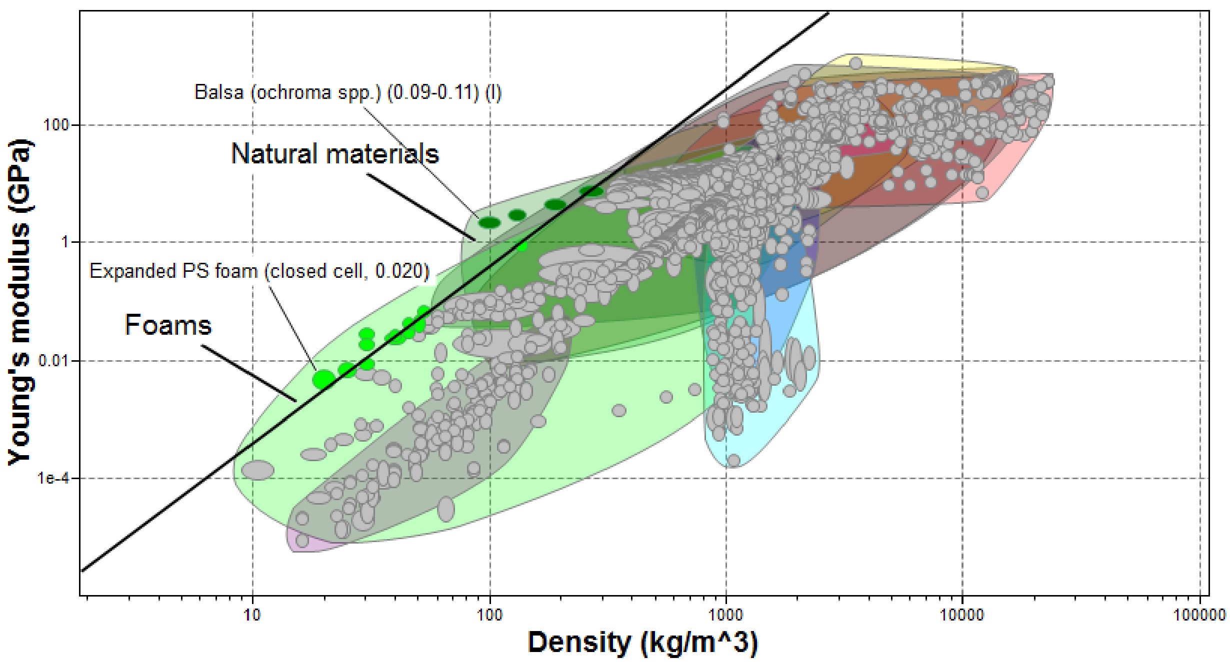
$$M2 = \frac{\sqrt{K_{1C}}}{\rho}$$

$$M3 = \frac{E^{\frac{1}{3}}}{C_m.\rho}$$

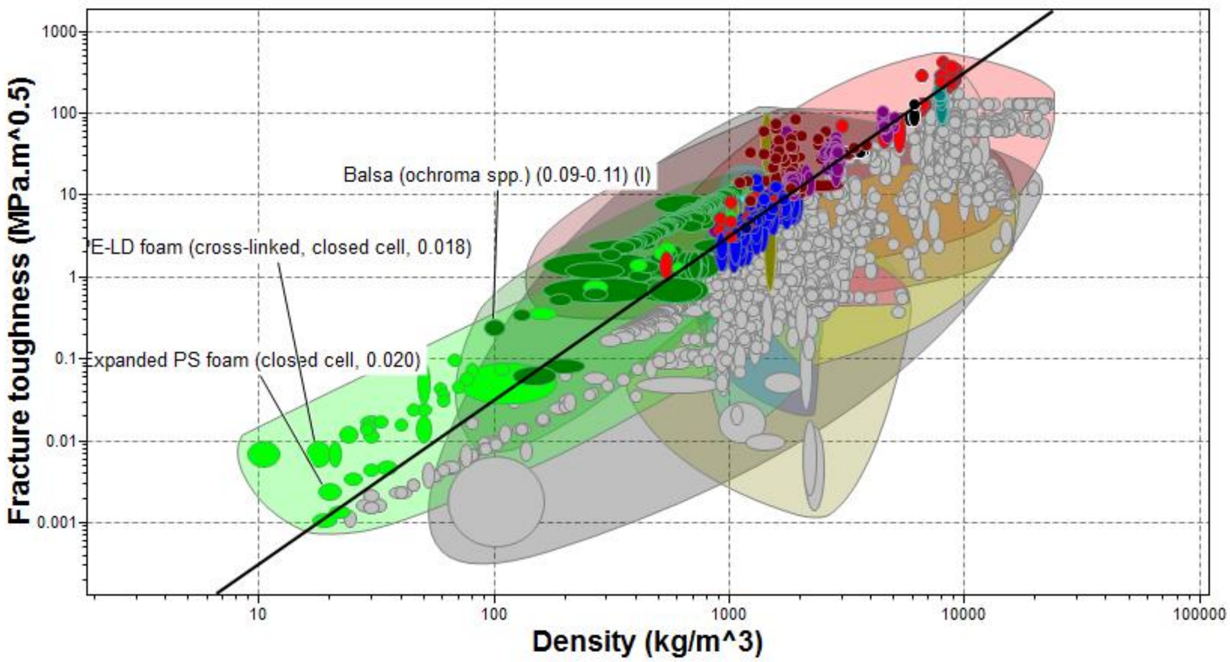
$$M4 = \frac{\sqrt{K_{1C}}}{C_m\rho}$$

Candidate material list

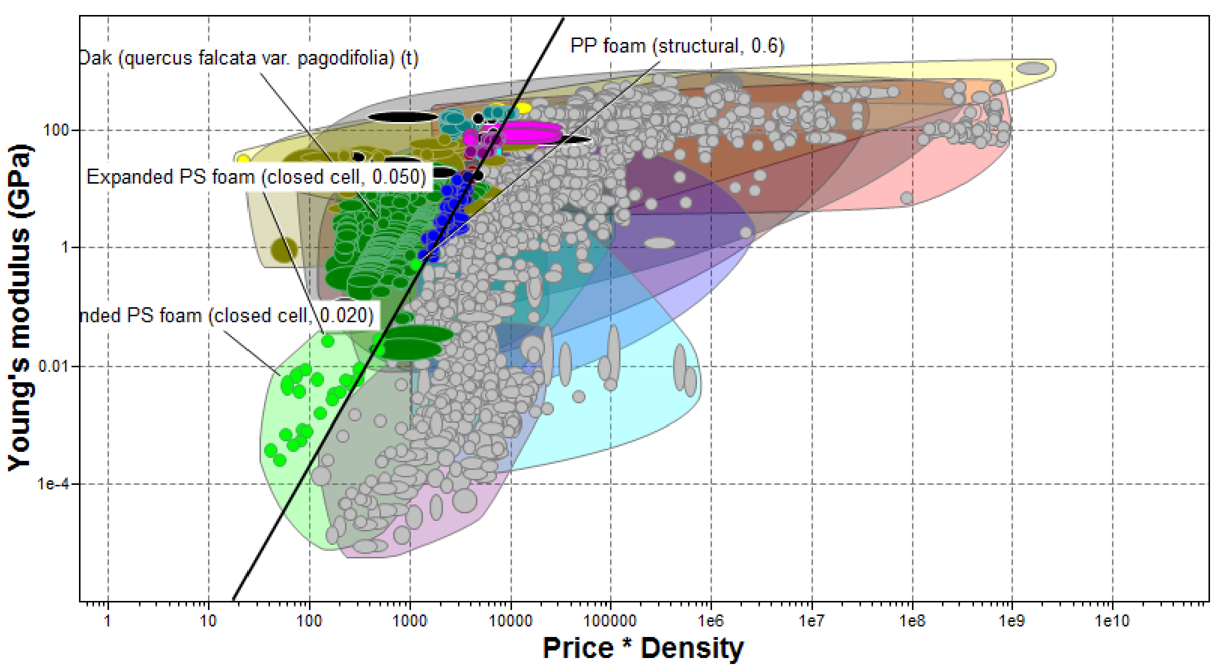
Material property charts with selection lines
M1



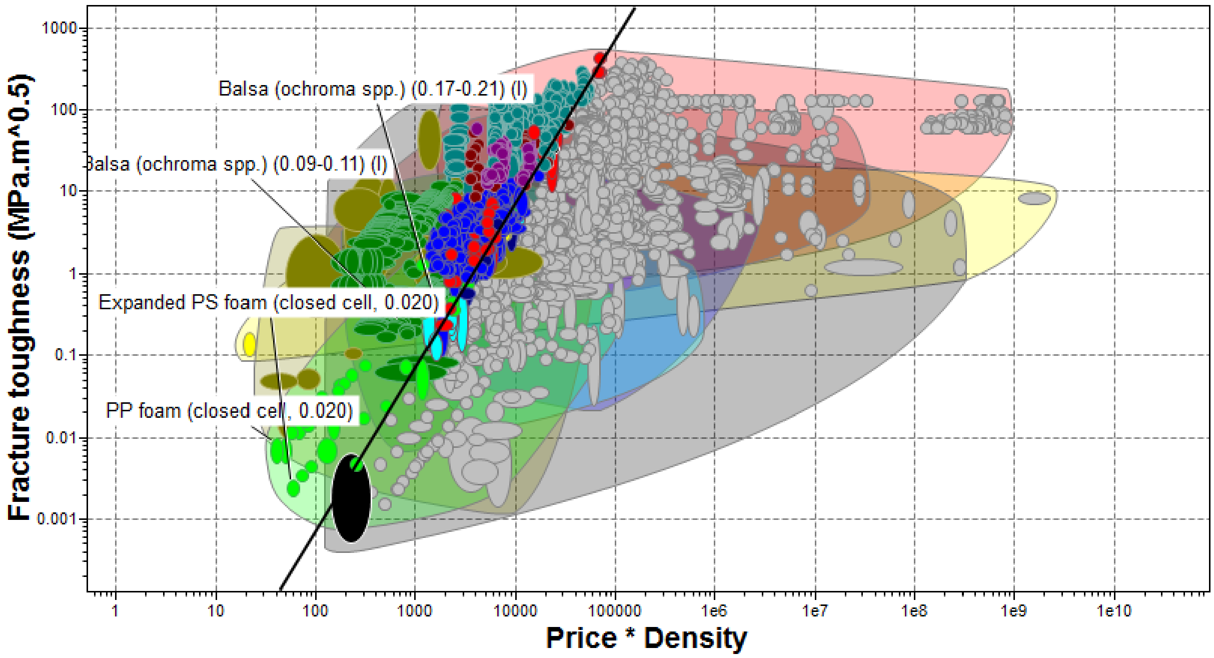
M2


Balsa (ochroma spp.) (0.09-0.11) (l)
E-LD foam (cross-linked, closed cell, 0.018)
Expanded PS foam (closed cell, 0.020)
1000
100
10
1
0.1
0.01
0.001
Fracture toughness (MPa.m^0.5)
10
100
1000
10000
100000
Density (kg/m^3)

M3


Oak (quercus falcata var. pagodifolia) (t)
PP foam (structural, 0.6)
Expanded PS foam (closed cell, 0.050)
nded PS foam (closed cell, 0.020)
100
1
0.01
1e-4
Young's modulus (GPa)
1
10
100
1000
10000
100000
1e6
1e7
1e8
1e9
1e10
Price * Density

M4



List of materials with material family identified

Sr. No.	Material	Objective Related Property		Constraint Relative Property	
		Density (kg/m^3)	Cost/kg	E (GPA)	K_{1C} (Mpa * $m^{0.5}$)
1	Expanded PS foam	18	2.78	0.007	0.003
2	PP foam	38	2	0.004	0.016
3	Insulation board	150	1.21	0.9	1
4	PE-LD foam	17	2.5	0.0003	0.001
5	Fir (abies concolor)	400	1.34	11	1.4
6	Pine (pinus sylvestris)	520	1.2	12.2	4.2
7	Mohogany (Khaya spp.)	540	3.3	10.4	4.1
8	Hemlock (tsuga hetrophylla)	510	1.34	11.1	3.5
9	Sande (I)	630	2.01	17	5.1
10	Balsa (ochroma spp.)(0.09-0.11)(I)	80	6.7	2.5	0.3

Different material families that satisfy the constraints are the natural materials and foams.

Mass calculation for each materials.

Sr. No.	Material	Mass from M1	Mass from M2
1	Expanded PS foam	0.54	1.51
2	PP foam	1.37	1.38
3	Insulation board	0.89	0.69
4	PE-LD foam	1.46	2.47
5	Fir (abies concolor)	1.03	1.55
6	Pine (pinus sylvestris)	1.3	1.2
7	Mohogany (Khaya spp.)	1.422	1.3
8	Hemlock (tsuga hetrophylla)	1.303	1.34
9	Sande (l)	1.4	1.42
10	Balsa (ochroma spp.)(0.09-0.11)(l)	0.33	0.67

Cost calculation for selected materials.

Sr. No.	Material	Cost from M3 ($)	Cost from M4 ($)
1	Expanded PS foam	1.501	4.2
2	PP foam	2.74	2.76
3	Insulation board	1.076	0.83
4	PE-LD foam	3.65	6.15
5	Fir (abies concolor)	1.38	2.07
6	Pine (pinus sylvestris)	1.36	1.44
7	Mohogany (Khaya spp.)	4.69	4.29
8	Hemlock (tsuga hetrophylla)	1.75	1.8
9	Sande (I)	2.81	2.854
10	Balsa (ochroma spp.)(0.09-0.11)(I)	2.21	4.5

Active Constraint identification

Free variable values

Sr. No.	Material	Height from M1	Height from M2
1	Expanded PS foam	0.0432	0.052
2	PP foam	0.035	0.047
3	Insulation board	0.023	0.0433
4	PE-LD foam	0.056	0.089
5	Fir (abies concolor)	0.012	0.037
6	Pine (pinus sylvestris)	0.009	0.023
7	Mohogany (Khaya spp.)	0.0067	0.018

8	Hemlock (tsuga hetrophylla)	0.0084	0.013
9	Sande (I)	0.004	0.0056
10	Balsa (ochroma spp.)(0.09-0.11)(I)	0.031	0.0421

From the above table it can be noted that mass from M2 (fracture)material index is more than the mass of the design obtained from M1 (stiffness) material index and hence fracture constraint is the dominant one. Also, the cost of the product from M4 (fracture) is more than the cost obtained from the M3 (stiffness) material index and hence cost obtained from M4 is an active constraint.

Hence, for subsequent steps material constraint M1 and M3 can be dropped since the satisfaction of M2 and M4 respectively will satisfy the basic conditions needed for M1 and M3. This also makes the entire process clear and simple to understand.

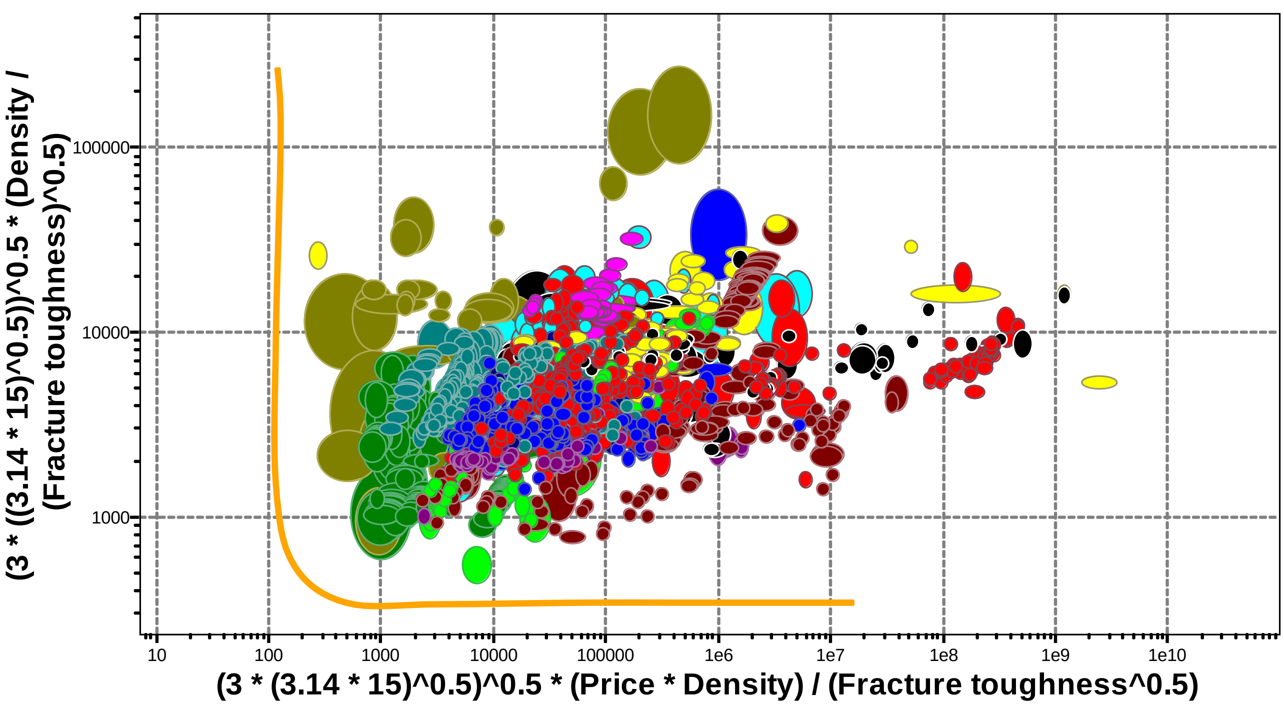
Ranking

Sorting candidate materials, best to worst, for each objective

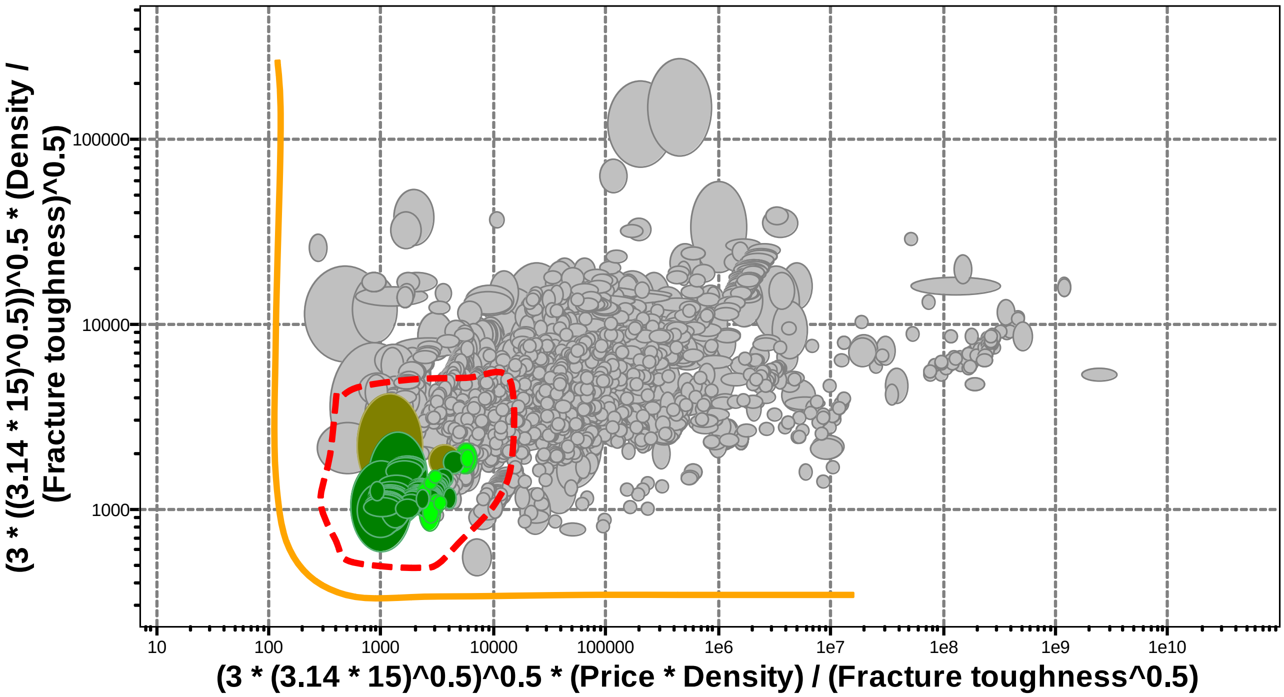
Material	**Rank for Minimum Mass**	**Rank for Minimum Cost**
Expanded PS foam	8	7
PP foam	6	5
Insulation board	2	1
PE-LD foam	10	10
Fir (abies concolor)	9	4
Pine (pinus sylvestris)	3	2
Mohogany (Khaya spp.)	4	8
Hemlock (tsuga hetrophylla)	5	3
Sande (I)	7	6
Balsa (ochroma spp.)(0.09-0.11)(I)	1	9

Rank	Minimum Mass	Minimum Cost
1	Balsa (ochroma spp.)(0.09-0.11)(l)	Insulation board
2	Insulation board	Pine (pinus sylvestris)
3	Pine (pinus sylvestris)	Hemlock (tsuga hetrophylla)
4	Mohogany (Khaya spp.)	Fir (abies concolor)
5	Hemlock (tsuga hetrophylla)	PP foam
6	PP foam	Sande (l)
7	Sande (l)	Expanded PS foam
8	Expanded PS foam	Mohogany (Khaya spp.)
9	Fir (abies concolor)	Balsa (ochroma spp.)(0.09-0.11)(l)
10	PE-LD foam	PE-LD foam

ii. Identify strong, intermediate, and weak materials across all objectives
Trade off plots



Plot showing all the 4 charts superimposed in CES software.



Strong Materials	Intermediate Materials	Weak Materials
Sande	Insulation Board	Expanded PS foam
Hemlock	Fir	PE-LD foam
Mohogany	Balsa (ochroma spp.)	PP foam
Pine		

Documentation

Material Preference	Material	Required Thickness (in m)	$Cost/kg
1	Insulation Board	0.043	1.21
2	Balsa	0.0421	6.7
3	PP foam	0.047	2
4	Expanded PS foam	0.052	2.78

This is a list of materials that are categorized based on their strength and ranking obtained in earlier comparisons. Some of the hard and soft woods discussed earlier are eliminated as they may not prove to be best shock absorbing materials and due to high value of their density can increase the weigh of the overall design which is not tolerable.

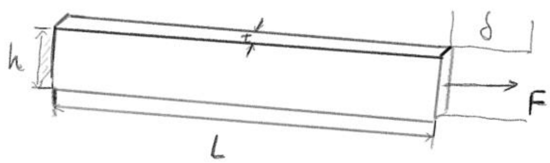
Discussion of final material selection

It has been found that those material which are best in terms of performance are often times costlier than the one's that have poor performance, making the right trade off creates a win-win situation. From the trade off plot shown above along with the chart showing the strong, intermediate and weak materials, it is found that most desirable properties are shown by the intermediate materials.

Surprisingly some of these materials like Insulation Board score high ranks in strength and cost but some other materials like Balsa Wood ranked first for performance is listed last for the price. Here we would like to make two selections and would recommend the designing team to consider a cheaper yet effective solution for using **Insulation Board** as a vibration damping material and for higher cost premium product the team can make use of **Balsa Wood**.

Component **3** (**Lace, Ge Zhu**):

a. Illustration of actual and simplified geometry, loads and constraints



b. Constraints and Objectives clearly defined and explained

Function	**abric Sleeve**
Constraints	• **Less than the yield strength** • **Stretched less than specified mm** • **Width b specified** • **Load F specified**
Objectives	• **Minimize mass** • **Minimize cost**
Free variables	• **Thickness t** • **Choice of Material**

c. Design variables listed and quantified

Design Variables		
F(N)	**L(mm)**	**H(mm)**
500	**500**	**10**

d. Translation into material indices

1.Consider about does not break

a). For Mass

Assuming the left view of the fabric sleeve is a rectangular with thickness t and height h.

$$m = \rho L h t$$

We can reduce the mass by reducing the cross-section, but there is a constraint: the section-area must be sufficient to carry the tensile load, requiring that:

$$\frac{F^*}{A} \leq \sigma_f$$
$$A = t \cdot h$$

Where σ_f is the failure strength.

Eliminating A between these two equations give

$$m \geq (F^*)(L)\left(\frac{\rho}{\sigma_f}\right)$$

Thus, we can define the material index $M_1 = (\frac{\sigma_f}{\rho})$

b). For Cost

$$Cost = m * C_m = (F^*)(L)(\frac{\rho}{\sigma_f})C_m$$

Thus, we can define the material index $M_2 = (\frac{\sigma_f}{\rho C_m})$

2. Consider about Stretched less than specified cm

a). For Mass

Assuming the left view of the fabric sleeve is a rectangular with thickness t and height h.

$$m = \rho Lht$$

And the equation of strain is

$$\varepsilon = \frac{\sigma}{E}$$

Where $\varepsilon = \frac{L-L_0}{L_0}$, and σ is also the failure strength

Thus, $\frac{l-l_0}{l_0} = \frac{\sigma_f}{E}$. Combine this with the equation of mass is

$$m = \rho hL(t_0)\left(\frac{\sigma_f}{E}\right) + t_0$$

Thus, we can define the material index $M_3 = (\frac{\sigma_f}{E})$

b.) For Cost

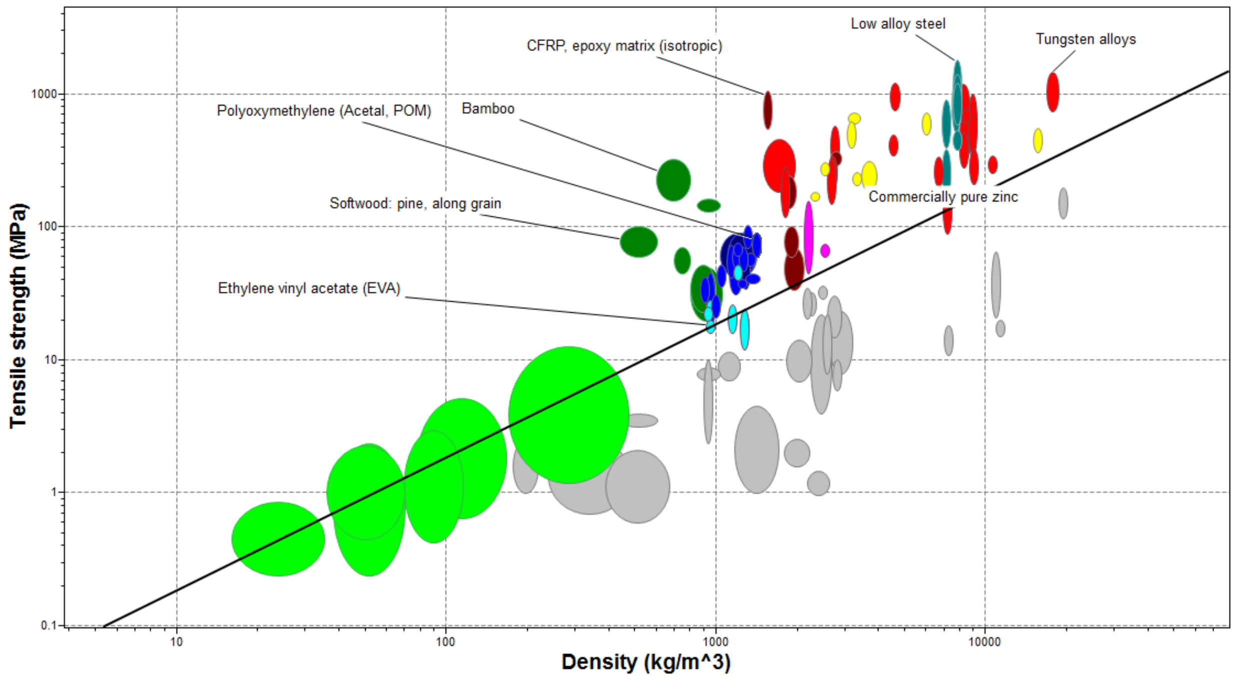
$$Cost = m * C_m = \rho hL[(t_0)\left(\frac{\sigma_f}{E}\right) + t_0)]C_m$$

Thus, we can define the material index $M_4 = (\frac{\sigma_f}{EC_m})$

Objectives	Constraints	Performances	Indices
$m = \rho Lbt$	$\frac{F^*}{A} \leq \sigma_f$ $A = t \cdot h$	$m \geq (F^*)(L)\left(\frac{\rho}{\sigma_f}\right)$	$M_1 = (\frac{\sigma_f}{\rho})$
	$\varepsilon = \frac{\sigma}{E}$ $\varepsilon = \frac{t - t_0}{t_0}$	$m = \rho hL(t_0)\left(\frac{\sigma_f}{E}\right) + t_0$	$M_3 = \left(\frac{\sigma_f}{E}\right)$
$cost = mC_m$	$\frac{F^*}{A} \leq \sigma_f$ $A = t \cdot h$	$Cost = m * C_m = (F^*)(L)(\frac{\rho}{\sigma_f})C_m$	$M_2 = (\frac{\sigma_f}{\rho C_m})$
	$\varepsilon = \frac{\sigma}{E}$ $\varepsilon = \frac{t - t_0}{t_0}$	$Cost = m * C_m = (\rho ht(t_0)\left(\frac{\sigma_f}{E}\right) + t_0)C_m$	$M_4 = (\frac{\sigma_f}{EC_m})$

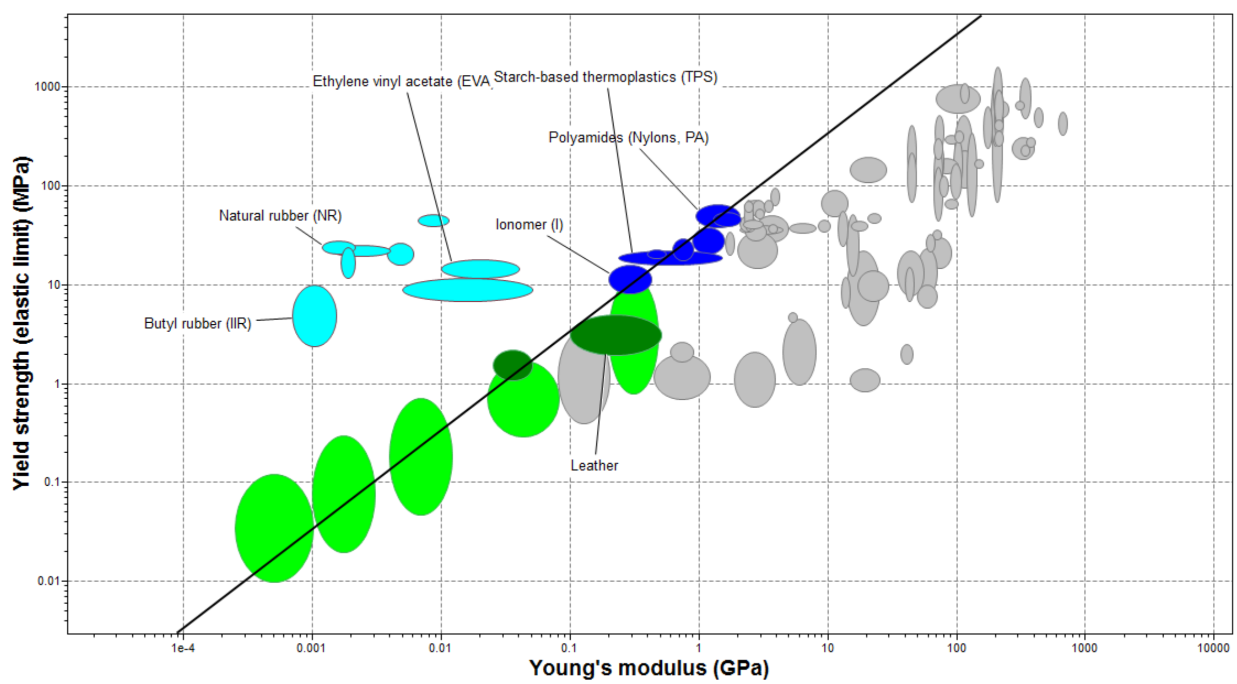
e. Candidate Materials List

M1



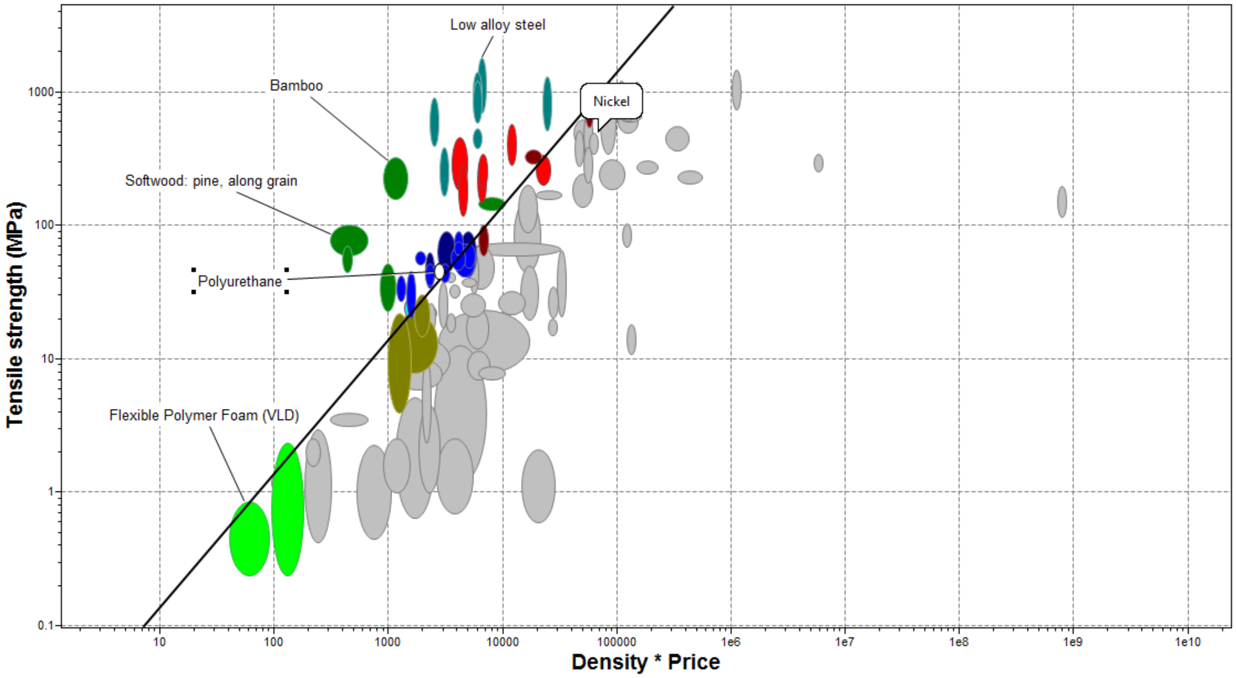
Optional materials: Ethylene vinyl acetate (EVA), Softwood: pine, along grain, Polyoxymethylene (Acetal, POM), Bamboo, CFRP, Low alloy steel

M3



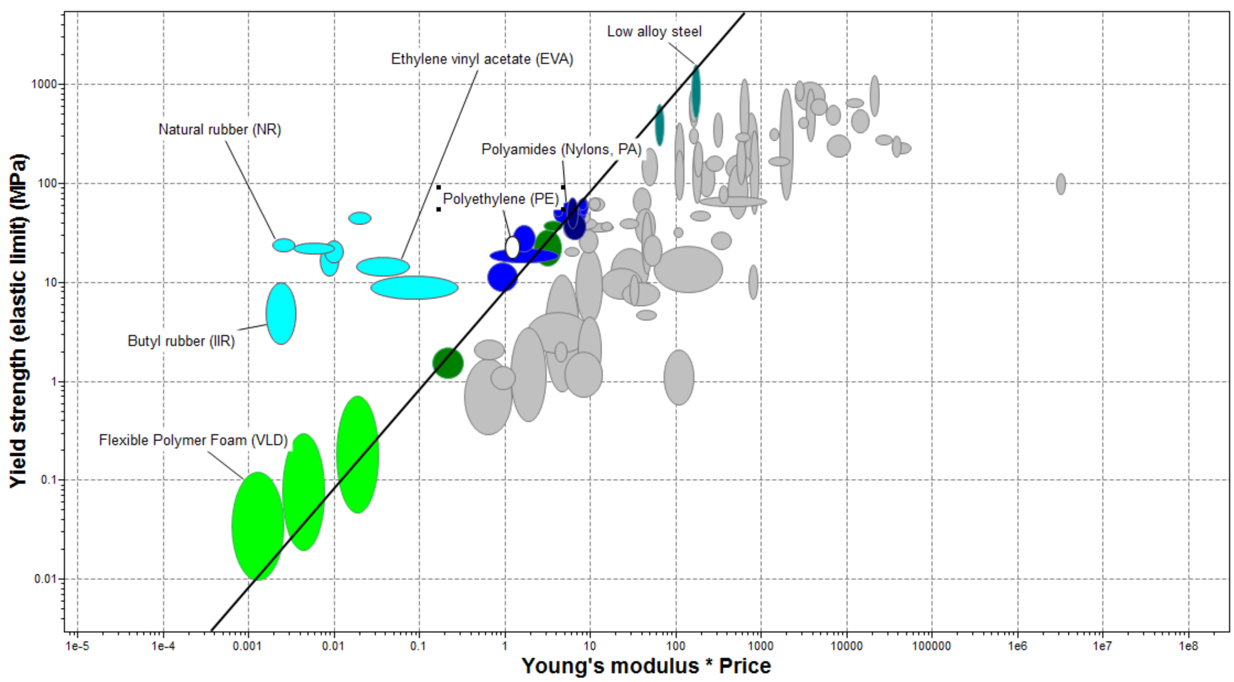
Optional Materials: Butyl rubber (IIR), Natural rubber (NR), Ethylene vinyl acetate (EVA), Starch based thermoplastics (TPS), Leather, Polyamides (Nylons, PA)

M2



Optional materials: Polyurethane, Softwood, Cast iron, Low alloy steel, Bamboo

M4



Optional materials: Flexible polymer foam (VLD), Butyl rubber (IIR), Natural rubber (NR), Ethylene vinyl acetate (EVA), Low alloy Steel.

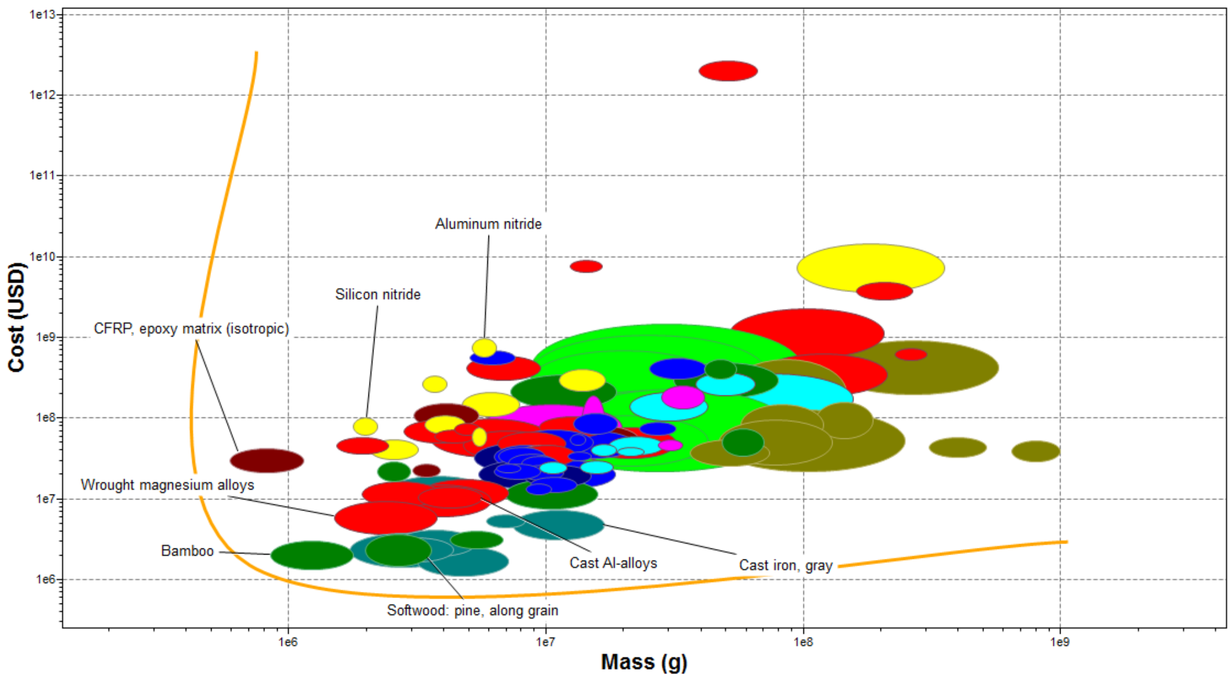
f. Active Constraint Identification

	A	B	C	D	E	F	G	H	I	J
1		Objective related properties			Constraint related properties					
2		Density	Cost		Young's modulus	Yield strength	Tensile strength		Free variables	
3	Mateials	Kg/m^3	USD/Kg		Gpa	Mpa	Mpa		t(M1,M2)	t(M3,M4)
4	Ethylene vinyl acetate	945	1.81		0.01	12	16		1.5625	11
5	Softwood	440	0.62		8.4	35	60		0.416667	5.020833
6	Polyoxymethylene	0.00139	2.79		2.6	48.6	60		0.416667	5.093462
7	Bamboo	602	1.34		15.1	35.8	160		0.15625	5.011854
8	CFRP	0.0015	34.6		69	550	550		0.045455	5.039855
9	Low alloy steel	0.0075	0.81		200	469	699		0.035765	5.011725
10	Butyl rubber	912	2.21		0.000702	2.4	2.4		10.41667	22.09402
11	Natural rubber	931	1.46		0.0012	21.1	21.1		1.184834	92.91667
12	Starch-based thermoplastics	0.00126	2.76		0.24	16	16		1.5625	5.333333
13	Leather	809	16.6		0.1	2	20		1.25	5.1
14	Polyamides	0.0012	3.37		0.94	39	42		0.595238	5.207447
15	Flexible Polymer Foam	16	2.41		0.00025	0.01	0.24		104.1667	5.2
16	Cast iron	0.00705	0.35517		170	246	400		0.0625	5.007235
17	Stainless Steel	0.00761	3.03		190	257	515		0.048544	5.006763
18										

g. Ranking

Objection for mass		Objection for cost					
Mass 1(g)	Mass2(g)	Cost1	Cost2		Rank(Mass)	Rank(Cost)	mult
5.90625	41.58	0.01069	0.01991		12	10	120
0.733333333	8.836666667	0.000455	0.003113		9	2	18
2.31667E-06	2.83196E-05	6.46E-09	0.014211		3	6	18
0.37625	12.06854517	0.000504	0.006716		10	4	40
2.72727E-07	3.02391E-05	9.44E-09	0.174379		4	14	56
1.07296E-06	0.000150352	8.69E-10	0.004059		6	3	18
38	80.59897436	0.08398	0.048828		13	11	143
4.412322275	346.0216667	0.006442	0.135658		14	13	182
0.000007875	0.00002688	2.17E-08	0.01472		2	7	14
4.045	16.5036	0.067147	0.08466		11	12	132
2.85714E-06	2.49957E-05	9.63E-09	0.017549		1	9	9
6.666666667	0.3328	0.016067	0.012532		8	5	40
1.7625E-06	0.000141204	6.26E-10	0.001778		5	1	5
1.47767E-06	0.000152406	4.48E-09	0.01517		7	8	56

h. Trade-off Plots



i. Documentation

It is not possible to select all the materials in the list, so we have to delete them step by step. First consider two constraints: don’t break and stretched should less than certain mm. This requires the material to have good tensile strength and yield strength. Meanwhile, when calculating the free variables – thickness, some material will make the thickness of the lace too thick. Thus, with reference to the actual situation, considering that it only plays a fixed knee pad and is convenient for users to wear. Thus, I assuming its thickness should be between 1mm and 15mm. Then depending on the thickness constraint, we can exclude some materials.8 materials reach the final selection as shown in the following chart.

	A	B	C	D	E	F
1	Matrials	Mass(g)	Cost	Rank(M)	Rank(C)	tickness t(mm)
2	Polyoxymethylene	0.000141598	1.42E-02	3	6	5.093462
3	Bamboo	60.34272583	0.006716	10	4	5.011854
4	CFRP	1.51E-04	1.74E-01	4	14	5.039855
5	Low alloy steel	0.000751759	4.06E-03	6	3	5.011725
6	Starch-based thermoplastics	0.0001344	1.47E-02	2	7	5.333333
7	Polyamides	0.000124979	1.75E-02	1	9	5.207447
8	Cast iron	0.00070602	1.78E-03	5	1	5.007235
9	Stainless Steel	0.000762029	1.52E-02	7	8	5.006763
10						

j. Discussion of final materials selections

Finally, as you can see from the picture we draw, there are two materials that are better. One is bamboo and the other is CFRP. However, CFRP may be more expensive than bamboo. But both can be considered.

In CFRP the reinforcement is carbon fiber, which provides the strength. The matrix is usually a polymer resin, such as epoxy, to bind the reinforcements together [**2**]. Because CFRP consists of two distinct elements, the material properties depend on these two elements. Extreme light weight, toughness and strength are good goals. Bamboos as a versatile raw product. Bamboo has a higher specific compressive strength than wood, brick or concrete, and a specific tensile strength that rivals steel. Bamboo fibers are all cellulose fiber extracted or fabricated from natural bamboo. In recent years, different technologies have been developed that allow bamboo fiber to be used for a wide range of textile and fashion applications. Bamboo yarn can also be blended with other textile fibers such as hemp or spandex. Bamboo is an alternative to plastic, but is renewable and can be replenished at a fast rate [**3**].

References

[1] Jiri Popelka (Dec., 2016); volleycountry; *3 Important Reasons to Use Knee Pads*

[2] "Sustainable Textiles: the Role of Bamboo and a Comparison of Bamboo Textile Properties-Part 2 – Waite – Journal of Textile and Apparel, Technology and Management". ncsu.edu.

[3] Kopeliovich, Dmitri. "Carbon Fiber Reinforced Polymer Composites". Archived from the original on 14 May 2012.. substech.com

[4] Michael Ashby, Material Selection in Mechanical Design; Fifth Edition; *Material Property Charts*; example E3.16;