Task 1: Selection basics

Instructions: Check the following questions and exercises. Read chapters 3, 4, and 5 of the course textbook (4th edition available in the Aalto Library as an e-book).

Chapter 3: Engineering Materials and Their Properties

It is conventional to classify the materials of engineering into the six broad families: metals, polymers, elastomers, ceramics, glasses, and hybrids.

- Metals are stiff. They have relatively high elastic moduli. Most, when pure, are soft and easily deformed. They can be made strong by alloying and by mechanical and heat treatment, but they remain ductile, allowing them to be formed by deformation processes.
- Ceramics, too, have high moduli, but unlike metal, they are brittle. Their "strength" in tension means the brittle fracture strength; in compression it is the brittle crushing strength, which is about 15 times greater.
- The lack of crystal structure suppresses plasticity, so, like ceramics, glasses are hard, brittle, and vulnerable to stress concentrations.
- Polymers are at the other end of the spectrum. They have moduli that are low, roughly 50 times lower than those of metals, but they can be strong— nearly as strong as metals. A consequence of this is that elastic deflections can be large. They creep, even at room temperature
- Elastomers are long-chain polymers above their glass-transition temperature,
- Hybrids are combinations of two or more materials in a predetermined configuration and scale. They combine the attractive properties of the other families of materials while avoiding some of their drawbacks.

Chapter 4: Material Property Charts

Each property of an engineering material has a characteristic range of values.

Materials are divided into Families (metals) and Classes (CU alloys)

- The modulus–density chart: Modulus and density are familiar properties. Steel is stiff; rubber is compliant: These are effects of modulus. Lead is heavy; cork is buoyant: effects of density.
- The strength–density chart: For metals and polymers, it is the yield strength, but since the range of materials includes those that have been worked or hardened in some other way as well as those that have been softened by annealing, the range is large. For brittle ceramics, the strength plotted here is the modulus of rupture. For elastomers, strength means the tensile tear strength. For composites, it is the tensile failure strength
- The modulus–strength chart
- The specific stiffness–specific strength chart
- The fracture toughness–modulus chart
- The fracture toughness–strength chart

Chapter 5: Materials Selection—The Basics

A material has attributes: its density, strength, cost, resistance to corrosion, and so forth.

The task of selection, stated in two lines, is that of

1. identifying the desired attribute profile, and then
2. comparing this with those of real engineering materials to find the best match

Ranking: Material indices

Attribute limits do not, however, help with ordering the candidates that remain. To do this we need optimization criteria. These are found in the material indices, developed next, which measure how well a candidate that has passed the screening step can perform.

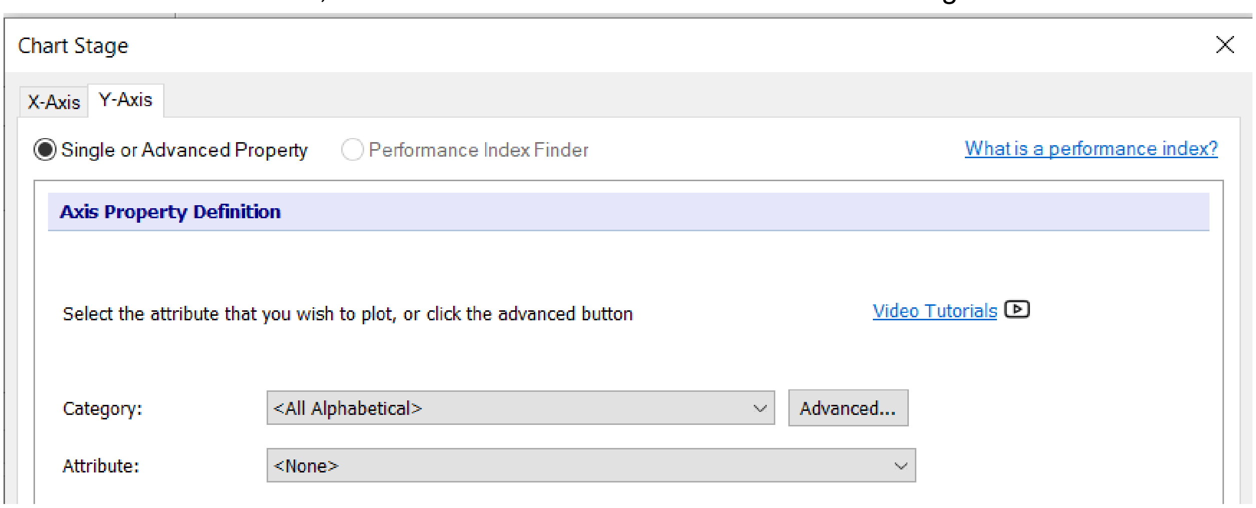
The outcome of the steps so far is a ranked short-list of candidates that meet the constraints and that maximize or minimize the criterion of excellence, whichever is required.To proceed further we seek a detailed profile of each candidate: its documentation. Documentation differs greatly from the structured property data used for screening. Typically, it is descriptive, graphical, or pictorial: case studies of previous uses of the material, failure analyses and details of its corrosion, information about availability and pricing, and the like. Such information is found in handbooks, suppliers' data sheets, case studies of use, and failure analyses.

Documentation helps narrow the short-list to a final choice, allowing a definitive match to be made between design requirements and material attributes. Without screening and ranking, the candidate pool is enormous and the volume of documentation overwhelming.

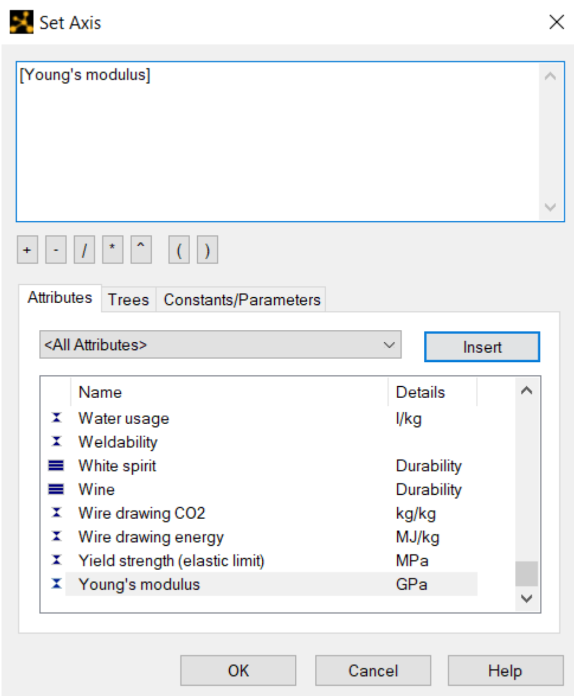
Granta Edupack Tutorial

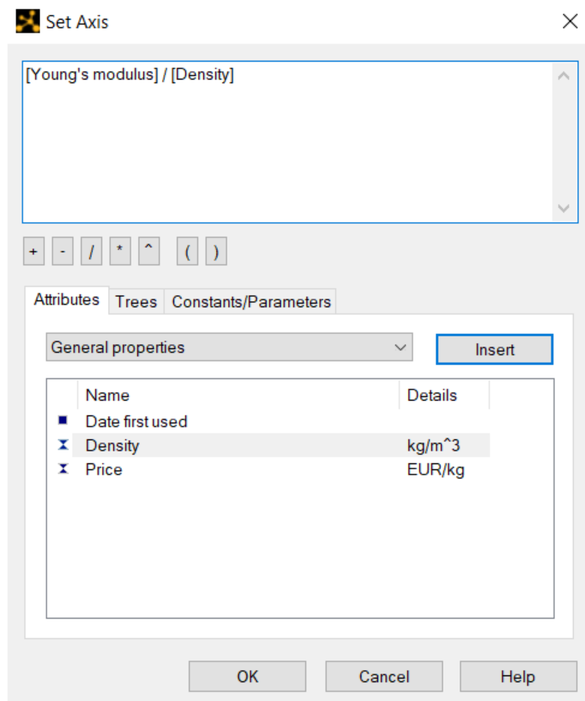
Advanced Chart Features in Ansys Granta EduPack

Choose Chart/Select tab, then click on Chart/Index under 2.Selection stages

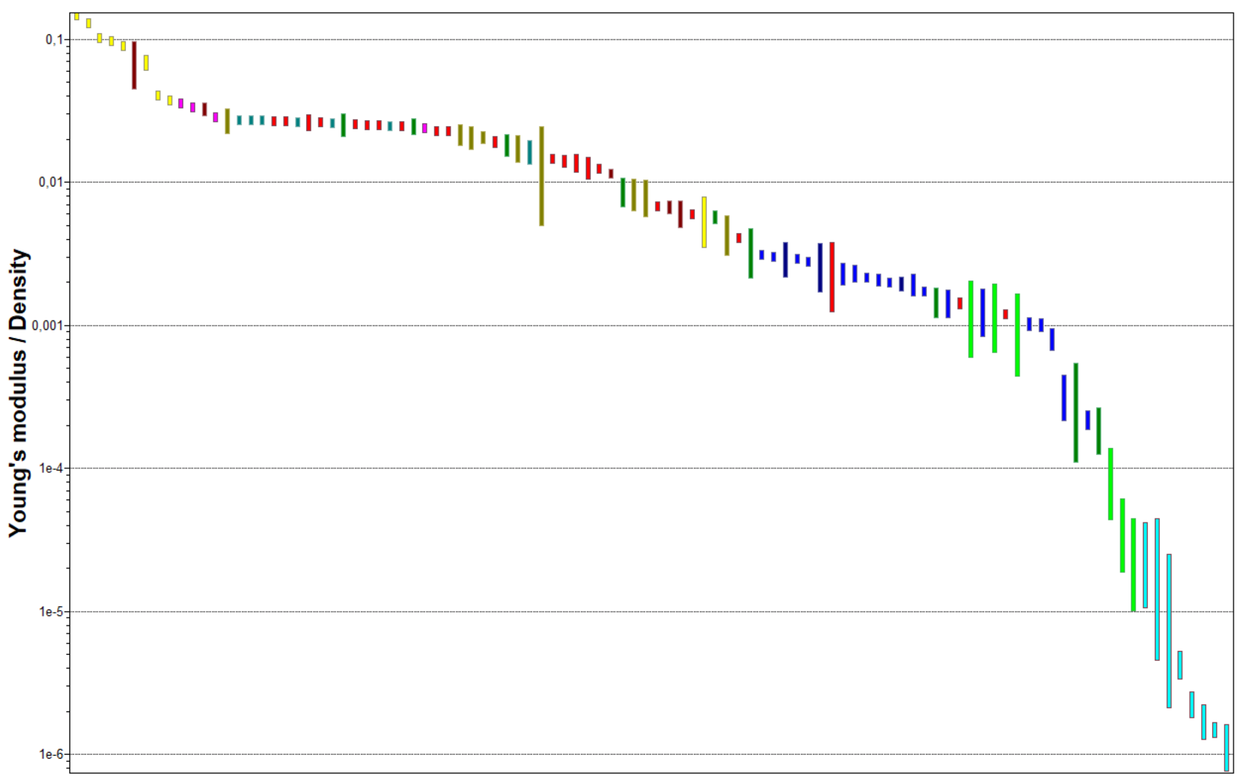


Now, click on the Advanced button. We can now operate on the Material properties to derive the Material Index. Scroll down to the end to find Young's modulus. After that, change to the General properties tab, then choose Density. Use division for the material index





Click OK to plot the chart



Opening plot settings again and choose X-axis => Advanced. Now choose the Tree tab. Now we can choose plastics and polymers, metals and glasses. Then click OK to all

What is Performance Index?
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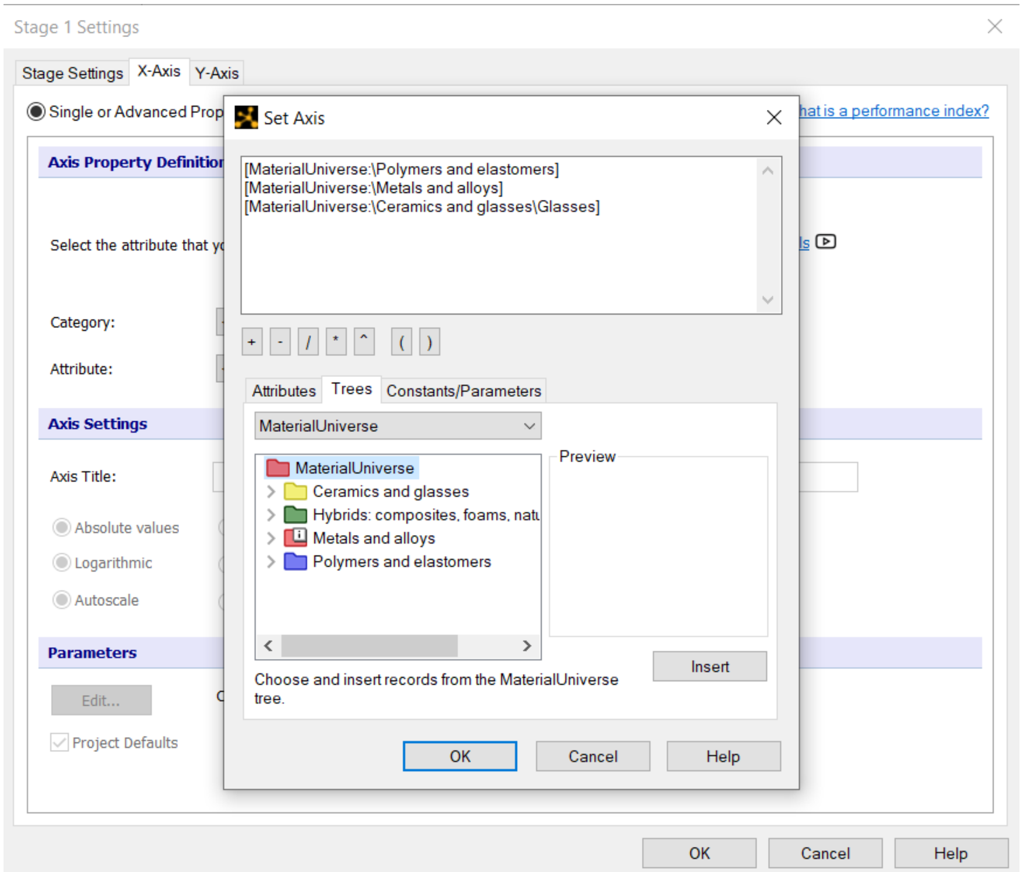


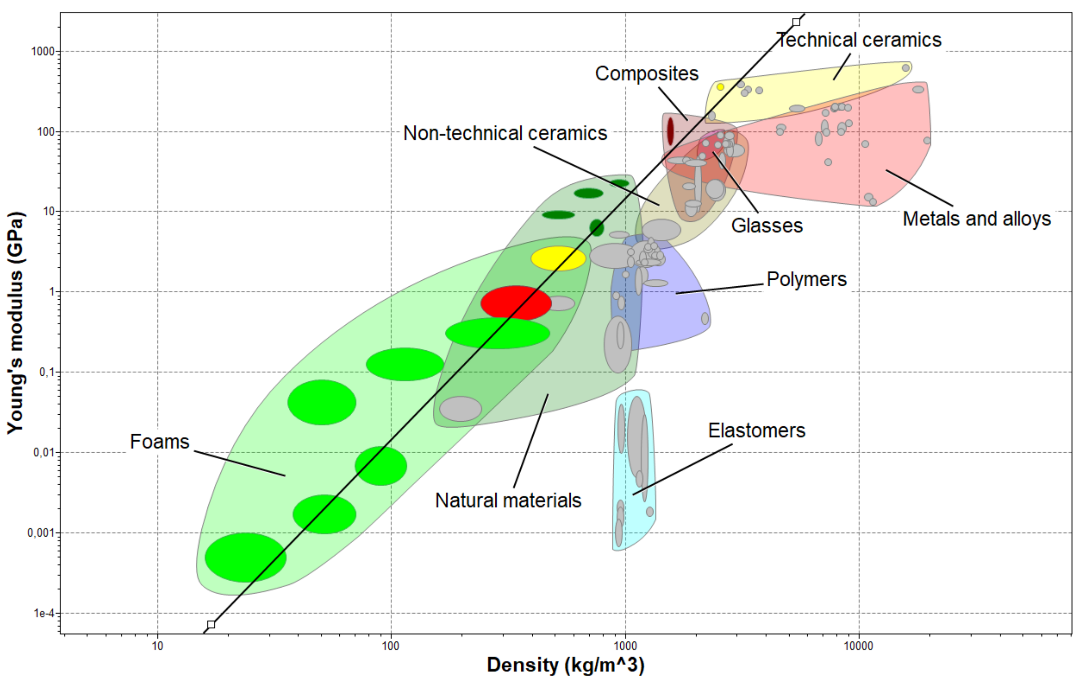
Criterion: A good report on this task demonstrates a good understanding of:

- how to **derive** a **material performance index** from the formulation of a performance objective,
- how to **use** a **material performance index** in material selection, and
- how to graphically represent this with **material selection lines** on the **material property map**

A performance index is defined by four design factors:

- The function is the basic geometry and load condition of the design (e.g. a panel loaded in bending).
- The limiting constraint is the main criterion to be met for the component to avoid failure (e.g. a stiffness-limited design, where a panel fails if it bends too far under an applied load).
- The objective is the main variable to optimize (e.g. minimize mass or cost).
- The free variable is the geometry parameter that is free to vary with material choice (e.g. the thickness of a panel).

Each combination of function, limiting constraint, objective, and free variable has a characteristic performance index. For example, a light (objective), stiff (limiting constraint), panel loaded in bending (function), with thickness as the free variable, has a performance index of $(E^{1/3})/\rho$, where Young's modulus is constraint for stiffness) and density is objective for minimizing mass.
Because the axis in Granta is usually log scale, we can transform it into linear form like this. Therefore,
$M = (E^{1/3})/\rho \Rightarrow E^{1/3} = M \times \rho \Rightarrow \log(E^{1/3}) = \log(M) + \log(\rho)$
$\Rightarrow \frac{1}{3}\log(E) = \log(M) + \log(\rho) \Rightarrow \log(E) = 3\log(\rho) + 3\log(M)$. This means we can plot the index line with slope = 3 on the Ashby graph. To maximize M, choose materials lying above the line



Task 1.1: Read the case study 6.2 “Materials for Oars” from the textbook.

Now follow the same method to choose one material from the material group listed below for a wind turbine blade. In the simplest case, the blade is a beam in bending. It should be as light as possible and have a given bending stiffness.

Hint: Draw the Material Selection Maps on level 2 with density and Young’s modulus as axes.

Composites	Plastics
Foams	Non-technical ceramics
Metals	Technical ceramics
Elastomers	Natural materials

How the material for oars (the tool used to row the boats) is chosen in the textbook:
Oars are designed on stiffness as they undergo a bending moment and they must be light.
For a light, stiff beam, the material performance index is:

$$M = (E^{1/2})/\rho$$

Constraints on the oars: Oars are dropped, and blades sometimes clash. The material must be tough enough to survive this, so brittle materials (those with a toughness G_1c less than 1 kJ/m^2) are unacceptable. This is the summary

Table 6.1 Design Requirements for the Oar

Function	Oar—meaning light, stiff beam
Constraints	Length L specified Bending stiffness S^* specified Toughness $G_{1c} > 1$ kJ/m^2
Objective	Minimize the mass m
Free variables	Shaft diameter Choice of material

Table 6.2 Materials for Oars

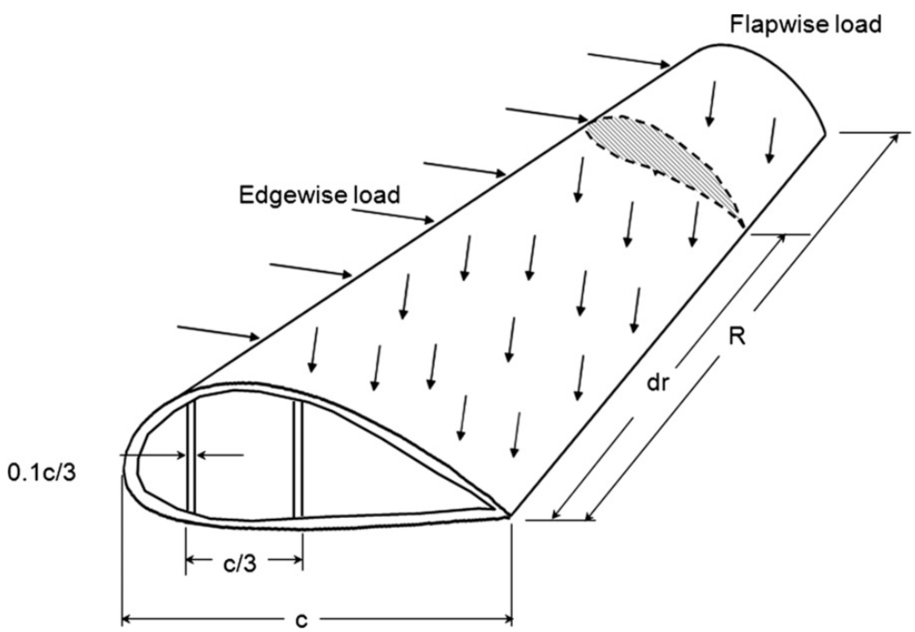
Material	Index M (GPa)$^{1/2}$/(Mg/m^3)	Comment
Bamboo	4.0–4.5	The traditional material for oars for canoes
Woods	3.4–6.3	Inexpensive, traditional, but with natural variability
CFRP	5.3–7.9	As good as wood, more control of properties
Ceramics	4–8.9	Good M but toughness low and cost high

A. Design requirements of the wind turbine blade

- First, define the **design requirements** in a table, including functions, constraints, objectives, and free variables, etc.

This is referred from a research paper on material selection for wind turbine blade [1]

Function	❖ airfoil beam subject to flapwise and edgewise bending
Constraints	❖ Fixed length L ❖ Given bending stiffness S*. ❖ Fatigue strength σ_f > 50 MPa under cyclic loading (10^7 cycles) [1] ❖ Fracture toughness K_{IC} > 15 MPa√m against aerodynamic loading [1]
Objective	❖ Minimizing blade weights
Free variables	❖ Blade airfoil shape ❖ Choice of material ❖ Material cost



Schematic diagram of a blade [1]

B. Performance index derivation

- Secondly, derive the formula for the material performance index from the performance objective. Note that the **derivation** (step-by-step) of the material performance index **must** be included in your report.

1. Mass and Volume Relationship:

The mass (m) of the beam can be expressed in terms of its volume (V) and density (ρ) as:

$$\mathbf{m = \rho \times V}$$

2. Volume and Dimension Relationship:

Let's consider a beam with a square cross-section of side t and length L. The volume is:

$$\mathbf{V = t^2 \ x \ L}$$

Substituting this into the mass equation, we get:

$$\mathbf{m = \rho \ x \ t^2 \ x \ L}$$

3. Bending Stiffness:

The stiffness (S) in bending for a beam is proportional to its Young's modulus (E) and its moment of inertia (I). For a beam with a square cross-section, the moment of inertia is:

$$\mathbf{I = (1/12) \ x \ t^4}$$

Thus, the stiffness is:

$$\mathbf{S^* = E \ x \ (1/12) \ x \ t^4}$$

4. Stiffness Constraint: Given that the stiffness S is specified (let's call it S∗), we can solve for t from the equation above

$$\mathbf{t^4 = 12 \ x \ (S^*/E) \Rightarrow \ t^2 = (12 \ x \ (S^*/E))^{1/2}}$$

5. Substituting the expression for t into the mass equation:

$$\mathbf{m = \rho \ x \ (12 \ x \ (S^*/E))^{1/2} \ x \ L}$$

Since L is fixed, we can see that to minimize **m**, we need to minimize **ρ** and maximize $\mathbf{E^{1/2}}$. In other words, we need to maximize the term dependent on material properties. This gives the material performance index as

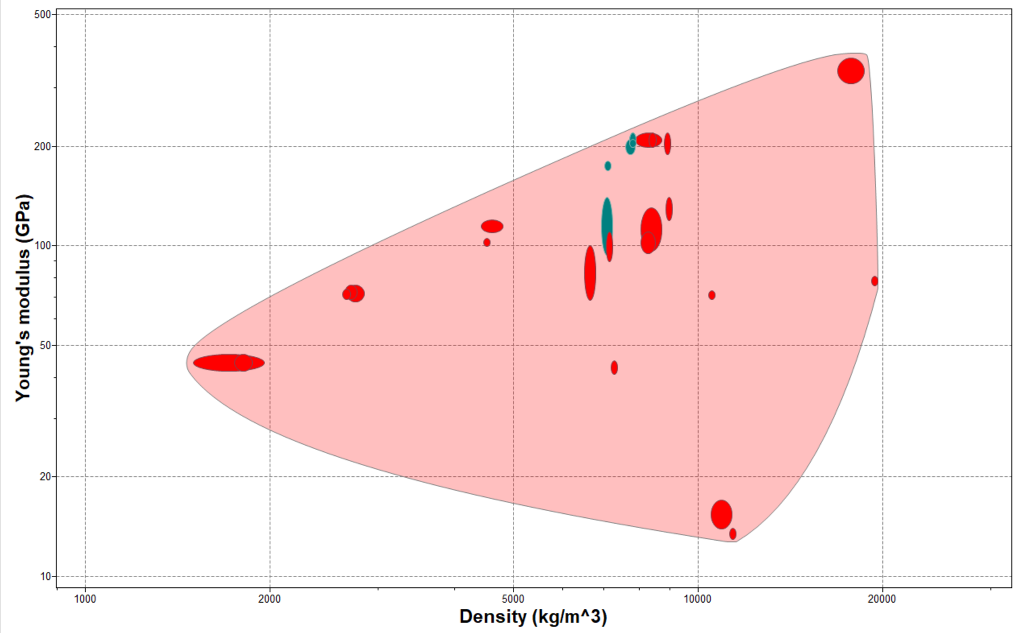
$$\mathbf{MPI = E^{1/2}/\rho}$$

This derived performance index suggests that for a beam loaded in bending, where stiffness is the limiting constraint and mass is the objective to minimize, materials with a high value of MPI are preferred. This index guides material selection to achieve a balance between stiffness and weight for optimal beam performance.

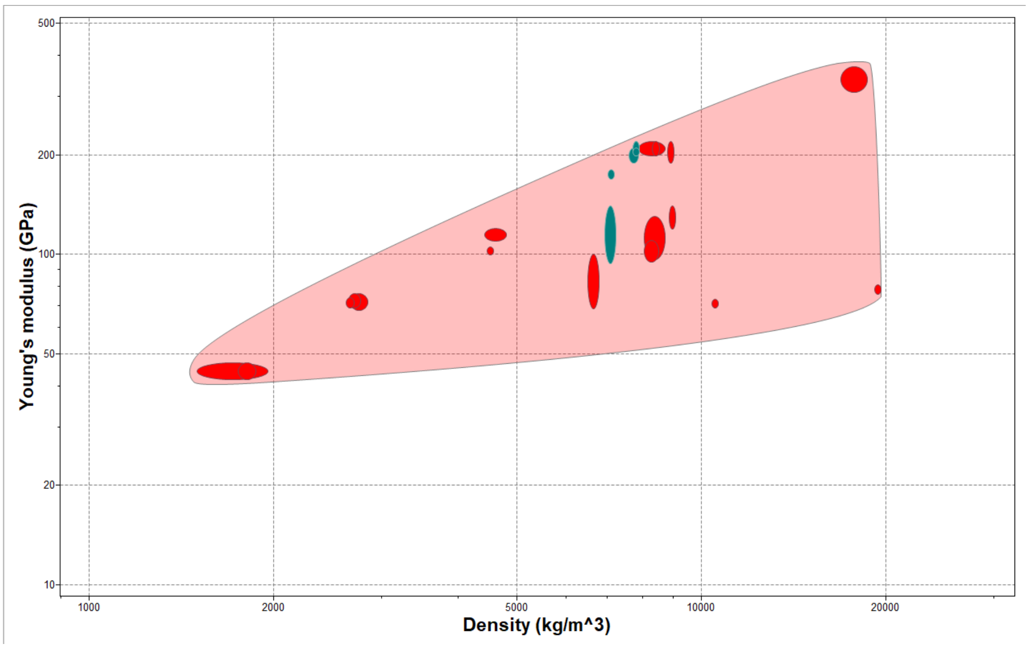
C. Drawing maps

- Then draw the **maps** with level 2 and explain what the correct material **selection lines** are for this task.

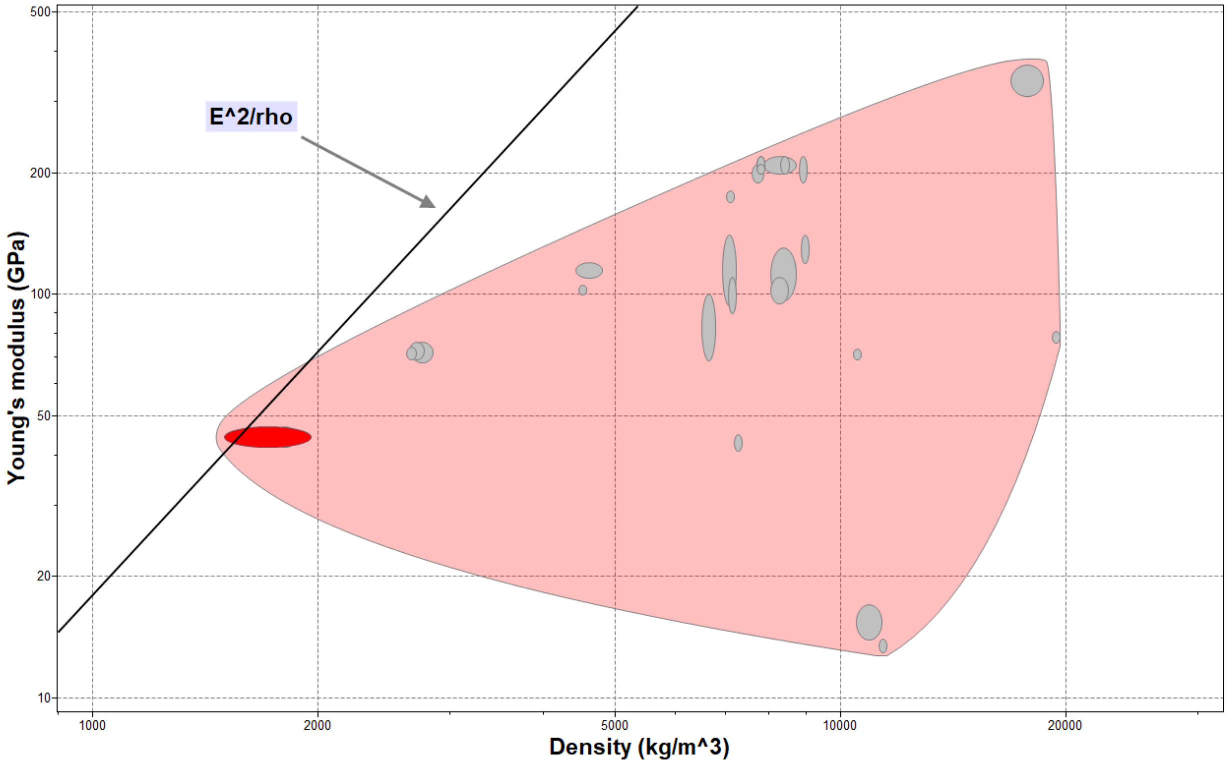
I choose only Metals as the material for the wind turbine plate

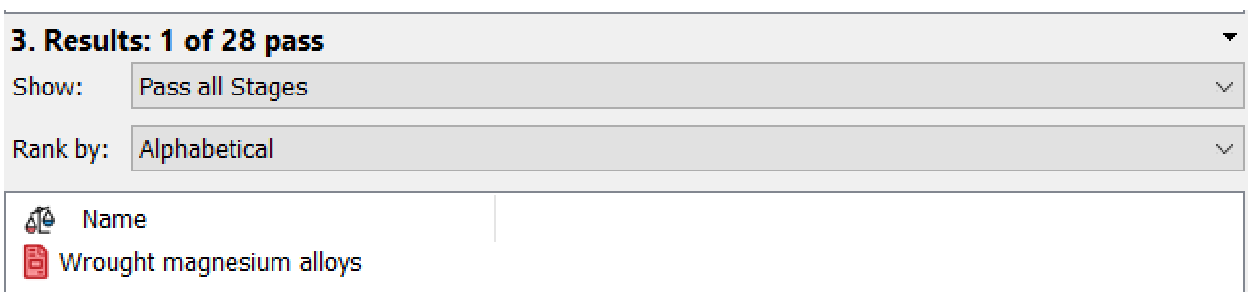


After apply the constraints of σ_f > 50 MPa and K_{IC} > 15 MPa√m, these metals remains:



When designing a structure where we want to maximize stiffness while minimizing weight, we are essentially trying to maximize the ratio of bending stiffness to weight. The selection line for the index M has a slope of 2, as explained above; it is positioned so that a small group of metals are left above it. They are the materials with the largest values of M and represent the best choice, provided they satisfy the other constraints.

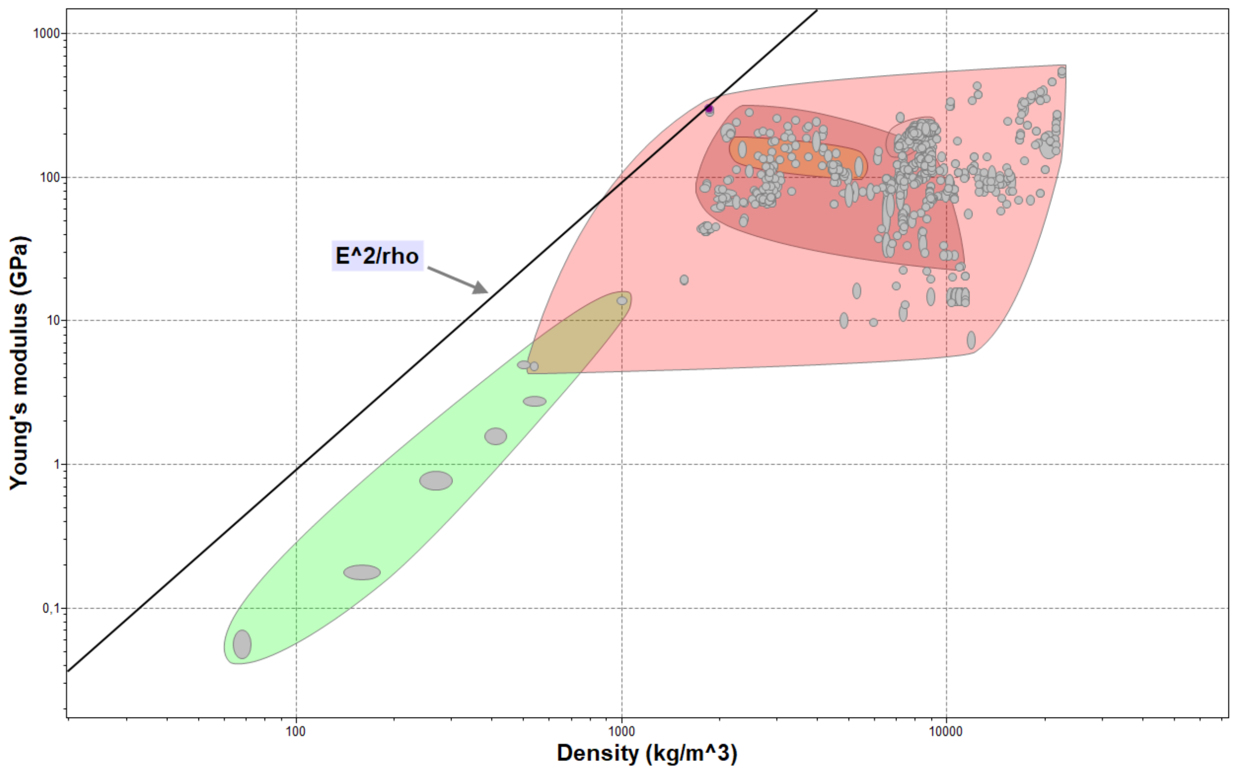




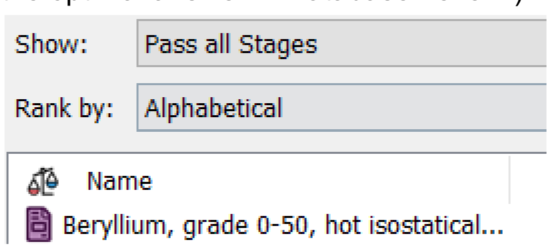
The best metal to be selected is the Wrought magnesium alloys pass, which is in line with the current materials used for wind turbine blades [2]

Task 1.2: Draw the maps from Task 1.1 on level 3. What differences do you notice? Give a detailed description based on your observation.

This is the map of material selection on level 3.



The difference is that a group of new metals have been defined instead of Magnesium (which is the optimal answer in Database Level 2). This new metal is made from Beryllium in Level 3



Main reason for this discrepancy

- **Magnesium Alloys**: These are known for their low density (lightweight) and good mechanical properties, making them suitable for cases where light weight is crucial.
- **Beryllium Metal**: Beryllium has an even lower density than magnesium and has excellent stiffness (high Young's modulus). It's also more expensive [3] and less common (rare earth metal) than magnesium. Its specific properties might make it the top choice when the database has more detailed data (as in Level 3). However, Beryllium's brittleness is the down side of its great stiffness [3]

References:

[1] Multi-objective material selection for wind turbine blade and tower: Ashby's approach
https://www.researchgate.net/publication/257086147_Multi-objective_material_selection_for_wind_turbine_blade_and_tower_Ashby%27s_approach
[2] https://igert.windenergy.iastate.edu/research/research-thrusts/thrust-3/
[3] About Beryllium
https://www.energy.gov/ehss/about-beryllium#:~:text=It%20is%20expensive%20and%20too,side%20of%20its%20advantageous%20stiffness.