

Materials selection in a critical raw materials perspective

Paolo Ferro ^{*}, Franco Bonollo

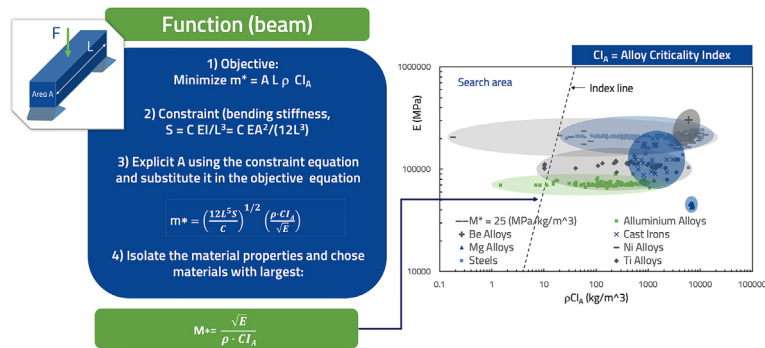
Department of Engineering and Management, University of Padova, Stradella S. Nicola 3, 36100 Vicenza, Italy



HIGHLIGHTS

- The criticality index quantifying the supply risk of raw elements used to produce the unit of mass of the alloy was defined
- The objective equation that quantifies the criticality issues linked to raw materials per unit of function was obtained
- A systematic approach for materials selection in a critical raw material perspective is illustrated

GRAPHICAL ABSTRACT



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ABSTRACT

Critical Raw Materials (CRMs) are those raw materials that are economically and strategically important for the European economy but have a high-risk associated with their supply. Used in environmental technologies, consumer electronics, health, steel-making, defence, space exploration, and aviation, these materials are not only 'critical' for key industry sectors and future applications, but also for the sustainable functioning of the European economy. In this scenario, 'mitigating actions' need to be developed to reduce criticalities linked to the use of those raw materials. Recycling and substitution, when possible, are strategic solutions but a more efficient use of such CRMs in design, obtained by a correct alloy selection, is become nowadays mandatory.

A method for metallic alloys selection in a CRMs perspective, based on the definition of the alloy critical index, is described. The proposed method allows selecting the alloy for the current application that minimizes its criticality associated to CRMs. The method is illustrated with examples.

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1. Introduction

Raw materials are crucial to World's economy. They form a strong industrial base, producing a broad range of goods and applications used in everyday life and modern technologies. Reliable and unhindered access to certain raw materials is a growing concern within the European Union (EU) and across the globe. To address this challenge,

the European Commission (EC) has created a list of critical raw materials (CRMs) for the EU [1], which is subject to a regular review and update. CRMs combine raw materials of high importance to the EU economy and of high risk associated with their supply.

The more recent list features 27 raw materials: Antimony, Beryllium, Borates, Cobalt, Coking Coal, Fluorspar, Gallium, Germanium, Indium, Magnesium, Natural Graphite, Niobium, Phosphate Rock, Silicon Metal, Tungsten, Platinum Group Metals, Light Rare Earths and Heavy Rare Earths, Baryte, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum, and Vanadium.

^{*} Corresponding author.

E-mail address: paolo.ferro@unipd.it (P. Ferro).

Table 1
Abundance Risk Level (ARL) values.

Abundance in the Earth's crust [ppm]	Abundance Risk Level
<0.01	5
From 0.01 to 1	4
From 1 to 100	3
From 100 to 10,000	2
>10,000	1

It is important to note that these materials are not classified as 'critical' because these materials are considered scarce, rather they are classified as 'critical' because:

- 1) they have a significant economic importance for key sectors in the European economy, such as consumer electronics, environmental technologies, automotive, aerospace, defence, health and steel;
- 2) they have a high-supply risk due to the very-high import dependence and high level of concentration of set critical raw materials in particular countries;
- 3) there is a lack of (viable) substitutes, due to the very unique and reliable properties of these materials for existing, as well as future applications.

Thus, the CRMs, are strongly important because they are linked to all industries across all supply chain stages, and they are linked to clean technologies. They are irreplaceable in solar panels, wind turbines, electric vehicles, and energy-efficient lighting. Furthermore, technological progress and quality of life rely on access to a growing number of raw materials. For example, a smartphone might contain up to 50 different kinds of metals, all of which contribute to its small size, light weight and functionality.

Raw materials criticality assessment is a very difficult task. For example, in their work, Achzet and Helbig [2] demonstrated how the different criticality assessment methods used by several working groups around the world are very heterogeneous. They focused their attention on the Indium supply risk evaluation in 15 criticalities assessment methods and showed a lack of consensus about which indicators give reliable information for raw material supply risk. In this scenario, Blengini et al. [3] discussed the specific elements of the European Community (EC) criticality methodology that were adapted by the Directorate General Joint Research Centre (DG JRC), highlighted their novelty and/or potential outcomes, and discussed them in the context of criticality assessment methodologies available internationally. That study was carried out in view of the CRMs list updating, planned for 2017.

Drawbacks related to CRMs should be taken into account even at the early stage of a new material or component development. With this objective, Helbig et al. [4] proposed a multidisciplinary approach as a guideline for materials scientists for a sustainable and more resource-efficient material development. Eleven indicators, within the scope of reduced supply risk and enhanced environmental sustainability at early stage of materials research, were identified, included a new developed Sector Competition Index. In a more recent work by Løvik et al. [5], industry activities, policy initiatives and European research projects carried out with the aim to secure an adequate supply of raw materials, were summarized. They found that strong emphasis on rare earth elements was putted in almost half of the identified projects. They also highlighted how the current research is coherent with the aims of the Raw Materials Initiative in that it addresses primary production, recycling, and substitution as means to secure the supply of critical metals. The stronger emphasis on recycling is in line with principles of sustainability. However, the prioritization of certain metals, especially REEs, was found stronger than what seems justified by differences in economic risk (or criticality) and should perhaps be replaced by a more balanced distribution of funds.

Finally, in another recent paper [6], Hofmann et al. showed that material scientists seem frequently not concerned with the criticality of raw materials in their work so that they suggested to advance the implementation of the concept of materials criticality in materials research and development.

Compared to the above-mentioned papers about raw materials criticality assessment, the present work is aimed to propose a methodology to reduce CRMs related issues by a proper metallic alloy selection that takes into account RMs criticalities. The materials selection strategy was first developed by Ashby et al. [7] and involves four basic steps: 1) translation of design requirements into a prescription for a material, identifying the constraints that it must meet and the objective that is desired; 2) screening out of all materials that fail to meet the constraints; 3) ranking of those that remain by their ability to meet the objective; 4) documentation of the top-ranked candidates, allowing them to be explored in depth. Further works by Ashby, showed how to manage the problems related to multi-objective optimization in material design and selection [8] and how to design hybrid materials [9].

The present work is aimed to define a strategy for materials selection in a critical raw material perspective. In order to reach this goal, the alloy criticality index (CI_A) that quantifies the supply risk of raw elements used to produce the unit of mass of the alloy itself is first defined. Basing on the alloy criticality index concept, the objective equation that quantifies the criticality issues per unit of function was then obtained. This last equation allows applying a systematic materials selection strategy in a critical raw materials perspective. Finally, simplified case studies are illustrated to show the potentiality of the proposed approach in design of components.

2. Raw materials criticalities assessment

The raw materials criticalities taken into account in the present work are: the 'Abundance Risk Level', the 'Sourcing and Geopolitical Risk', the 'Environmental country risk', the 'Supply Risk', the 'Economic Importance' and the 'End of Life Recycling Input Rate'. Definition and values of such kind of criticalities are taken from literature and summarized in the following paragraphs. It's worth mentioning that both the definition and values of CRMs criticalities may change or be improved during time since a common recognized strategy for CRMs criticality assessment is still lacking in literature [2]. However, the materials selection strategy in a CRMs perspective proposed in the next paragraphs is always valid.

2.1. Abundance Risk Level (ARL)

The Abundance Risk Level is quantified by a number ranging from 1 to 5 associated to the value of the attribute 'Abundance in the Earth's crust [ppm]' (Table 1).

The value of the Abundance in the Earth's crust for each CRMs was taken from the GRANTA database [10].

2.2. Sourcing and geopolitical risk Herfindahl-Hirschman Index

This index indicates the supply disruption risk due to political factors, based on the countries in which the element is produced (e.g. in

Table 2
Correspondence between the end of life recycling input rate and the EOL-RIR index.

EOL-RIR [%]	EOL-RIR index
From 0 to 5	5
From 5 to 10	4
From 10 to 20	3
From 20 to 30	2
>30	1

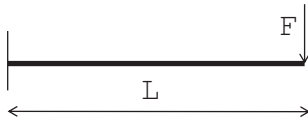


Fig. 1. Schematic of a beam loaded in bending.

terms of political stability and control of corruption) and the concentration of worldwide production. A higher value means a higher risk.

According to EU Report of the Ad-hoc Working Group on defining critical raw materials (2010, [11]), the sourcing and geopolitical risk Herfindahl-Hirschman Index (HHI_{WGI}) for an element 'i' is a modified and scaled Herfindahl-Hirschman Index, calculated as (Eq. (1)):

$$HHI_{WGI} = \sum_c (S_{ic})^2 WGI_c \tag{1}$$

where WGI_c is the World Bank's "Worldwide Governance Indicator" for the producing country 'c' and S_{ic} is the percentage (%) of worldwide production of the raw material 'i' within country 'c' [11].

The World Bank "Worldwide Governance Indicator" measures the political and economic stability of producing countries. In particular, this widely recognized indicator measures six broad components of governance: voice and accountability; political stability and absence of violence/terrorism; government effectiveness; regulatory quality; rule of law; and control of corruption.

In this context it is useful to remember that the Herfindahl-Hirschman Index (HHI) gives an indication of the level of concentration of production of a raw material within any one country, in terms of its annual worldwide production. In economic terms, it is used to gauge the risk of monopolistic production within the supply chain of the material under consideration. A value close to 0 indicates that production is widely distributed and occurs in many countries. A value close to 10,000 (the maximum possible value) indicates that production is highly concentrated in a small number of countries. The Herfindahl-Hirschman Index (HHI) for a raw material is calculated using the percentage of worldwide production (by mass) that takes place in each of the countries it is produced in. Thus, the HHI for a raw material 'i' is

given by the following Eq. (2) [11]:

$$HHI = \sum_c (S_{ic})^2 \tag{2}$$

2.3. Environmental country risk Herfindahl-Hirschman Index

It indicates the risk that worldwide supply of an element may be restricted in future as a result of environmental protection measures taken by any of its producing countries. A higher value means a greater risk that environmental legislation may restrict supply in the future.

The environmental country risk Herfindahl-Hirschman Index (HHI_{EPI}) for an element 'i' is a modified and scaled Herfindahl-Hirschman Index, given by Eq. (3):

$$HHI_{EPI} = \sum_c (S_{ic})^2 \left(10 - \frac{EPI_c}{10}\right) \tag{3}$$

where EPI_c is the Environmental Performance Index calculated by Yale University, for the producing country 'c' [11]. The Environmental Performance Index (EPI) is a method of quantifying and numerically marking the environmental performance of a state's policies [12]. The greater the EPI_c indexes, the lower the risk of supply disruption induced by environmental legislation.

2.4. Supply risk

The Supply Risk (SR) indicator quantifies the inadequate supply of a raw material to meet industrial demand. It is calculated by taking into account estimation of how stable the producing countries are (considering the level of concentration of raw material producing countries), the extent to which a raw material 'i' may be substituted, and, finally, the extent to which raw material needs are recycled. The formula for the calculation of the SR index is given by Eq. (4) [11]:

$$SR = g(1-f)HHI_{WGI} \tag{4}$$

where g is the raw material substitutability (defined in Eq. (5)) and f is the recycling rate that is the ratio of recycling from old scrap to European consumption.

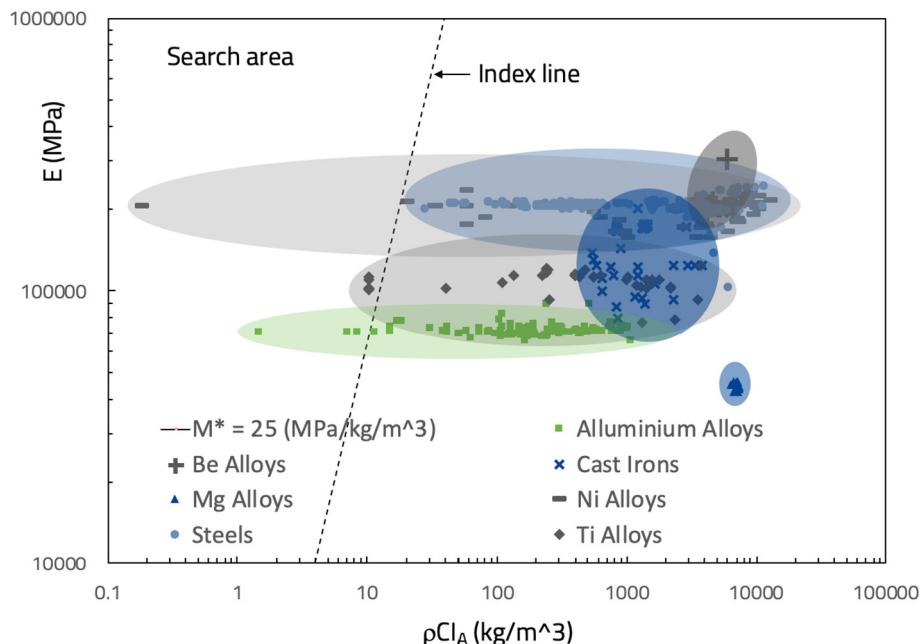


Fig. 2. Materials map ρCl_A -E (total number of plotted metallic materials, 1070).



Fig. 3. Schematic of a bicycle and forces applied on the forks.

The substitutability, g , represents the possibility of substituting the raw material and it is calculated as a weighted average over the end-uses/sectors, as follows [11]:

$$g = \sum_s A_s g_s \quad (5)$$

where A_s is the share of material consumption in a given end-use sector (s) and the g_s value may be zero if the raw material (RM) is easily and completely substitutable at no additional cost, 0.3 if the RM is substitutable at low cost, 0.7 if the RM is substitutable at high cost (and/or loss of performance) and finally 1.0 if the RM is not substitutable. Thus, the higher is g the lower is the substitutability.

The supply risk is increased if the producing countries are unstable and provide a high share in the world production, because the substitutability is low (g is high), and because the recycled rate is low ($(1 - f)$ is high).

2.5. Economic importance

The importance for the economy of a raw material is measured by breaking down its main uses and attributing to each of them the value added of the economic sector that has this raw material as input [11]. The economic importance of a raw material (EI), is calculated as the weighted sum of the individual megasectors (expressed as gross value added), divided by the.

European gross domestic product (GDP) (Eq. 6) [11,13]:

$$EI = \frac{1}{GDP} \sum_s A_s Q_s \quad (6)$$

In Eq. (6), A_s is the share of consumption of a RM in a given end-use sector, s , while Q_s is the economic importance of the sector, s , that requires that raw material and it is measured by its value-added. The values for economic importance of each material were scaled to fit in the range from 0 to 10, with higher scores indicating higher economic importance.

2.6. End of life recycling input rate (EOL-RIR)

The End of life recycling input rate (EOL-RIR) is ‘the input of secondary material to the EU from old scrap to the total input of material (primary and secondary)’. In the EC criticality assessments (EC 2011, 2014), recycling rates and EOL-RIR refer only to functional recycling. Functional recycling is ‘the portion of EOL recycling in which the material in a discarded product is separated and sorted to obtain recyclates’. Recyclates obtained by functional recycling are used for the same functions and applications as when obtained from primary sources; as opposed to recyclates generated from non-functional recycling which substitute other raw materials, and therefore do not contribute directly to the total supply of the initial raw material. In the present work, in order to assess the overall criticality index for each CRM, an EOL-RIR index was scored as shown in Table 2.

2.7. Overall CRM criticality index (CI_{CRM}) and alloy criticality index (CI_A)

One of the main challenges in raw materials criticality assessment is how to aggregate the above defined indexes in only one material criticality index. For simplicity, in this work, the overall criticality index of a CRM ‘ i ’ (CI_{CRM_i}) is obtained by averaging the above-defined criticalities indexes values. As a consequence, the alloy criticality index (CI_A) can be quantified by the following Eq. (7):

$$CI_A = \sum_{i=1}^n CI_{CRM_i} \frac{Wt\%_{CRM_i}}{100} \quad (7)$$

where n is the number of CRMs in the alloy chemical composition and

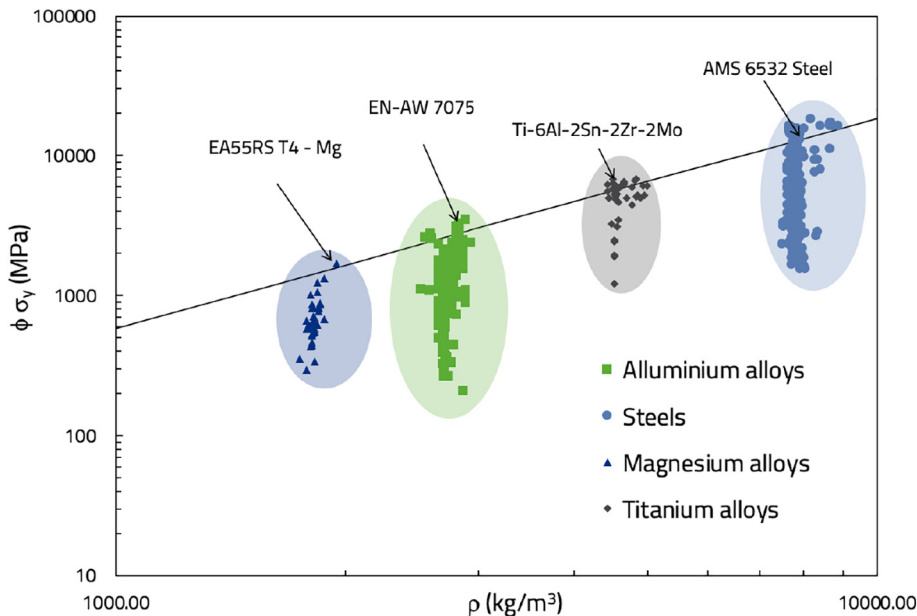


Fig. 4. Materials map ρ - $\phi\sigma_y$.

Table 3
Metallic materials for bicycle forks when performance (weight reduction) is to be maximized.

Material	σ_y (MPa)	ρ (Mg/m ³)	ϕ	Index ^a $\sigma_y^{2/3}/\rho$	Index ^a M $(\phi\sigma_y)^{2/3}/\rho$
Steel AMS 6532 aged at 468–482 °C	1620–1790	7.85–7.93	7.5	18	69
EN AW 7075 T6	359–530	2.78–2.81	5.9	21	68
Ti-6Al-2Sn-2Zr-2Mo	1240–1340	4.46–4.55	5.9	25	80
EA55RS T4 Magnesium Alloy	371–435	1.94–1.95	4.25	28	73

^a The values of the indices are based on mean values of the materials properties. The units of the indices are (MPa)^{2/3}/(Mg/m³).

wt%_{CRM*i*} is the amount of the CRM ‘i’ in the alloy, measured in weight percent. It is observed that the alloy criticality index (CI_A) represents an overall criticality value per unit of mass of the alloy. Values of the criticality indexes for each CRM are reported in Appendix A.

3. Method for materials selection in a CRMs perspective

The proposed methodology for materials selection in a CRM perspective is based on the alloy criticality index definition (Eq. 7) and follows the method first developed by Ashby [7–9].

Following the Ashby’s approach, the materials selection (MS) process consists of four steps:

1. Definition of the design requirements (constraints, objectives, free variables)
2. Screening using constraints
3. Ranking using objective
4. Seeking supporting information

Starting from the functional requirements of the component, constraints, objectives to be optimized and free variables are first defined. In a CRM perspective the objective to be minimized will be the criticality of the designed component. This objective equation (m*) is obtained by multiplying the mass of the component (m) by the alloy criticality index (Eq. 8):

$$m^* = m \cdot CI_A \tag{8}$$

Since CI_A represents an overall criticality value per unit of mass of the alloy, m* quantifies the overall criticality of the whole component.

Materials that do not satisfy the constraints are then removed and the surviving materials are ranked according to the objective (m*).

Materials with the lowest values of m* will be selected and the final choice will be made by taking into account the supporting information about each of them. It is worth mentioning that the proposed approach is restricted to metallic materials or alloys.

In order to reduce m* the Ashby’s method can be used. Consider, as an example, the material selection for a rigid beam of square cross section and length L (Fig. 1). The objective is to minimize its criticality described by the following Eq. (9):

$$m^* = H \cdot L \cdot \delta \cdot CI_A \tag{9}$$

where ρ is the density of the alloy of which the beam is made and H is the cross-section area. The applied force F and the length L are specified; the section area is free. The beam must meet the constraint on its stiffness S, meaning that it must not deflect more than δ under a load FL. It is thus required that:

$$S = \frac{FL}{\delta} = \frac{C_1 EI}{L^3} \geq S^* \tag{10}$$

where S is the desired stiffness, E is Young’s modulus, C₁ is a constant which depends on the distribution of load and I is the second moment of the area of the section, which, for a beam of square section H is

$$I = \frac{H^2}{12} \tag{11}$$

Using Eqs. (10) and (11) to eliminate H in Eq. (9) gives the objective function for the performance metric m*:

$$m^* \geq \left(\frac{12S^*}{C_1 L}\right)^{1/2} (L^3) \left(\frac{\rho CI_A}{E^{1/2}}\right) \tag{12}$$

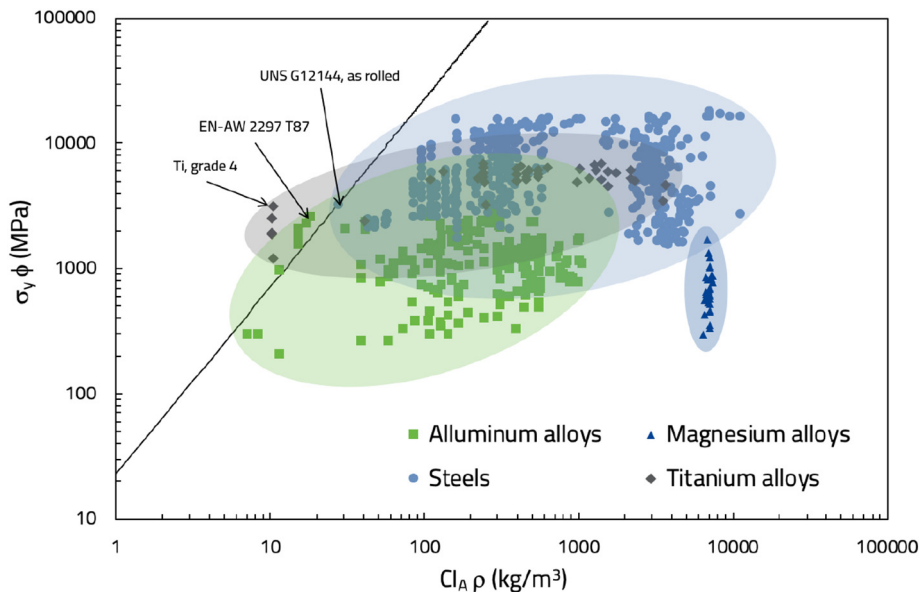


Fig. 5. Materials map CI_Aρ–φσ_y.

The brackets are ordered as functional requirement, geometry and material. m^* represents the grade of criticality *per unit of function* to be minimized. The best alloys for a low-criticality, stiff beam are those with the smallest values of $\rho C_{IA}/E^{1/2}$ or the highest value of its inverse that is:

$$M^* = \frac{E^{1/2}}{\rho C_{IA}} \quad (13)$$

M^* is called *material index* and represents the performance metric for the selection of a low-criticality, stiff beam. In general, its expression depends on the geometry of the component, load conditions and constraints. In a log-log plot, E against ρC_{IA} (Fig. 2), Eq. (13) is a family of parallel diagonal lines, linking materials having the same material index (M^*) value. As the M^* value increases, the straight diagonal line moves toward the upper left corner of the graph. The subset of materials with particularly good values of the index is identified by picking a line that isolates a search area containing a reasonably small number of candidates. Attribute limits can be added, narrowing the search window: that corresponding to a constant value of E is represented as a horizontal line in Fig. 2. The short-list of candidate materials is expanded or contracted by moving the index line.

3.1. Case-study: forks for a bicycle

The alloy selection in a CRM perspective for the production of forks for a bicycle is illustrated. The problem was deliberately simplified in order to allow focusing only on the proposed approach. The first consideration in bicycle design is that the forks should not yield or fracture in normal use. The forks are loaded predominantly in bending (Fig. 3) and for racing purpose, they should be as light as possible. But if the issues associated to critical raw materials are of primary importance, which will be the best alloy to use? The forks can be modelled as beams of length L that must carry a maximum load F without plastic collapse or fracture.

Constraints are thus the length, L, and the load value, F; free variables are the alloy, the cross-section area and shape. The objective function to be minimized in a CRMs perspective is given by Eq. (8) that in this case can be rewritten as follows (Eq. (14)):

$$m^* = \rho \cdot L \cdot H \cdot C_{IA} \quad (14)$$

where ρ is the alloy density and H is the area of the cross-section. The constraint equation is given by the following relation (Eq. (15)):

$$\sigma_{\max} = \frac{FLy_m}{I} = \frac{FL}{Z} \leq \sigma_y \quad (15)$$

where I is the second moment of area of the section, y_m is the distance between the neutral axis and the outer surface of the beam, Z is the section modulus and σ_y is the yield stress of the alloy. Now, by defining the shape factor (ϕ) as the ratio between Z and Z_0 , where Z_0 is the section modulus of the reference beam of square section with the same cross-sectional area, H, the following equation holds true:

$$\phi = \frac{Z}{Z_0} = \frac{6Z}{H^3/2} \quad (16)$$

Table 4
Metallic materials for bicycle forks when risks associated to CRMs are to be minimized.

Material	σ_y (MPa)	ρ (Mg/m ³)	ϕ	C_{IA}	Index ^a M^* ($\phi\sigma_y$) ^{2/3} /($C_{IA}\rho$)
UNS G12144, as rolled steel	342–517	7.83–7.91	7.5	0.003	7.9
EN AW 2297 T87	361–417	2.62–2.68	5.9	0.006	10
Ti – grade 4	483–570	4.54–4.55	5.9	0.002	20
Magnesium AZ 61	160–170	1.80–1.81	4.25	3.76	0.01

^a The values of the indices are based on mean values of the materials properties. The units of the indices are (MPa)^{2/3}/(kg/m³)

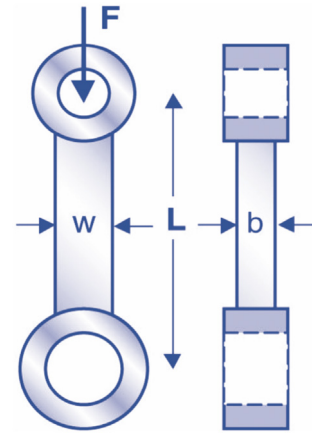


Fig. 6. Schematic of a connecting rod.

Replacing Z by ϕ using Eq. (16) gives:

$$\sigma_y = 6 \frac{FL}{\phi H^{3/2}} \quad (17)$$

Using Eq. (17) to eliminate H in Eq. (14) gives:

$$m^* = (6FL)^{2/3} L \frac{\rho \cdot C_{IA}}{(\phi \cdot \sigma_y)^{2/3}} \quad (18)$$

The best alloy that mitigates the issues related to CRMs in forks production is that with the greatest value of the material index (M^*):

$$M^* = \frac{(\phi \cdot \sigma_y)^{2/3}}{\rho \cdot C_{IA}} \quad (19)$$

It is observed that the material index M^* is very similar to the Ashby's material index for light, strong beams, but with an added information about the alloy criticality.

Eq. (19) can be rewritten as follows:

$$\log(\phi \cdot \sigma_y) = \frac{3}{2} \log(\rho \cdot C_{IA}) + \frac{3}{2} \log(M^*) \quad (20)$$

If $C_{IA} = 1$, Eq. (20) is a family of straight parallel lines of slope 3/2 on a plot of $\log(\phi\sigma_y)$ against $\log(\rho)$, each line corresponding to a value of the constant M ($= (\phi\sigma)^{2/3}/\rho$). The higher the M value, the lower the forks weight or mass (m). All the materials that lie on a line of constant M = $(\phi\sigma)^{2/3}/\rho$ perform equally well as a light, strong fork; those above the line are better (Fig. 4).

Table 3 collects possible candidates corresponding to four alloys families: magnesium alloys, titanium alloys, aluminium alloys and steels. It is noted that even if steels are characterized by the highest values of M (Fig. 4), alloys having a fracture toughness <20 MPa m^{0.5} were not taken into account for safety reasons. The shape factors listed in Table 3 are those achievable using normal production methods.

Table 5
Alloy selection for con-rod.

Alloy	ρ (kg/m ³)	E (GPa)	σ_e (MPa)	m_1 (kg)	m_2 (kg)	m (kg)	C_{IA}	m_1^* (kg)	m_2^* (kg)	m^* (kg)
Ti-6-4	4430	113	634	0.10	0.21	0.21	0.082	0.01	0.02	0.02
Be	1840	290	380	0.07	0.05	0.07	3.262	0.23	0.18	0.23
Al 7075 T6	2770	69	152	0.27	0.17	0.27	0.117	0.03	0.02	0.03
AZ61	1800	40	100	0.27	0.14	0.27	3.837	1.03	0.57	1.03

Table 6
Material indexes values.

Alloy	M ₁ kg/(m ³ MPa)	M ₂ kg/(m ³ MPa ^{1/2})	M ₁ [*] kg/(m ³ MPa)	M ₂ [*] kg/(m ³ MPa ^{1/2})
Ti-6-4	6.98	13.17	0.57	1.08
Be	4.84	3.41	15.78	11.13
Al 7075 T6	18.22	10.54	2.13	1.23
AZ61	18.00	9.00	69.06	34.53

When the main goal is the reduction of the risks associated to CRMs content in the alloy, the material index M* (Eq. (19)) must be maximized. A log-log plot Cl_Aρ-φσ_y is helpful in this case (Fig. 5).

Eq. (20) is plotted as straight line in Fig. 5 with a M* value equal to 8 (MPa)^{2/3}/(kg/m³) while Table 4 collects candidates that maximize M* for each alloy family.

It is observed that in a CRMs perspective, the best alloy is Titanium (grade 4) while the magnesium alloy is the worst because of its highest value of Cl_A and lowest value of strength (σ_y). A competition in a CRMs perspective is there between aluminium alloys and steels for forks production.

3.2. Case-study: con-rod for high performance engines

As a second example, the material selection for a con-rod for high performance engines in a CRMs perspective is illustrated. A connecting rod in a high-performance engine, compressor or pump, is a critical component. It means that if it fails, catastrophe follows. Yet to minimize inertial forces and bearing loads it must weigh as little as possible, implying the use of light, strong materials, stressed near their limit. Furthermore, the minimization of the risks linked to CRMs used for the alloy production is now required. The connecting rod must not fail by high-cycle fatigue or elastic buckling. Stroke, and thus con-rod length L, is specified (Fig. 6). Free variables are the material choice and the section area. For simplicity, it is assumed that the shaft has a rectangular section H = bw (Fig. 6). When the performance must be optimized, the objective equation to be minimized is the con-rod mass (m):

$$m = \beta \cdot \rho \cdot L \cdot H \tag{21}$$

where L is the length of the con-rod, ρ is the density of the material, H is

the cross-section of the shaft and β is a constant multiplier to allow for the mass of the bearing housings.

When the criticality of the con-rod needs to be taken into account, the objective equation to be minimized becomes:

$$m^* = \beta \cdot \rho \cdot L \cdot H \cdot Cl_A \tag{22}$$

The fatigue constraint requires that:

$$\frac{F}{H} \leq \sigma_e \tag{23}$$

where σ_e is the endurance limit of the material of which the con-rod is made. Using Eq. (23) to eliminate H in Eqs. (21) and (22) gives:

$$m_1 = \beta FL \left(\frac{\rho}{\sigma_e} \right) \tag{24}$$

$$m_1^* = \beta FL \left(\frac{\rho Cl_A}{\sigma_e} \right) \tag{25}$$

From Eqs. (24) and (25) the following materials index are obtained, respectively:

$$M_1 = \frac{\rho}{\sigma_e}, \quad M_1^* = \frac{\rho Cl_A}{\sigma_e} \tag{26}$$

The buckling constraint requires that the peak load F does not exceed the Euler buckling load:

$$F \leq \frac{\pi^2 EI_{min}}{L^2} \tag{27}$$

with (I_{min} = b³w/12). Writing b = αw, where α is a dimensionless 'shape constant', and eliminating H from Eqs. (21) and (22) gives:

$$m_2 = \beta \left(\frac{12F}{\alpha \pi^2} \right)^{1/2} L^2 \left(\frac{\rho}{E^{1/2}} \right) \tag{28}$$

$$m_2^* = \beta \left(\frac{12F}{\alpha \pi^2} \right)^{1/2} L^2 \left(\frac{\rho Cl_A}{E^{1/2}} \right) \tag{29}$$

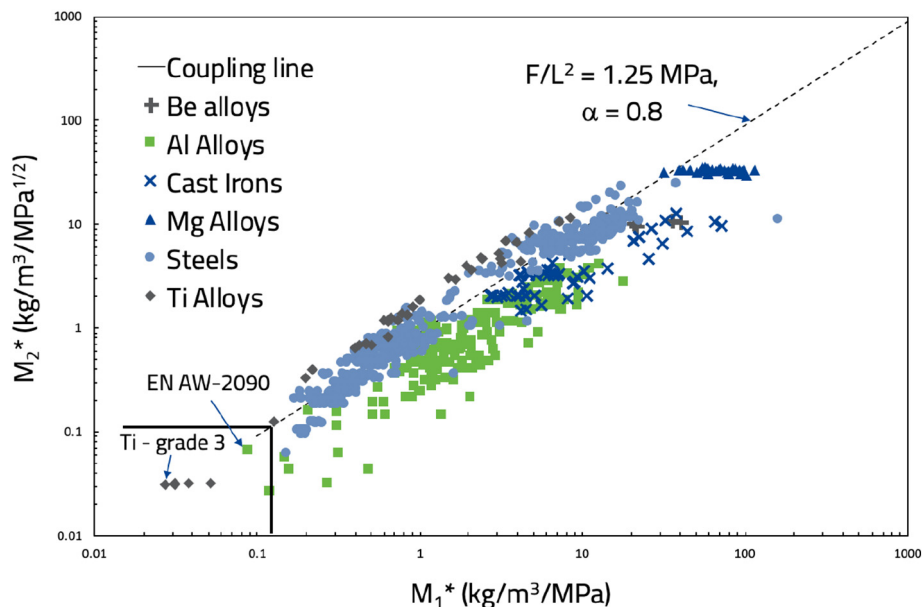


Fig. 7. Materials map M₁^{*} against M₂^{*}.

where the material indexes are:

$$M_2 = \frac{\rho}{E^{1/2}}, \quad M_2^* = \frac{\rho C I_A}{E^{1/2}} \quad (30)$$

The con-rod, to be safe, must meet both constraints. For a given length, L , the active constraint is the one leading to the largest value of m or m^* . Using a materials database and specifying the constants values (i.e.: $L = 200$ mm, $F = 50$ kN, $\alpha = 0.8$ and $\beta = 1.5$) m_1, m_1^*, m_2, m_2^* can be calculated (Table 5). For each material, $m = \max(m_1, m_2)$ and $m^* = \max(m_1^*, m_2^*)$ are then considered and the minimum value of m and m^* will give the best material choice in terms of performance and reduced criticality, respectively. As an example, Tables 5 and 6 summarizes the results obtained for four different alloys used in the con-rods production.

Con-rods have been made from all the materials in Tables 5 and 6. Aluminium and magnesium alloys in road cars, titanium and (rarely) beryllium in racing engines. Certainly, if the performance (m) is of primary importance, beryllium is the best choice; but if CRMs issues need to be taken into account (m^*) the titanium alloy is the best solution, followed by the aluminium alloy with a value of m^* very closed to that of the titanium alloy. The magnesium alloy is the worst choice among the materials considered, in terms of both performance and criticality aspects.

A more systematic alloy selection based on optimum combination of M_1^* and M_2^* is possible by creating a chart with these indices as axes (Fig. 7). Now, setting m_1^* equal to m_2^* , the equation of the so-called coupling line can be obtained (Eq. (31)):

$$M_2^* = \left[\left(\frac{\alpha \pi^2 F}{12 L^2} \right)^{1/2} \right] M_1^* \quad (31)$$

Appendix A

Table 7

Values of the criticality indexes coming from literature for different CRMs [14].

CRM	ARL	HHI _{WGI}	HHI _{EPI}	SR	EI	EOL-RIR index	CI _{CRM}
Sb	4	3.6	3.31	4.3	4.3	2	3.585
Ba	2	1.44	1.13	1.6	2.9	5	2.345
Be	3	2.5	2.77	2.4	3.9	5	3.262
Bi	4	4	3.67	3.8	3.6	5	4.012
B	3	2.81	2.29	3	3.1	5	3.200
Ce	3	5.57	4.09	4.9	3.6	5	4.360
Cr	2	1.2	1.1	0.9	6.8	2	2.333
Co	3	2.34	1.7	1.6	5.7	5	3.223
F	–	–	–	1.3	4.2	5	1.750
Ga	3	3.83	3.53	1.4	3.2	5	3.327
Ge	3	3.88	3.59	1.9	3.5	5	3.478
Hf	3	0.729	0.871	1.3	4.2	5	2.517
He	2	–	–	1.6	2.6	5	1.867
In	4	1.99	1.71	2.4	3.1	5	3.033
Ir	5	3.06	2.87	2.8	4.3	3	3.505
La	3	4.68	4.31	4.9	3.6	5	4.248
Mg	1	4.37	4.02	4	7.1	4	4.082
Mo	3	1.23	1.17	0.9	5.2	2	2.250
Natural graphite (carbon)	2	3.89	3.59	2.9	2.9	5	3.380
Nb	3	3.05	2.66	3.1	4.8	5	3.602
Os	5	3.06	2.9	–	–	–	1.827
Pd	4	1.73	1.34	1.7	5.6	4	3.062
Pt group (PGM)	4	2.19	2.03	2.5	5	3	3.120
P	–	–	–	1	5.1	3	1.517
Pt	4	2.19	2.03	2.2	4.9	3	3.053
Pr	3	4.68	4.31	4.9	3.6	3	3.915
Rh	5	3.06	2.9	2.5	6.6	2	3.677
Ru	5	3.06	2.9	3.4	3.5	3	3.477
Sc	3	5.57	4.09	4.9	3.6	5	4.360
Si	1	2.99	2.74	1	3.8	5	2.755
Ta	3	1.61	1.54	1	3.9	5	2.675
W	3	4.03	3.7	1.8	7.3	1	3.472
V	2	2.47	2.22	1.6	3.7	1	2.165
Y	3	5.57	4.09	4.9	3.6	5	4.360

where the quantity in the square brackets is called coupling constant C . The solution will be somewhere in the lower left corner identified by the selection box shown in Fig. 7. Compared to the previous solutions already used in the market, the titanium (grade 3) and the aluminium alloy EN AW-2090 appears as the best solutions that minimize the risks linked to CRMs. However, it is worth mentioning that some solutions, such as pure metals like EN AW 1000, may be only apparent because, due to their low mechanical properties, they could not satisfy geometrical limitations or other restrictions not specified in this simplified example.

4. Conclusions

A systematic method was proposed for the selection of metallic materials in a critical raw materials perspective. The procedure is based on the definition of the alloy criticality index, CI_A , that measures the overall criticality of the alloy per unit of mass and averages different criticalities issues defined and quantified by EU. Using the material selection strategy, first developed by Ashby, and the CI_A concept, a material index, M^* , can be obtained and used as excellence criterion for materials selection. It is observed that CI_A values, like the cost attribute, may change during time and should thus be updated accordingly.

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Glossary

- CRMs: Critical Raw materials
 EU: European Union
 EC: European Commission
 CI_A : Alloy Criticality Index
 CI_{CRM} : Critical Raw Material Criticality Index
 ARL: Abundance Risk Level
 HHI: Herfindahl-Hirschman Index
 HHI_{WGI} : Sourcing and Geopolitical Risk Herfindahl-Hirschman Index
 WGI_c : World Bank's Worldwide Governance Indicator for the producing country 'c'
 S_{ic} : Percentage (%) of worldwide production of the raw material 'i' within country 'c'
 EPI_c: Environmental Performance Index
 HHI_{EPI} : Environmental country risk Herfindahl-Hirschman Index
 SR: Supply Risk
 g: Raw material substitutability
 f: Recycling rate
 A_s : Share of material consumption in a given end-use sector (s)
 EI: Economic importance
 GDP: European gross domestic product
 Qs: Economic importance of the sector s
 EOL-RIR: End of life recycling input rate
 m: Mass
 M: Material index
 ϕ : Shape factor
 σ_y : Yield stress
 ρ : Alloy density
 Z: Section modulus of the beam
 Z_0 : Section modulus of the reference beam of square section
 I: Second moment of area
 C: Coupling constant