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Lightweight design versus raw materials criticalities

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ABSTRACT

The 4th list of Critical Raw Materials has been published by the European Commission at the beginning of September 2020. A trend of increased criticality is observed for all raw materials in 2020 compared to 2017 and four new critical raw materials appeared (bauxite, titanium, lithium, and strontium) that pose new restrictions in lightweight design of metallic components. Based on a materials selection methodology developed in literature to face such emerging issues, the criticality assessment of light alloys is evaluated and rationally considered in lightweight design by using a trade-off material selection strategy. A simplified case-study is proposed as an example.

1. Introduction

The world is approaching to a new era in which sustainability is one of the key factors [1–3]. Sustainability is inevitably linked, among the others, to lightweight design which in turn depends on multi-materials products development. Today cars are an easy example in which advanced high strength steel, composites, polymeric materials as well as light alloys are extensively used together to maximize the performances, reduce weights and therefore the polluting gases emission [4,5]. Weight reduction is an imperative goal also because of the growing importance given by Europe to new strategic sectors or technologies such as e-mobility, drones, robotics, 3D printing, defense and aerospace. What can be observed is that materials demand is driven by technological changes [6] of new strategical mega sectors. Defense, in particular, and therefore raw materials it depends on, is gaining in importance due to the emerging conflicts that people are witnessing over the world (say, Russo-Ukraine conflict that is of great concern for Europa as well as wars in Congo, Middle East, Yemen) in this historical period [7]. Focusing on light alloys, such as magnesium, aluminum, beryllium, or titanium alloys, that cannot be substituted by composites or polymers when the working temperature exceeds 200–300 °C, it is noted that they suffer from a high criticality issue according to European Community (EC) [8,9]. As a matter of fact, the European Commission is used to investigate which raw material is considered critical according to different criteria or indicators that quantify the economic importance (EI), the supply risk (SR), the recyclability input rate, the substitutability issue, etc. The critical raw materials list is updated every three years and the last report dates September 2020 [8]. It is worth mentioning that the criticality assessment of raw materials is not an easy task and that there is not a recognized method to reach that goal in literature [10,11]. In a recent paper, Hofmann et al. [12] 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. The SCARCE method to enhance the assessment of critical resource use at a country level was proposed by Bach et al. [13]. To measure social aspects the categories small scale mining, geopolitical risk and human rights abuse are introduced. Environmental aspects are considered within the categories sensitivity of the local biodiversity, climate change and water scarcity. Additionally, next to metals also fossil fuels are included allowing a direct comparison of both abiotic resources. In a recent paper, Bongartz et al. [14], focusing on metal requirements for lithium-ion batteries in electric vehicles, defined overall criticality indicators obtained by aggregating the criticalities based on supply risks, vulnerability to supply risks and environmental implications. In their work, Graedel et al. [15] characterized the criticality of 62 metals and metalloids in a 3D “criticality space” consisting of supply risk, environmental implications, and vulnerability to supply restriction. They found that the metals of most concern tend to be those with three characteristics: they are available largely or entirely as byproducts, they are used in small quantities for highly specialized applications, and they possess no effective substitutes. Finally, the reader is suggested to read the paper ‘review of methods and data to determine raw material criticality’ published by 27 international experts in order to deepen the issues related to raw material criticality assessment [16].

Among possible mitigating actions against CRMs drawbacks,

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substitution was explored by different authors in literature. Pavel et al. [17] face the problem of rare earths substitution in electric road transport applications. They showed how the problem is extremally complex and challenging since there are no apparent effective substitutes for the rare earths used in permanent magnets despite several high potential options for permanent magnets synchronous-traction motors (PMS) exist and could be rapidly brought to commercialization to face rare earths increasing demand.

In this scenario, Ferro et al. [18–21], in the frame of Ashby's material selection method [22], developed a procedure to assess the material's index containing information about criticality that can be used in design to consider the problems related to CRMs. In this regard, it is worth mentioning that the criticality concept is very relative since it depends on the Country where it is formulated. In fact, the supply risk, for instance, is a geopolitical factor, based on the natural resources of a country [10]. The technology to process and recycle a raw material also varies from country to country, and it affects both the SR and the EI; and last, but not least, the strategic technologies and the strategic sectors, also vary through the globe. It is noted, in fact, that, since defense, drones and robots are today considered strategic sectors for Europe, the updated CRM list contains titanium as well as bauxite, among the others, as new critical raw materials [9]. Aluminum is not a CRM yet, but, obviously, bauxite can be related to primary aluminum production used in the fabrication of high performances aluminum alloy components. Magnesium and Beryllium, as well, were present in the previous 'blacklist' and still lays in the new one.

Since the product efficiency strictly depends on CRMs, it is clear that the raw materials criticality concept must be urgently included in the lightweight design. Materials that minimize the component weight don't necessarily reduce the criticality issues related to their CRMs content; thus, a multi-objective strategy taking advantage from trade-off diagrams is necessary. As a matter of fact, an alloy could have a lower amount of critical raw materials but not necessarily higher mechanical properties able to reduce the weight of the component. On the contrary, most CRMs in alloy composition are used to improve the mechanical properties followed by a proper heat treatment (say, secondary Al—Mg (T6) alloys, where Mg is a CRM). The more the CRMs in the alloy the higher the mechanical properties and the lower the component weight.

In the first part of the work, the criticality assessment of raw materials is updated according to the new report coming from EC. In the second part, a method to quantify the criticality issues linked to raw materials is described and trade-off plots are proposed that link light weight design objectives with the product criticality reduction in a CRMs perspective. Finally, a simplified case studies is illustrated to show the potentiality of the proposed approach in product design.

2. Critical raw materials and criticalities assessment

According to the European Commission, raw materials (RM) are classified basing on their supply risk (SR) and economic importance (EI) values. In particular, CRMs are those RM that are characterized by a SR ≥ 1 and an EI ≥ 2.8. Fig. 1 shows the CRMs list (red points) dated 2017 and the new one, dated 2020.

It is interesting to observe the increasing trend of the economic importance indicator for the majority of raw materials in 2020 compared to 2017 as well as the new added CRMs, i.e., bauxite,

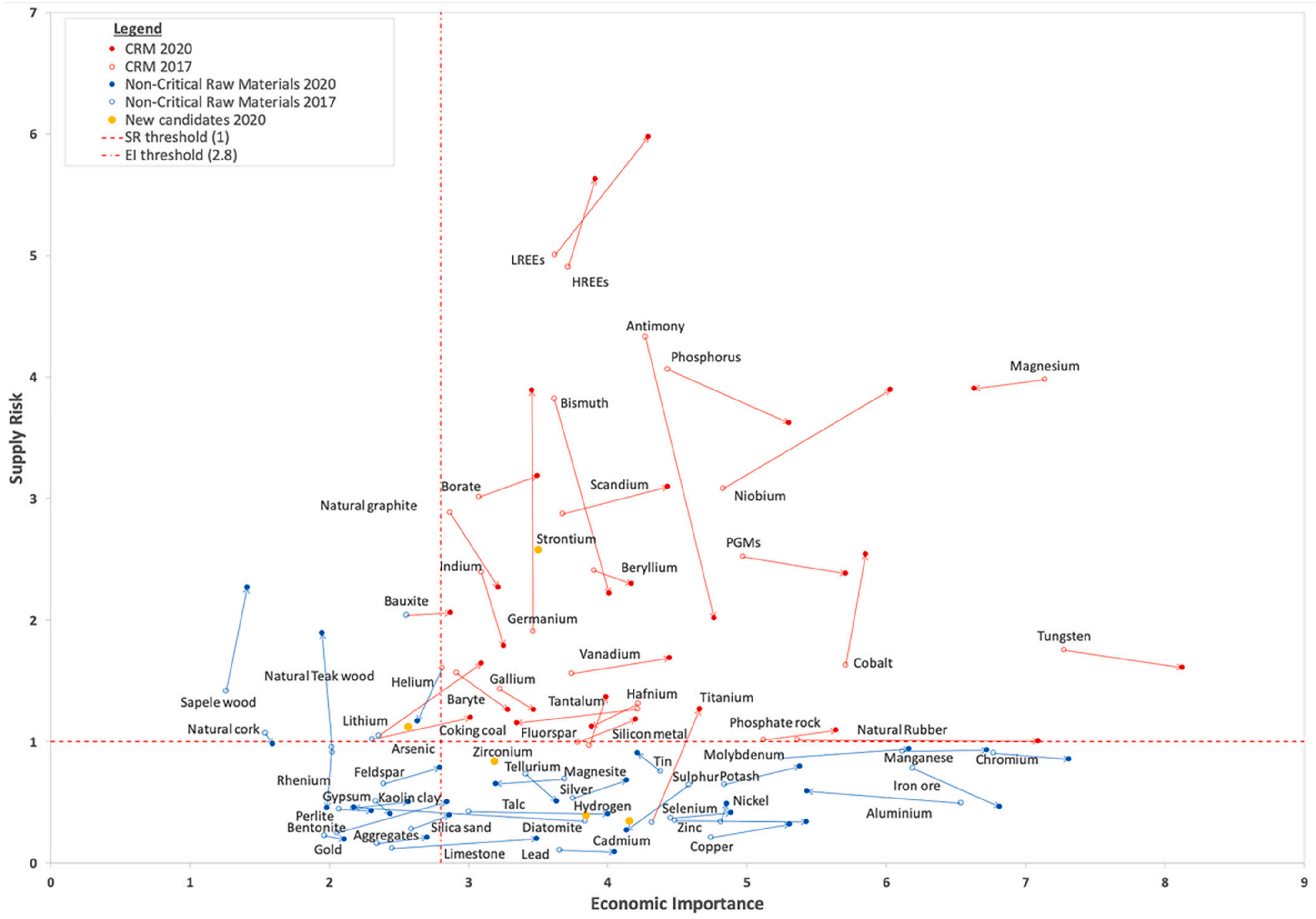

Fig. 1. European Raw Materials classification according to EI and SR: 2017 list versus 2020 list.

titanium, lithium, and strontium. Niobium, for example, increased both its SR index value and its EI index. Niobium, in fact, has a primary role in high-strength stainless steel and super-alloys [23] for most strategic technologies (i.e.: 3D printing, drones, wind turbines and robotics). Moreover, Niobium is also foreseen to be used in future anode and cathode materials for electric batteries [24] that are the most crucial and strategic technology since it also serves robotics, drones and digital technologies and it is relevant for all the strategic sectors considered by the European Union. Dealing with light metals (Mg, Ti, primary Al), all of them are practically critical since even if Al doesn't take part to the 'blacklist' directly, it is considered critical in its primary form coming from bauxite.

It is worth mentioning that the criticality issue linked to RMs it's a very complex drama that for its nature cannot be reduced to the definition of two indicators only (say, SR and EI). This is the reason why other aspects of the RMs criticality need to be quantify by other indicators such as the abundance risk, the sourcing and geopolitical risk, the environmental country risk and, finally, the end-of-life recycling input rate. To be able to use all of them in lightweight design, it is convenient to find and aggregation procedure to reduce all the criticality indicators in an overall general indicator for each critical raw material [25]. One possibility should take the normalized value of each index to remove the units and reduce them to a common scale. Then, they may eventually be weighted to reflect the perceived seriousness of each criticality, and finally, the weighted, normalized measures should be summed or averaged to give the overall indicator. For the sake of simplicity, in this work the criticality indicator for a CRM 'i' (CI_{CRMi}) is obtained by averaging the different normalized criticalities indexes as follows:

$$CI_{CRM_i} = (k_{ARL}ARL_i + k_{SGR}SGR_i + k_{ECR}ECR_i + k_{NSR}NSR_i + k_{NEI}NEI_i + k_{RDI}RDI_i)/6 \quad (1)$$

where k is a non-dimensional coefficient which value is in between 0 and 1, according to the seriousness of the corresponding criticality aspect, ARL_i is the normalized value of the Abundance Risk Level of the CRM 'i', SGR_i is the normalized value of the Sourcing and Geopolitical Risk of the CRM 'i', ECR_i is the normalized value of the Environmental Country Risk of the CRM 'i', NSR_i is the normalized Supply Risk of the CRM 'i', NEI_i the normalized value of the Economic Importance index of the CRM 'i' and finally RDI_i is the normalized value of the Recycling Drawback Index of the CRM 'i'. Detailed description of each of the above-mentioned normalized criticality indicators can be found in reference [26] and Appendix A, while the 2020 updated list of their values is collected in Table 1 (with $k_i = 1$, see Eq. (1)). It is observed how the highest CI values are reached by rare earth elements and palladium metals group. While, the most 'critical' metal, among those used as matrix in light alloys and marked with pink colour in Table 1, is Magnesium. Since in a general alloy different elements are present in its composition, including CRMs, it is reasonable to assess the alloy criticality issue by using the following index:

$$CI_A = \sum_{i=1}^{n} CI_{CRMi} \cdot P_{CRMi} \quad (2)$$

where n is the number of CRMs in the alloy chemical composition and P_{CRMi} is the weight amount of CRM 'i' in the alloy considered. It is observed that the alloy criticality index (CI_A) represents an overall criticality value per unit of mass. In a CRMs perspective, the objective to be minimized will be the criticality of the designed component (unit of function). This objective is formulated by multiplying the mass of the component (m) by the alloy criticality index (Eq. 2) [16]:

$$m^{CRM} = m \bullet CI_A \quad (3)$$

As above mentioned, since CI_A represents an overall criticality value per unit of mass of the alloy, m^{CRM} quantifies the criticality of the whole component in a CRMs perspective.

Table 1

Criticality indicators value (grey: Palladium Group Metals (PGMs); blue: Light Rare Earth Elements, LREEs; green: Heavy Rare Earth Elements, HREEs; light red: metals used as matrix in light alloys where Bx (bauxite) should be considered equivalent to primary Al). CRMs used as matrix in light alloys are marked with pink colour.

CRM	ARL	SGR	ECR	NSR	NEI	RDI	**CI**
Sb	6.22	6.47	6.44	3.22	5.92	3.33	5.27
Ba	3.03	2.15	2.16	2.03	4.09	9.76	3.87
Bx	0.64	1.24	1.18	1.33	3.56	10.00	2.99
Be	5.50	4.56	4.46	3.74	5.22	10.00	5.58
Bi	6.62	7.46	7.44	3.72	5.00	10.00	6.71
B	4.59	2.39	2.39	5.14	4.31	9.76	4.76
Co	4.59	5.38	4.21	4.14	7.40	4.76	5.08
Cc	-	3.73	3.72	1.98	3.78	10.00	-
Fl	3.08	5.17	5.13	1.94	4.15	9.76	4.87
Ga	4.58	7.47	7.44	2.07	4.33	10.00	5.98
Ge	5.68	7.47	7.45	6.32	4.33	9.52	6.80
Hf	5.09	2.64	2.00	1.76	4.84	10.00	4.39
In	7.08	3.09	3.02	2.88	3.90	10.00	4.99
Li	4.44	1.72	1.98	2.68	3.86	10.00	4.11
Mg	1.50	9.18	9.16	6.42	7.49	6.90	6.78
Gr	5.82	5.75	5.76	3.71	4.05	9.29	5.73
Nr	-	2.03	2.00	1.62	8.82	9.76	-
Nb	4.74	8.55	7.63	6.38	7.40	10.00	7.45
Phs	2.71	2.97	2.95	1.82	7.03	5.95	3.91
P	2.71	6.55	6.54	5.84	6.61	10.00	6.37
Sc	4.68	5.93	5.69	5.32	5.52	10.00	6.19
Si	0.00	5.16	5.14	1.93	5.24	10.00	4.58
Ta	5.87	2.70	2.58	2.19	4.98	10.00	4.72
Ti	2.02	0.83	0.88	2.02	5.82	5.48	2.84
V	3.84	3.42	3.34	2.72	5.56	9.52	4.73
W	5.54	7.82	7.80	2.57	10.00	0.00	5.62
Sr	3.26	2.60	1.99	4.42	4.39	10.00	4.44
Ir	10.48	7.84	8.89	5.08	5.21	6.67	7.36
Pd	9.11	3.33	2.99	1.93	8.67	3.33	4.89
Pl	9.12	4.94	5.51	2.62	7.41	4.05	5.61
Rh	8.82	6.11	6.86	3.62	9.25	3.33	6.33
Ru	9.29	8.00	9.08	5.96	5.06	7.38	7.46
Ce	4.02	8.58	8.56	9.69	4.43	9.76	7.51
Nd	4.39	10.00	10.00	9.49	5.96	9.76	8.27
La	4.33	10.00	10.00	9.08	1.91	9.76	7.51
Pr	4.97	8.58	8.56	8.63	5.38	7.62	7.29
Sm	5.15	8.58	8.56	10.00	9.09	9.76	8.52
Eu	5.82	8.58	8.56	4.95	4.06	0.95	5.49
Tb	5.98	8.58	8.56	7.50	5.14	8.57	7.39
Gd	5.22	8.58	8.56	9.20	5.83	9.76	7.86
Er	5.46	8.58	8.56	9.60	3.87	9.76	7.64
Dy	5.23	8.58	8.56	9.59	8.96	10.00	8.49
Y	4.50	8.58	8.56	6.83	4.29	2.62	5.90
Ho	5.86	8.58	8.56	10.00	4.18	9.76	7.82
Tm	6.35	8.58	8.56	10.00	4.18	9.76	7.90
Lu	6.33	8.58	8.56	10.00	4.18	9.76	7.90
Yb	5.53	8.58	8.56	10.00	4.18	9.76	7.77

3. Lightweight design in a CRMs perspective: A trade-off strategy

Dealing with lightweight design in a CRMs perspective the goal is to minimize both the weight, or the mass m, of the component and its criticality issue quantified by the function m^{CRM}. Unfortunately, the lightest alloys are not at the same time the least critical alloys, using the above defined index (Eq. 2). Therefore, a trade-off strategy is required to reach a compromise. By taking advantage from Ashby's methodology [27], a value function (V), or penalty function (a global objective), can be defined as follows:

$$V = \alpha_m \bullet m + \alpha_{m^{CRM}} \bullet m^{CRM} \quad (4)$$

where V is measured conventionally in units of currency ($, €, etc.), while m is the mass of the component and α_m and $\alpha_{m^{CRM}}$ are the so-called exchange constants [27] or parameter influence coefficients, defined by the following relations:

$$\alpha_m = \left(\frac{\partial V}{\partial m}\right)_{m^{CRM}} \quad \alpha_{m^{CRM}} = \left(\frac{\partial V}{\partial m^{CRM}}\right)_{m} \tag{5}$$

The exchange constant converts the units of one metric (say, m or m^{CRM}) into the other, cost, making the sum of different metrics, (m and m^{CRM}) possible. α measures the value of a unit change of the performance metric (i.e.: m or m^{CRM}) (Eq. 5). In particular, $\alpha_{m^{CRM}}$ quantifies the penalty (in units of currency) provided or perceived by a unit increase of m^{CRM} and α_m is the penalty V, quantified in terms of currency, provided or perceived by a unit increase of m.

With this problem formulation, the goal is to minimize the function V (Eq. 4). This can be done via both analytical and graphical method. The first one consists in evaluating the value of V for each alloy, ranking the results starting from the lowest value obtained and taking the three or four top ranked materials to be used for the final choice, according to supporting information. The graphical method requires to draw the trade-off plot as schematized in Fig. 2.

Each point in Fig. 2 is a material. Those which have the characteristic that no other solution exists with lower values of both the performance metrics are said to be *non-dominated* solutions (grey colored in Fig. 2); the line on which they lie (approximated with a smooth continuous line, without sharp corners (Fig. 2)) is called the optimal trade-off surface. Now, by rearranging Eq. (4), the following relation is obtained:

$$m^{CRM} = -\frac{\alpha_m}{\alpha_{m^{CRM}}} m + \frac{V}{\alpha_{m^{CRM}}} \tag{6}$$

Eq. (6) defines a linear relationship between m^{CRM} and m. More in detail, it describes a family of parallel lines called V-lines of slope $-\alpha_m/\alpha_{m\hat{}CRM}$, which position depends on the value of V. The lower the V value, the closer the V-line to the trade-off surface (Fig. 2). Therefore, the best choice lies nearest the point at which the V-line is tangential with the trade-off surface. It is interesting to observe that the best material choice depends on exchange constants values. In the graphical approach, those values are related to the V-line slope (Fig. 2). Therefore, the solution is a question of relative importance assigned to the two objectives to be minimized or, in other words, to the values assigned to the exchange constants.

4. Application: Spar beam design for aircraft wings

Aircraft construction is a typical lightweight design application where the cost is much less important than the performances. Typical alloys used in aircraft structures are aluminum alloys, magnesium alloys, titanium alloys as well as high strength steels [28,29]. The key properties used to select the best material are stiffness, density, strength, durability, damage tolerance. Fig. 3 shows the raw materials today used for the construction of a combat aircraft.

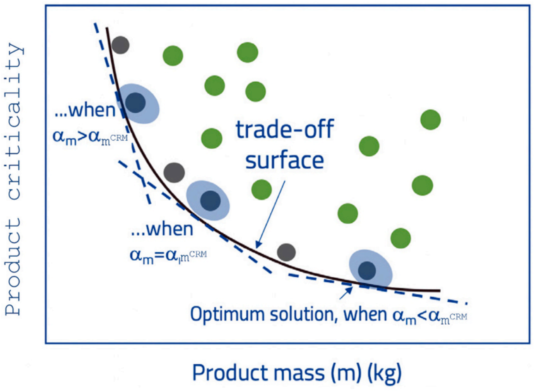

Fig. 2. *Trade-off plots criticality* versus *mass.*

Among the aluminum alloys, perhaps the mostly used ones, because of their high fatigue strength and fracture toughness, are AA 2024-T3, AA 7075-T6 and the relative recent Aluminum –Lithium alloys. They show an excellent strength-to-weight ratio and a good corrosion resistance, but a lower stiffness compared to steels. Among the titanium alloys, Ti-6Al-4 V is the mostly used one. Although heavier than aluminum alloys, it has a much higher stiffens, static and fatigue strength, corrosion resistance in seawater and marine atmosphere and working temperatures. For this reason, it finds increasing use in military aircraft (for instance, the F-15 contains 26%, structural weight, titanium). Due to their high density, high strength steels are used only where strength and yield stress are critical. Examples include landing gear units and highly loaded fittings made of 300 M steel [30]. Unfortunately, they are characterized by poor corrosion resistance so that they need to be protected by coatings.

In the material selection approach, the analyzed component, the spar for aircraft wings, can be schematized as a cantilever beam subjected to a bending load as shown in Fig. 4 (for material selection purpose torsion can be neglected).

It could be convenient to consider, as reference, the today used alloy to produce the spar of the Lockheed Martin F-16 Falcon, the AA 7075-T6 (Fig. 5), and try to look for if better alternatives exist in a CRMs perspective.

The first objective equation to be minimized, the mass m, can be written as:

$$m = AL\rho \tag{7}$$

where A is the cross-section area of the spar, L is its length and ρ is the material density. On the other hand, the drawbacks linked to CRMs used to produce the spar are reduced if the criticality per unit of function (m^{CRM}) is minimized (Eq. (8)):

$$m^{CRM} = AL\rho \cdot CI_A \tag{8}$$

Now, the spar will work if the stiffness is equal or greater than the design value (S*):

$$S = C\frac{EI}{L^3} \geq S^* \tag{10}$$

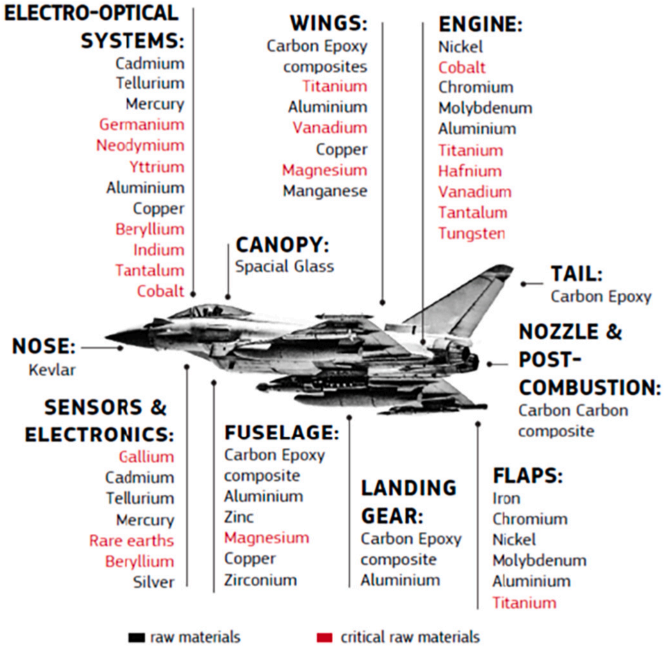

Fig. 3. Raw materials used in a combat aircraft.

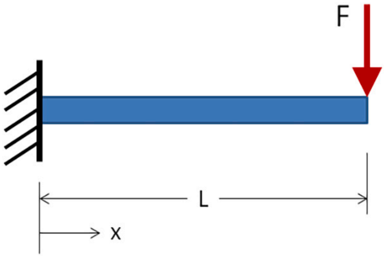

Fig. 4. Spar for aircraft wings schematized as a cantilever beam.

Fig. 5. Fighter Jet: F-16 Fighting Falcon.

In the constrain eq. (10), C is a constant depending on clamping condition and loads, E is the Young's modulus, I is the second moment of area. If for the sake of simplicity, the cross section has a square shape, I = $A^2/12$ and therefore, Eq. (10) can be rewritten as:

$$S = C\frac{EA^2}{12L^3} \geq S^* \tag{11}$$

Now, by making explicit the free variable, A, from Eq. (11) and by substituting it into Eqs. (7) and (8), the objective equations become:

$$m = \left(\frac{12L^3S^*}{C}\right)^{1/2} L\left(\frac{\rho}{\sqrt{E}}\right) \tag{12}$$

$$m^{CRM} = \left(\frac{12L^3S^*}{C}\right)^{1/2} L\left(\frac{\rho CI_A}{\sqrt{E}}\right) \tag{13}$$

m and m^{CRM} are minimized by materials that minimize the so-called material indexes $M = \rho/\sqrt{E}$and $M^{CRM} = \rho CI_A/\sqrt{E}$, respectively. To minimize both, one must seek the minimum of the value function (V):

$$V = \alpha_m\left(\frac{\rho}{\sqrt{E}}\right) + \alpha_{m^*}\left(\frac{CI_A\rho}{\sqrt{E}}\right) = \alpha_m M + \alpha_{m^*}M^{CRM} \tag{14}$$

or, referring to the aluminum alloy 7075-T6 having density ρ_0, modulus E_0 and alloy criticality index CI_{A0}:

$$V^* = \alpha_m^*\left(\frac{\rho\sqrt{E_0}}{\rho_0\sqrt{E}}\right) + \alpha_{m^*}^*\left(\frac{CI_A\rho\sqrt{E_0}}{CI_{A0}\rho_0\sqrt{E}}\right) = \alpha_m^* M^* + \alpha_{m^*}^* M^{CRM*} \tag{15}$$

By rearranging the terms of Eq. (15) the following family of parallels V* contours are obtained (with varying the V* value):

$$M^{CRM*} = -\frac{\alpha_m^*}{\alpha_{m^*}^*}M^* + \frac{V^*}{\alpha_{m^*}^*} \tag{16}$$

The trade-off plot M^{CRM*} versus M* is shown in Fig. 6. Each contour encloses a family of alloys used in the aircraft production. The point (1,1) is occupied by the reference material (AA 7075-T6). Therefore, in the quadrant A lay all the alloys with lower values of both M^{CRM*} and M*. It is easy to observe that beryllium alloys are much better than aluminum alloys; however, several problems arise when dealing with such kind of materials so that, in this example, they are not considered, so far. In quadrant B lay the alloys that are better in term of weight reduction compared to AA 7075-T6 but worst in terms of criticality. In quadrant D lay alloys better in terms of criticality but worst in terms of weight reduction and finally, in quadrant C lay alloys that are worst, compared to the reference one, in term of both mass reduction and criticality.

The trade-off surface (Fig. 6) is almost tangential to the magnesium alloys, aluminum alloys, and steels. The V*-line, tangent to the trade-off surface, is also plotted in Fig. 6, having a slope equal to −1 (meaning the criticality issues and mass reduction are valued equally). It is observed that the alloy more closed to the tangent point is that indicated with the red arrow in Fig. 6. Therefore, the trade-off plot identifies as the best

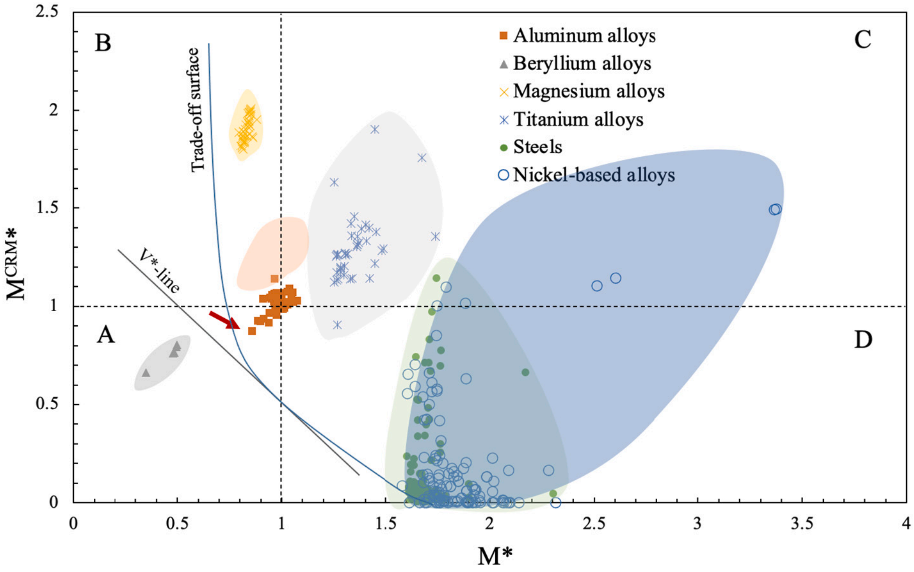

Fig. 6. Trade-off plot for material selection of a combat aircraft spar beam.

solution the aluminum alloy EN AW-8090 (EN AW-Al Li2.5Cu1.5 Mg1) in the heat-treated condition. However, further considerations can be done before reaching the final choice. The spar cross-section area should be first verified according to geometrical restrictions; fatigue strength could be also considered as restraint condition. However, the described procedure, although simplified, can propose alternatives to the reference alloy that are better in terms of both weight and criticality reduction.

To apply the present approach to a general design it is firstly necessary to have a materials data base covering for each member information about physical and mechanical properties as well the updated material criticality indicator value (Eq. (2)). The first step is the 'translation' in which, basing on what the component should do, constraints, free variables and objectives are defined. Within free variables the material is always present while the objectives are clear: both criticality and mass reduction (Eqs. 7 and 8). If the objective equation and the constraint are linked to each other through a free variable (i.e., the spar cross section area), a material index is calculated for each objective (i.e., M and M^{CRM}) that is a function of two or more material properties.

In the second step all materials are screened using constraints (such as corrosion resistance, formability, etc.). In the third step the remaining materials are ranked according to the material index value. Since mass and criticality are objectives in conflict to each other, a trade-off procedure is required as described in paragraph 3. Finally, the top ranked materials are analyzed according to 'supporting information' collecting case studies, supplier information, availability and so on. Therefore, the final choice is done. An important part of the method is the schematization of the component (i.e., Fig. 4) which must be enough simple to allow the application of engineering equations (say, Eq. 10) and describe at the same time the main component function (to bear bending loads). Details on geometry are not important for the method because they do not influence the final material choice.

It is worth mentioning that the power of the proposed method consists in the quantification of the component criticality by Eq. (3). Moreover, the selection can be focused on just particular aspects of the criticality, according to the designer concern, by simply fixing different values of k coefficients in Eq. (1).

5. Conclusions

Basing on the concept of alloy criticality index proposed in literature, a systematic approach was described to face the lightweight design integrating the growing drawbacks linked to the use of critical raw materials. It takes advantage from the method proposed first by Ashby and the use of trade-off plots, m against m^{CRM}, proposed in this work. Best materials depend on the relative seriousness attributed to the two objectives quantified by the ratio between the two corresponding exchange constants.

CRediT authorship contribution statement

Paolo Ferro: Conceptualization, Methodology, Data curation, Writing – original draft. **Franco Bonollo:** Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Here the criticality indicators definitions used in Eq. (1) are summarized. It is observed that they come from studies did by the European Commission. Normalization, scaling and aggregation methodology is instead proposed by the present authors to conveniently use them in the design process (Eqs. 1 and 2).

The Abundance Risk Level (ARL) of the CRM 'i' is associated to the value of the 'Abundance in the Earth's crust (AEC) [ppm]' by the following proposed relation:

$$ARL_i = 10 - \left[10 + log\left(\frac{AEC_{CRM_i}}{AEC_{CRM_{\max}}}\right)\right] \tag{1A}$$

where AEC_{CRMi} stays for the amount in the Earth's crust of the CRM 'i' (measured in ppm) and AEC_{CRMmax} is the maximum value found in the CRMs list.

The Sourcing and Geopolitical Risk (SGR) index indicates the supply disruption risk due to political factors, based on the countries in which the element is produced (e.g., in 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), the sourcing and geopolitical risk for an element 'i' is a modified and scaled Herfindahl-Hirschmann Index, calculated as (Eq. 2A) [31]:

$$HHI_i^{WGI} = \sum_c (S_{ic})^2 WGI_c \tag{2A}$$

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'.

The World Bank "Worldwide Governance Indicator" measures the political and economic stability of producing countries. In this context it is useful to remember that the Herfindahl-Hirschmann 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. The higher its value, the higher the risk. In the present work the SGR index of the CRM 'i' is normalized and scaled as follows:

$$SGR_i = \frac{HH_i^{WGI}}{HH_{\max}^{WGI}}\cdot 10 \tag{3A}$$

where $HHI_{\max}^{WGI}$ is the maximum value reached by the index HHI_i^{WGI} in the CRMs list.

The Environmental country risk (ECR) indicates the risk that worldwide supply of an element may be restricted in future because 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. It is quantified, for an element ‘i’, by the following equation:

$$ECR_i = \frac{HHI_i^{EPI}}{HHI_{\max}^{EPI}}\cdot 10 \tag{4A}$$

where,

$$HHI_i^{EPI} = \sum_c (S_{ic})^2 \left(10 - \frac{EPI_c}{10}\right) \tag{5A}$$

and $HHI_{\max}^{EPI}$ stays for the maximum value reached by the index HHI_i^{EPI} in the CRMs list.

EPI_c is the Environmental Performance Index calculated by Yale University, for the producing country ‘c’. The Environmental Performance Index (EPI) is a method of quantifying and numerically marking the environmental performance of a state's policies [32]. The greater the EPIc indexes, the lower the risk of supply disruption induced by environmental legislation.

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 for the element ‘i’ is given by eq. (6A) [33]:

$$SR_i = g_i(1 - f_i)HHI_i^{WGI} \tag{6A}$$

where g_i is the raw material substitutability (defined in eq. (7A)) and f_i is the recycling rate that is the ratio of recycling from old scrap to European consumption.

The substitutability, g_i, represents the possibility of substituting the raw material ‘i’ and it is calculated as a weighted average over the end-uses/sectors, as follows [23]:

$$g_i = \sum_s A_s g_s \tag{7A}$$

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 g_i, the lower 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_i is high), and because the recycled rate is low ($(1 - f_i)$ is high). In this work, the normalized and scaled SR indicator (NSR) is used:

$$NSR_i = \frac{SR_i}{SR_{\max}}\cdot 10 \tag{8A}$$

where $SR_{\max}$ stays for the maximum value reached by the index SR_i in the CRMs list.

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 [33]. The economic importance of a raw material ‘i’ (EI_i), is calculated as the weighted sum of the individual megasectors (expressed as gross value added), divided by the European gross domestic product (GDP) (Eq. 9) [31]:

$$EI_i = \frac{1}{GDP_i}\sum_s A_s Q_s \tag{9A}$$

In Eq. (9A), 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.

In the present work, the normalized and scaled EI indicator (NEI) is defined as follows:

$$NEI_i = \frac{EI_i}{EI_{\max}}\cdot 10 \tag{10A}$$

where $EI_{\max}$ stays for the maximum value reached by the indicator EI_i in the CRMs list.

Finally, 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, the EOL-RIR index is substituted by the recycling drawback index (RDI) defined as follows:

$$RDI_i = 10 - \frac{EOL - RIR_i}{EOL - RIR_{\max}}\cdot 10 \tag{11A}$$

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