

FLIGHT CRITICAL? A PERSPECTIVE ON THE ASSESSMENT OF RAW MATERIALS IN THE AVIATION INDUSTRY

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Abstract

The aviation industry is characterised by a strong dependence on particular raw materials due to high-performance requirements and strict certification standards. These materials are essential to the development of both economically and environmentally efficient aircraft and therefore form the foundation of the aviation industry as a whole. However, the supply chains for many of these materials are highly concentrated and have repeatedly proven to be vulnerable to disruptions, meaning that such dependence poses a systemic risk. To help stakeholders identify and mitigate such risks, a wide range of criticality assessment methodologies and lists of so-called critical raw materials have been developed. Yet, these criticality assessments are not standardised, are rarely tailored to specific industries and have seen only very limited use in aviation.

Therefore, we investigate how criticality assessment methodologies can be applied to the aviation industry. To do so, we first analyse existing criticality assessments and their underlying methodologies. In a second step, we apply a modified version of the GeoPolRisk methodology to both existing aircraft and a potential future design.

The results of the application step show that a large share of the materials used in aircraft qualify as critical raw materials. Although the criticality of individual materials varies across models and generations, the overall level of criticality remains consistently high, including in future aircraft. These findings demonstrate that the existing methodologies can be applied to aviation-related use cases and yield meaningful results. Nevertheless, they require adaptation to the specific requirements of the aviation industry and its stakeholders. Based on these findings, we propose further investigations into an aviation-specific criticality assessment methodology.

1. INTRODUCTION

Critical Raw Materials (CRMs) are essential to the functioning and development of the aviation industry. Their specific properties enable applications such as lightweight structures, high-performance engines, and advanced electronic systems. In this way, CRMs contribute to lighter structures and overall, more efficient aircraft designs.

However, most of these materials are associated with highly concentrated supply chains, considerable environmental burdens, and a susceptibility to supply disruptions. Increasing geopolitical tensions, including trade disputes and export restrictions, can further intensify these risks. The criticality of CRMs therefore does not primarily result from their geological scarcity. Instead, it predominantly originates from the geographical concentration of mining, processing, and refining activities, which are often located in regions associated with poor human rights and governance practices. [1, 2]

Criticality assessment methodologies support stakeholders in identifying and evaluating such material-related supply risks. They typically assess the risk of supply-chain disruptions alongside other relevant parameters and combine these into a criticality score for individual materials. Such assessments can support the identification and prioritisation of suitable mitigation strategies [3].

Integrating criticality considerations into preliminary design can help ensure that resulting products are not only optimised for their intended application and production, but are also more resilient to potential supply disruptions [4].

The aviation industry is characterised by several sector-specific requirements that can influence material criticality and the ability to respond to supply disruptions. These include stringent certification requirements, long development and production lead times, and a high concentration of certain suppliers and original equipment manufacturers [5]. Such characteristics can restrict the short-term substitution of materials, recycling possibilities and other mitigation strategies.

Despite these specific characteristics, material criticality in aviation has received limited academic attention. Existing criticality assessment methodologies are generally not tailored to the particular requirements and constraints of the aviation industry. Consequently, no aviation-specific criticality assessment currently exists, and it remains unclear whether existing methodologies sufficiently capture the risks relevant to the sector.

To address this gap, this study examines the criticality of materials used in current and potential future civil aircraft production. Existing criticality assessment methodologies are reviewed with regard to their applicability to the specific

characteristics of the aviation industry. The analysis covers the Airbus A320, A330, and A350, as well as the Boeing B777 and B787, which were selected to represent different aircraft types and generations. To extend the analysis towards potential future aircraft designs, a conceptual turbofan aircraft based on DLR's EXACT concepts is considered [6].

2. METHODOLOGY

2.1. Criticality Assessment Selection

As a first step, existing criticality assessment (CA) methodologies were analysed to identify an approach suitable for application to the aviation industry. Several reviews of criticality assessment methodologies already exist, including Schrijvers *et al.* [3], Perossa *et al.* [7] and Hackenhaar *et al.* [8]. These studies consider different methodologies with varying objectives, system boundaries and perspectives, resulting in conflicting recommendations. For the present study, the selection was based primarily on methodological simplicity, adaptability to an aviation-specific context and usability.

Based on these criteria, the GeoPolRisk methodology [9] was selected for the subsequent analysis. The detailed method is presented in FIGURE 1. GeoPolRisk assesses material criticality based on the geographical concentration of resources (mine production data), the economic value of the respective material (trade data) and the political stability (political stability data) of exporting countries [9, 10]. The methodology was selected due to its relative accessibility and the recommendation of the extensive review conducted by the Horizon 2020 project "Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy" [8]. The availability of an accompanying Python implementation further facilitates its application and adaptation.

2.2. Methodology Adaptation

While GeoPolRisk covers a broad range of raw materials, its underlying datasets do not consistently distinguish between material grades and processing stages relevant to specific industries. This represents a limitation for aviation, where highly processed and specialised material grades are commonly required. Both material prices and geographical supply concentrations can differ considerably between an unprocessed raw material and its aviation-grade equivalent. Titanium provides a particularly relevant example. Approximately 95% of global titanium ore production is used for titanium dioxide pigment production [11]. Consequently, the economic value represented in aggregated titanium datasets is strongly influenced by relatively low-value titanium oxides. Aviation-grade titanium metal, in contrast, requires additional processing steps that are substantially more expensive and geographically more concentrated. Its actual supply criticality can therefore be underestimated when ore-level data is used.

To take the aforementioned possible increase in criticality for aviation-grade materials into account, the Characterization Factors (CFs) are updated as follows. First, the material trade values used in the GeoPolRisk tool are compared to ones obtained by the German Raw Material Agency's (DERA) Preismonitor – a monitor of global material prices [12]. The resulting comparison reveals that the material prices in the GeoPolRisk tool are generally undervalued and thus lead to lower CFs. Although the supply chain concentration of these materials also differs, these changes are not revealed at the ore level used in GeoPolRisk. Continuing with the example of titanium, the price of titanium metal sponge is approximately 18 times higher than that of titanium oxides. According to the GeoPolRisk methodology, this difference results in an 18-fold increase in the CF for titanium. Since the increased concentration of this sponge production is disregarded, however, the criticality score would rise even higher in reality.

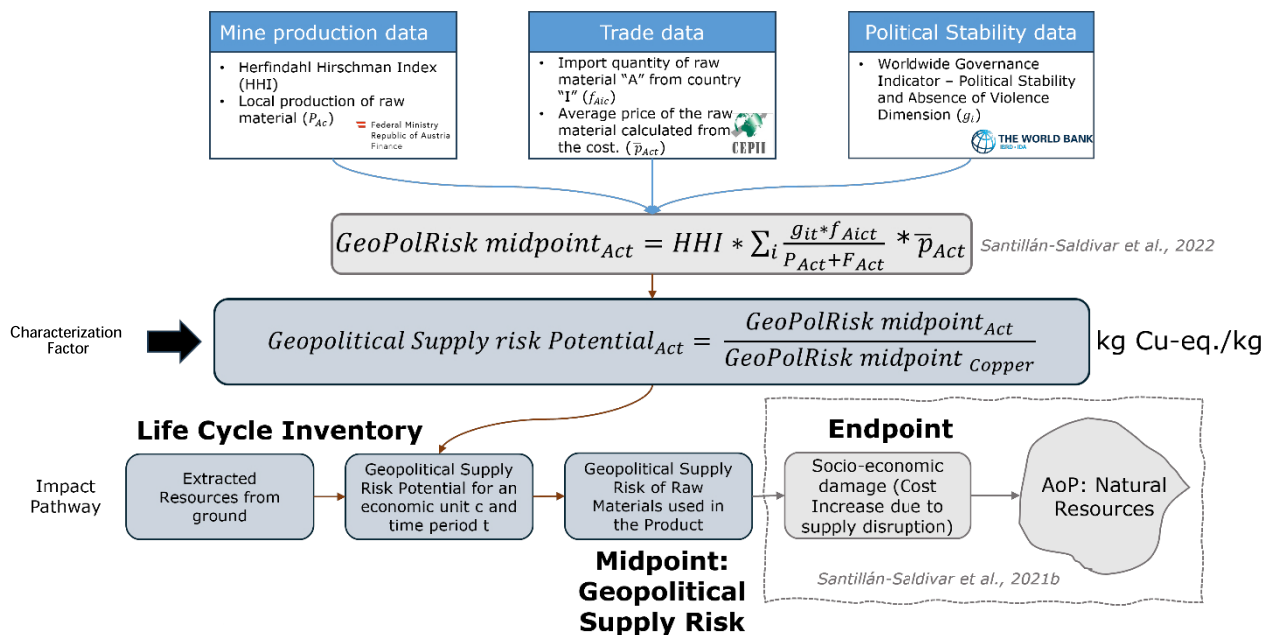


FIGURE 1: GeoPolRisk methodology based on Koyamparambath *et al.* [9]

Due to the unavailability of data for some CRMs, not all CFs could be updated according to the described procedure. Namely, the CFs for Rare Earth Elements (REEs) are identical due to the averaging of REE pricing and supply chain criticality in GeoPolRisk. Further, beryllium price could not be updated due to unavailable data in Preismonitor. Finally, the CF of vanadium (having had no value previously) is based on the supply chain of titanium since it is often a by-product of titanium production, combined with vanadium's market price.

2.3. Criticality Assessment

The updated values and the resulting CFs are subsequently adopted into the criticality analysis of the aforementioned aircraft (A320, A330, A350, B777, B787 and the conceptual turbofan aircraft based on EXACT, named D250-TF). The changes to the CFs of each raw material are presented in TAB 1.

Material	Original CF	Updated CF	Change from Original CF
Aluminium	0.80	0.57	-28.6%
Titanium	0.13	2.45	+1776%
Vanadium	0.00	9.26	+∞
Beryllium	0.06	0.06	-
Copper	0.19	0.51	+171%
Nickel	0.07	0.32	+389%
Cobalt	19.83	20.89	+5.30%
Niobium	25.60	33.36	+30.3%
Manganese	0.08	0.31	+273%
Tantalum	39.28	28.11	-28.4%
Magnesium	0.01	0.02	+177%
Tungsten	20.95	21.22	+1.31%
Lanthanum	3.12	3.12	-
Cerium	3.12	3.12	-
Lithium	5.57	22.85	+310%

TAB 1: Raw material original and updated characterization factors (CF) (rounded)

The criticality assessment requires a Bill of Materials (BoM) for each investigated aircraft. BoMs were compiled based on published data sources: Howe *et al.* [13] for the A320 model, Dolganova *et al.* [14] for the A330, Piquet and Blumenfeld [15] for the A350, Mouritz [16] for the B777, Ramakrishnan [17] for the B787, and Rahn *et al.* [18] for the future aircraft developed by DLR, which is based on the A321neo. Since most available BoMs provide only aggregated material categories rather than specific alloys, these material breakdowns are refined using representative aviation alloys from the literature. The resulting alloy compositions are then broken down into their constituent elements according to their respective mass fractions. This provides the material composition required for the subsequent criticality assessment.

The analysis is performed for the year 2022 due to the availability of the required trade and mining data used in the GeoPolRisk tool. Geographically, the assumed countries of aircraft production are France, Germany, Spain, UK, and United States, corresponding to the main production sites of the two major aircraft manufacturers Airbus and Boeing. Combining the updated CFs with the material composition of the aforementioned aircraft models, the overall criticalities (in terms of kilogram of copper equivalent mass) are obtained.

3. RESULTS

The absolute mass of CRMs in all aircraft designs is shown in FIGURE 3. The results show that the total mass and the mass fraction of CRMs vary substantially from one aircraft model to another. It can also be seen that newer aircraft models, such as the A350, B787, and D250-TF, have a lower share of critical raw materials relative to their Operating Empty Weight (OEW). This is primarily due to their higher share of Carbon Fibre Reinforced Polymer (CFRP) in the fuselage, wings, and structural components. CFRP is not considered a critical raw material in GeoPolRisk.

The calculated criticality of the CRMs in each aircraft is shown in FIGURE 2. The right-hand column for each aircraft shows the proportional contribution of each material to the total criticality impact, expressed in kilograms of copper-equivalent mass. Compared to the absolute values in FIGURE 3, titanium contributes a substantially larger share of the criticality impact. This is mainly due to its considerably higher CF of 2.45, compared with 0.57 for aluminium. Nevertheless, aluminium and titanium together account for the majority of the total criticality impact across all investigated aircraft designs.

When the criticality impact is considered relative to the OEW, all aircraft show similar values of slightly above 50%. This pattern of proportional criticality extends to the future D250-TF aircraft. The lower CRM mass fractions of newer, CFRP-intensive aircraft are largely offset by their higher titanium content and its high CF. Titanium is used to a greater extent in aircraft with a high proportion of CFRP in order to prevent galvanic interaction between the CFRP and aluminium. This results in comparable relative criticality impacts across all investigated designs.

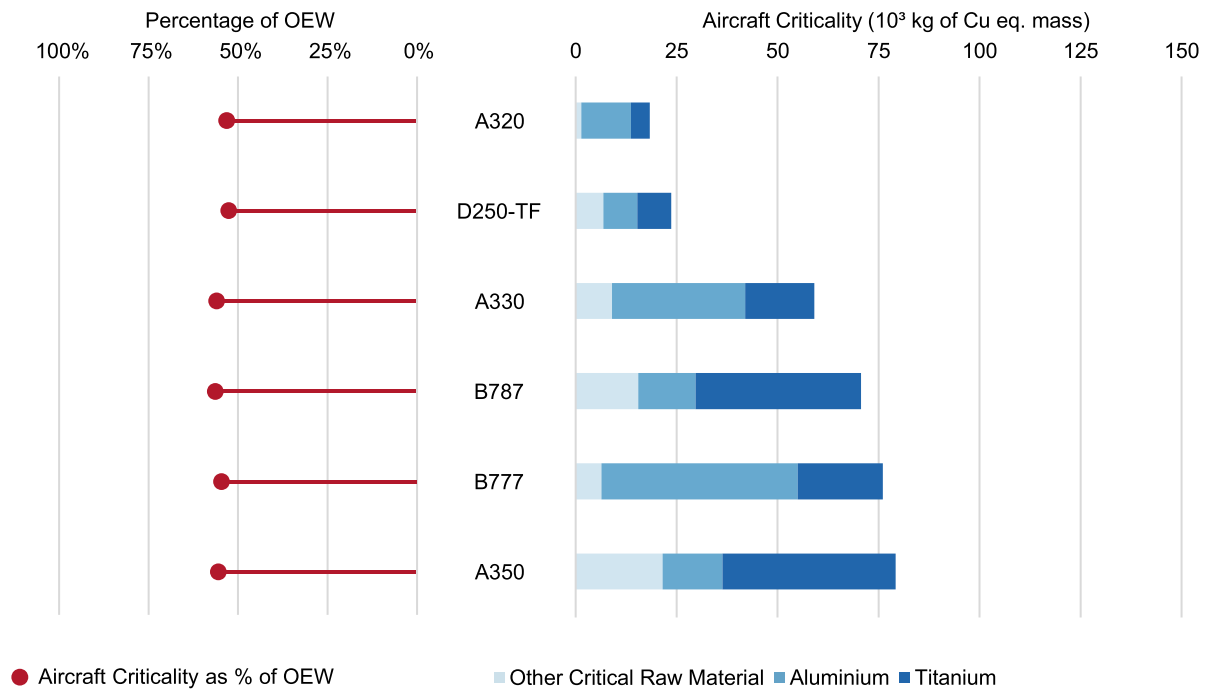


FIGURE 2: Critical raw materials in different aircraft designs (relative values, expressed as kilogram of copper equivalent mass)

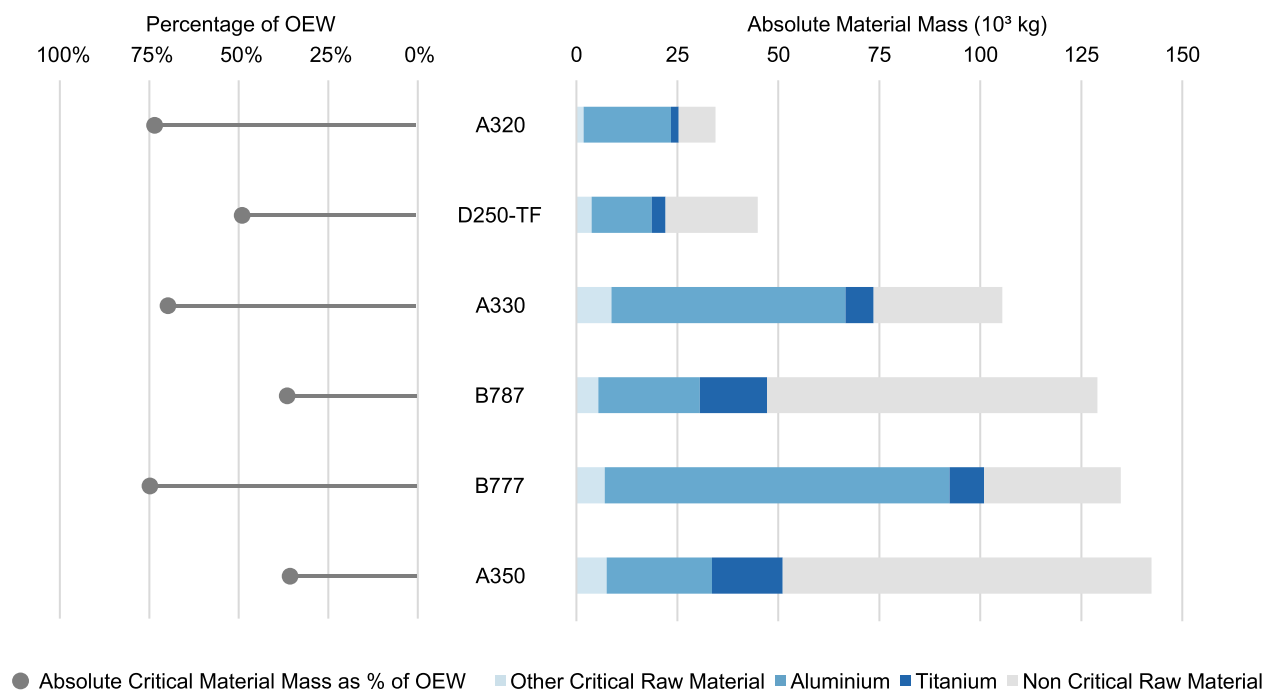


FIGURE 3: Critical raw materials in different aircraft designs (absolute values)

4. DISCUSSION

The results show a shift in the main contributors to material criticality across different aircraft generations. Aluminium has the highest impact in older aircraft, mainly due to its large mass fraction and widespread use. In newer aircraft, titanium becomes more important. This is linked to the higher use of CFRP and the related demand for titanium in composite-intensive structures. Newer aircraft also use more advanced alloys that contain elements with higher criticality, such as lithium in aluminium-lithium alloys and vanadium in titanium alloys.

Despite clear differences in absolute CRM mass and material composition, all investigated aircraft show a similar criticality impact relative to their OEW. The lower metallic content of newer aircraft is therefore partly offset by the higher criticality of materials such as titanium and selected alloying elements. This demonstrates that a lower total CRM mass does not automatically result in a lower overall criticality. As a result, newer aircraft designs do not necessarily reduce or increase material criticality, but shift it towards smaller amounts of more critical materials.

The available BoM data represent an important limitation of the analysis. Detailed alloy-level information was not available for all aircraft, and representative alloys had to be assumed for several material categories. This especially affects the A330, A350, B777, and B787. More detailed material data would therefore be needed to confirm whether the similar relative criticality values are a general trend. At the same time, such data are difficult to obtain, as detailed material compositions and production processes are often not known even for material assemblers, such as aircraft or component manufacturers.

The analysis also shows several limitations of applying existing criticality assessment methodologies to aviation. In GeoPolRisk, the contribution of a material is strongly influenced by the amount of material used. However, supply risk does not necessarily increase linearly with material mass. Even a material used in very small quantities can create a major supply risk if it cannot easily be substituted or obtained from another supplier. Other factors, such as stock levels, supplier concentration, certification requirements, substitution potential, and procurement lead times, may therefore be equally or more relevant depending on the application.

A further limitation concerns the geographical concentration represented in GeoPolRisk. While the adapted material values better reflect aviation-relevant material forms, the concentration of production is still largely based on mining data and pre-processing stages. More specialised stages, such as titanium sponge production, can be considerably more concentrated. This is also the case for many other critical raw materials for which bottlenecks exist not at the mining but processing stage. The criticality of aviation-grade materials may therefore still be underestimated.

The importance of material value for aviation can also differ compared to other sectors. For high-value products such as aircraft, the direct price or price volatility of a material may be less relevant than the consequences of its unavailability. In addition, a product-level assessment only considers materials contained in the final aircraft. Process materials

and manufacturing losses, for example due to high buy-to-fly ratios, are not fully represented. Additional assessments at process, supply-chain, or company level could therefore provide further information, particularly where more specific data on material origins, suppliers, processing routes, and inventories are available.

5. CONCLUSION

This study examined the applicability of criticality assessment methodologies to the aviation industry by reviewing existing approaches and applying an adapted GeoPolRisk methodology to current and potential future aircraft designs. The results show that a substantial share of aircraft materials contributes to material criticality and that the overall criticality remains at a similar level across different aircraft generations. While the main contributing materials shift from aluminium towards titanium and other more critical alloying elements, future aircraft designs do not show a clear reduction or increase in overall material criticality.

Nonetheless, the adaptations introduced in this study improve the applicability of GeoPolRisk to aviation. In particular, using more representative material values and processed material forms provides a more realistic representation of materials such as aviation-grade titanium. At the same time, the results show that further adaptation is required to better reflect aviation-specific supply chains and material requirements.

Future studies should therefore focus on improving both data quality and practical applicability. More detailed aircraft BoMs and aviation-specific data on material prices, processing routes, suppliers, and substitution options would improve the accuracy of the assessment. Future work should also examine how such methods can be applied in practice. In particular, it remains important to determine whether criticality scores provide useful information for decisions in material selection, procurement, supply-chain management, and preliminary aircraft and component design.

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