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The impact of circular strategies on titanium supply and demand in the aviation industry

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ABSTRACT

The supply of critical raw materials, especially titanium, poses a significant challenge for the aviation sector. Increased circularity is often proposed as a solution by industry and policymakers. However, the effects of circular strategies remain insufficiently understood. Therefore, this paper analyses different circular strategies, namely recycling, a pure lifetime extension, and an enhanced lifetime extension that includes an engine aircraft, based on real-world data up to the year 2040. The findings indicate that recycling retired aircraft only marginally affects the required rising inflow of titanium by less than 5%. The engine upgrade strategy shows similar results. In contrast, a pure lifetime extension shows the greatest potential for mitigating supply constraints and can be further enhanced to a potential of more than 10% when combined with recycling. The results highlight the complexity of circular strategies and emphasise a stronger focus on lifetime extension for the aviation sector and other industrial sectors.

1. Introduction

Resilient and flexible supply chains have been and continue to be a key challenge for the aviation sector, which is particularly vulnerable due to its complex, globalised, multi-level supply chains (Wirths, 2019) and a significant reliance on specific Critical Raw Materials (CRMs) (Dolganova et al., 2022). This has been highlighted by the COVID-19 pandemic and the Russian invasion of Ukraine.

Titanium metal[1] is particularly critical to the aviation industry, due to both its importance in modern aircraft design and near-total import reliance. The material is listed as critical in the United States of America (USA) (U.S. Geological Survey, 2024), the European Union (EU) (European Commission, 2023), and China (Chong et al., 2020), meaning it pairs high economic importance with potential future supply risks. Nevertheless, titanium is not a frequent topic of research (Watari et al., 2020).

The unique mechanical properties of titanium include a high strength-to-weight ratio, high operating temperature tolerance, corrosion resistance, and – perhaps most crucially – high compatibility with composite materials. The utilisation of titanium and its associated alloys thus results in weight savings and space efficiency when compared to other materials, such as steel, aluminium, or nickel (Boyer, 1995). As a consequence, the share of titanium in aircraft is continuously increasing, despite its high price (Nyamekye et al., 2023). Today two-thirds of the titanium metal in Europe is being allocated to the aviation sector (JRC et al., 2025). Military aircraft generally have a higher share of titanium as they are less cost-sensitive and have higher performance targets (Boyer, 2010).

Supply risks of titanium have already manifested in disruptions, e.g., 2022 led to delays in the assembly of Boeing's 737 MAX (Rudge, 2024) or even altered aircraft design with a reduced percentage of titanium in the design of the B767 due to perceived shortages (Whittaker and Froes, 2015). Such CRM-related disruptions are also common in other industries, such as the automotive industry or the energy sector (Sprecher and Kleijn, 2021). They mostly occur when exponential demand is met by unstable supply (Habib et al., 2021).

Due to the frequent occurrence of CRM supply chain disruptions, a wide range of strategies have been developed to mitigate their impact, with the EU in particular focusing on those related to increased circularity. This is supported multiple policies such as the Critical Raw Materials Act (European Union, 2024), the Clean Industrial Deal (European

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[1] The scope of this study is limited to titanium metal. Titanium oxide is not relevant to this study. To improve readability, the authors mostly refer to titanium metal as "titanium".

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Commission, 2025) or the Fly the Green Deal (European Commission, 2022). At the same time, the aviation sector already incorporates circular approaches, such as high product stewardship (Jensen and Remmen, 2017), long lifetimes of approximately 25 years (International Air Transport Association, 2018), reuse of aircraft, and a large variety of repair, refurbishment, and remanufacturing activities throughout the lifecycle. Also at an aircraft's end-of-life, components and engines are often reused, refurbished, or remanufactured (Cimprich et al., 2023).

These activities are commonly referred to as Maintenance, Repair and Overhaul (MRO) services inside the industry (Cimprich et al., 2023). Parts that are removed from end-of-life aircraft, refurbished or remanufactured, and reinstalled in aircraft are referred to as surplus material. Upgrading or remanufacturing of aircraft is commonly known as retrofitting (Wirths, 2019). Such unclear terminology presents a known hurdle in circularity-related research in relation to the aviation industry, as it incorporates different definitions and wordings for similar activities. Throughout the paper, the authors therefore used aviation-specific but commonly understandable terminology.

As much as MRO in aviation is an established industry activity, it is often overlooked, especially in regards to the circular potential of its activities. This is especially true if the potential to mitigate supply chain-associated risks is considered. This is equally evident for different end-of-life strategies including but not limited to recycling. The aim of this paper is therefore to examine to what extent circular strategies, including material recycling and various degrees of lifetime extension, can contribute to establishing a resilient and sustainable supply of titanium. The research question is thus:

What are the effects of circular strategies on the demand and supply of titanium in the aviation industry?

2. State of the art

In this section, salient characteristics of the aviation sector, the titanium supply chain, titanium recycling and circularity-related research are described. Aircraft are highly complex products, consisting of more than a million parts (Howe et al., 2013), with a commensurate highly complex supply chain (Al-kaabi et al., 2007). This supply chain is characterised by strongly positioned component manufacturers who act as competitors and suppliers to the Original Equipment Manufacturers (OEMs) simultaneously (Viera and Loures, 2016). Each of these actors is also present during the whole lifecycle of the aircraft, as they are often providing MRO services for their components and participate in the management of their end-of-life (Wirths, 2019).

The typical stages and actors involved in the forward titanium supply chain are well documented (Baldassarre, 2025) (see Fig. A.1 in Appendix A). Both leading aircraft manufacturing regions, the EU and the USA, are significantly reliant on imports of titanium. They lack production capacity for titanium sponge, a precursor for the production of titanium ingots and mill products (JRC et al., 2025). The industrial base for aviation-grade titanium sponge is situated in Japan (41%), Russia (30%), Kazakhstan (17%), and China (12%) (U.S. Geological Survey, 2024), with China only recently becoming capable of producing significant amounts of titanium sponge in the required quality (Georgitzikis et al., 2022; Li et al., 2022). Before the invasion of Ukraine, the Russian company VSMPO-AVISMA was the major supplier of titanium parts to both leading civil OEMs Boeing and Airbus and to component manufacturers such as Safran or Rolls-Royce (Georgitzikis et al., 2022). In older aircraft, titanium is predominantly used in the engine and to a smaller amount in the landing gear; newer aircraft incorporate large amounts of titanium in their structure (Mouritz, 2012b).

Research shows that aircraft and engines, which contain a high accumulation of multiple CRMs (Dolganova et al., 2022), present a potentially significant material stock at their end-of-life (Woidasky et al., 2017). In practice, however, this material stock often remains unexploited, effectively trapped in retired or stored aircraft parked at airports and in deserts around the world (Ribeiro and de Oliveira Gomes, 2015). Consequently, the main focus of existing circularity publications is on improving end-of-life recycling strategies and realising their environmental benefits. At the same time, recycling is often not pursued in practice due to limited economic potential (Scheelhaase et al., 2022; Ribeiro and de Oliveira Gomes, 2015; Asmatulu et al., 2013). From a circularity point of view recycling is considered to be of lower value, as other strategies, e.g. lifetime extension, retain a higher product value and could have more economic and environmental potential (Blomsma and Brennan, 2023; Allwood, 2014). Aviation in general misses research that is linked to such circular strategies, especially in relation to CRMs (Joensuu, 2023). There is also a need for a better understanding of titanium-related circular strategies in the aviation sector (Baldassarre, 2025).

Limited work exists on the titanium supply chain from a circular perspective. In contrast to the forward supply chain, scrap handling and recycling remain less well documented, in part due to its global character (Takeda and Okabe, 2019; Takeda et al., 2020). Baldassarre (2025) analyses strategies to enhance titanium circularity and reduce European import dependencies. The author finds that buy-back schemes for production scrap from US companies, as well as the country's dominant role in aircraft end-of-life handling, act as a barrier to increased titanium circularity in the EU. Again, two of the proposed counter strategies are recycling-related, including increased metal scrap collection from end-of-life aircraft. Buesa et al. (2024) assess the economic and greenhouse gas emission impacts of an increased titanium circularity in aerospace. While the calculated effects in both categories are minimal, the publication does not address the impact on an aircraft level or goes in-depth regarding possible effects on future supply and demand.

In contrast to the economic dimension, the technical perspective presents a low barrier to increasing titanium circularity. Most of the titanium is incorporated in disassemblable components (Baldassarre, 2025; Mouritz, 2012b), and approximately 60% of all materials can be recovered from the structure (Scheelhaase et al., 2022). The theoretical potential is even higher (85%–99%), but increasing the recycling rate comes with financial burdens (ecube, 2025; Airbus, 2022; European Union Aviation Safety Agency et al., 2022).

Once separated from the aircraft, recycling titanium presents few challenges. Many metals dissipate[2] over their lifetime. However, the dissipation rate of titanium metal during use can be neglected, and its recycling potential is theoretically 100% (Ciacci et al., 2015). The recycling process is an established industry practice based on vacuum arc remelting, electron beam melting and plasma arc melting. A combination of these procedures is typically used to reduce contamination (Takeda et al., 2020). These remelting technologies achieve a yield of approx. 95%, causing almost no losses of material (Charpentier Poncelet, 2021). Although a 50%–70% additive scrap ratio is common practice and recycling rates are high, this is restricted to production scrap (Takeda and Okabe, 2019). Even if collected, end-of-life material is currently not reintroduced into the aviation industry (Airbus, 2022). It is often downcycled to ferro-titanium (Takeda et al., 2020) (see Fig. A.1 in Appendix A), effectively dissipating.

In contrast to titanium, aluminium, and especially composites, both bulk materials in modern aircraft, are extensively studied from a circular point of view (Asmatulu et al., 2013). Especially composites are often a topic in sustainability and circularity-related research due to their challenges in the end-of-life phase and their increasing usage in modern aircraft (Lefeuvre et al., 2017; Scheelhaase et al., 2022). Connected Life-Cycle Assessment (LCA)-focused research provides a solid data basis for material compositions, raw material extraction and material dissipation, and includes specific documentation for MRO approaches (Rahn et al., 2022, 2024). However, LCAs in general do not specifically consider CRM or titanium-related issues.

[2] Dissipation is defined by Zimmermann and Gößling-Reisemann (2013) as "[...] losses of material into the environment, other material flows, or permanent waste storage that result in concentrations in the receiving medium such that a recovery of these materials is technically or economically unfeasible.".

3. Methodology

The amount of titanium in past and present aircraft was researched and collected from various sources. Given the presence of conflicting data from multiple literature sources partly due to the utilisation of differing or unclear reference aircraft weights, expert judgement and plausibility checks by the authors were applied in order to ensure the validity of the input data in the methodology. In addition, all sources, including conflicting data, are transparently presented in Tables A.1 and A.2 in Appendix A. Generally, the authors decided to utilise the lowest value in order to ensure a conservative approach. These data points were then combined with the commercial aircraft database Cirium, which provides a wide range of real-world data regarding the aviation sector, of which the "Fleets Analyzer" was accessed, which provides extensive data of all active, ordered or retired aircraft.

Next, the specific type, weight, order date, build year, entry into service (EIS) year, retirement year, location and current status from the two major OEMs, Boeing and Airbus, commercial passenger jet aircraft fleet were extracted from the database at the 6th of January 2025. This added up to 55,101 individual aircraft of the types B707, B727, B737, B747, B767, B757, B777, B787, A300/A310, A320, A330/A340, A380 and A350, including all their subtypes and different versions. In combination with the collected material data, the individual titanium mass of each aircraft was calculated. This enabled the derivation of the historical (up to the year 2024) and future titanium demand of commercial aircraft production. Note that this excludes production waste, so-called "buy to fly" ratios, which have been documented to reach up to 10:1 in the aviation industry (Alsabeeha et al., 2024; Pierrat et al., 2021; Whittaker and Froes, 2015; Li et al., 2022).

To address the geographical dimension described, the subset of stored aircraft was analysed. The total mass of titanium in the stored aircraft was derived for each storage location to provide an indication of the global distribution of accessible titanium in these aircraft. The authors decided against the application of this methodology for end-of-life aircraft, as the final airport is often not specified in the database and component dismantling could be undertaken elsewhere.

The future demand is based on the orders of specific aircraft that are deposited in the database as well as an extrapolated growth rate. The latter was based on the years 2028 and 2029, as this represents the last year where consistent order data was assumed. Orders are registered after the year 2029 up to the year 2039 but do not yet seem complete; consequently, demand would be underestimated otherwise. The growth rate is approximated to be 4.5%, representing a conservative estimation, as it represents the average growth rate of commercial aviation (Fleming and de Lèpinay, 2019), but excludes a future growth of titanium share in the aircraft. The assumptions and boundary conditions that were utilised throughout the study are summarised in Table A.3 in Appendix A.

In the subsequent step, three distinct strategies were conceptualised, representing a prospective circular approach. Each strategy is presented in detail in Table 1 and is further differentiated in the context of a conservative, a base, and a progressive scenario. They were subsequently assessed regarding their potential in either reducing the demand or increasing the supply of titanium in the time horizon 2020 to 2040.

For the recycling strategy, the assessment meant to derive the outflow of titanium per year, multiply it by the assumed recycling rates and reintroduce it into aircraft production, effectively subtracting it from the required inflow in the same year. They are therefore including material losses and dissipation from the end-of-life till the reintroduction in new aircraft. The lifetime extension strategies required a more complex approach, manipulating each individual aircraft according to the description of the proposed strategies. For the pure lifetime extension, the retirement year of the old aircraft and the build and retirement year of the newly produced aircraft were increased by 5 years if the defined thresholds were met. For the engine upgrade strategy, the retirement year was changed to the retirement year of the substituted aircraft. Additionally, the required titanium inflow and available outflow at the retirement year of the old aircraft and the new retirement year had to be adapted. A simplified flowchart of the conducted analysis is presented in Fig. A.2 in Appendix A.

Table 1
Overview of conceptualised circular strategies.

Name	Description	Scenarios
Recycling	Collection of titanium from retired aircraft and recycling into aviation-grade input material with a fixed recycling rate (RR), substituting raw material.	Cons: $RR = 15\%$ Base: $RR = 25\%$ Prog: $RR = 35\%$
Lifetime extension *Pure*	Extension of aircraft lifetime by 5 years (equivalent to one major aircraft maintenance check (D-Check) (Deng and Santos, 2022)), if the aircraft is retired before the age of X. The production of a new aircraft of the same type will be delayed by this 5 years.	Cons: $X = 18$ years Base: $X = 22$ years Prog: $X = 26$ years
Lifetime extension *Engine Upgrade*	In the event that an aircraft is retired before the age of X, it will be fitted with a new generation engine and will substitute an aircraft of the same type that is supposed to be manufactured in the same year. Its lifetime is therefore prolonged by the lifetime of the substituted aircraft.	Cons: $X = 10$ years Base: $X = 15$ years Prog: $X = 20$ years

The new resulting titanium demand and potential supply were then derived based on the manipulated dataset. All strategies were exclusively tested on the B737 and A320 families, which encompass several upgraded and overhauled subversions. This allowed for the assumption that an aircraft of an older generation can delay or substitute the production of a newer generation aircraft. This was applied to the B737, B737NG, and B737MAX, as well as the A320 and A320neo. These aircraft families represent a homogeneous data set of 38,805 aircraft and therefore the majority of the past and present commercial aircraft fleet.

4. Results

The increasing utilisation of titanium in both civil and military aircraft is highlighted by the collected data presented in Fig. 1, with both sectors exhibiting nearly parallel growth. While military aircraft demonstrate greater variance in titanium usage, they also show a higher average share compared to civil aircraft. This is due to lower cost-sensitivity, higher performance targets e.g. maximum flight speed and consequently higher structural loads, as aforementioned. Notable outliers in both directions, such as the MS-21, the Tu160, the J10, and the Eurofighter, can be observed. With a titanium share of approximately 85% the SR71 has been a pioneering aircraft, but up to now a historical exception as well.[3] See Tables A.1 and A.2 in Appendix A for more details and references.

Fig. 2 illustrates the global distribution of titanium in stored aircraft. As can be seen, the mass accumulates in a small number of airports that are commonly used as storage facilities. The two largest are located in Europe. The first is Tarbes-Lourdes-Pyrénées Airport in France (612t of titanium) and the second is Teruel Airport (560t) in Spain. The total mass of stored titanium was calculated to be 13,639 tonnes. Storage in the US accounts for 19.4% (2644t) of this total, followed by China with 8.9% (1214t), France with 7.1% (962t) and India with 6.4% (873t). The EU's share is slightly higher than that of the US at 20.6% (2810t).

[3] Furthermore, the aircraft represents an early example for supply issues, as the USA did not have the capabilities for sufficient titanium production at the time and had to circumvent export control mechanism of the Soviet Union (USSR) (JRC et al., 2025; Dowling, 2013).

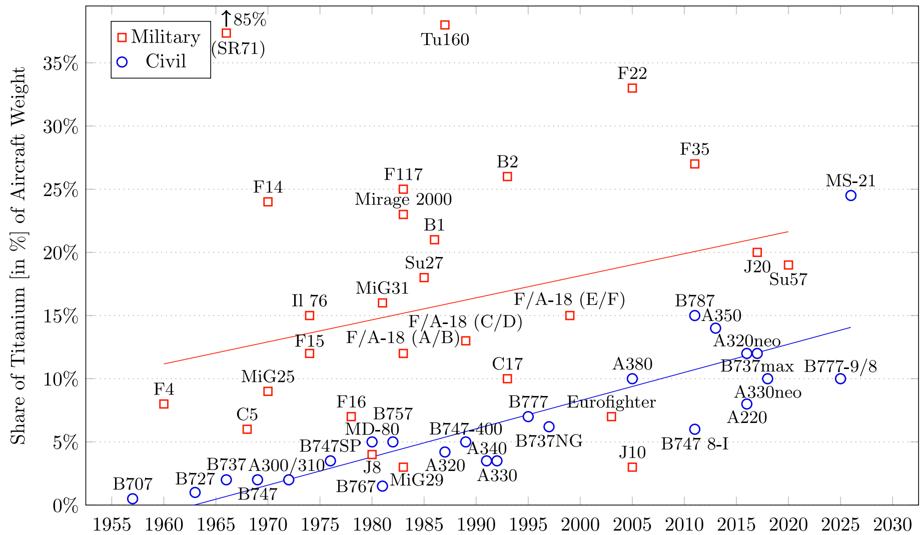

Fig. 1. Share of titanium in civilian and military aircraft. See Tables A.1 and A.2 for a detailed overview and references.

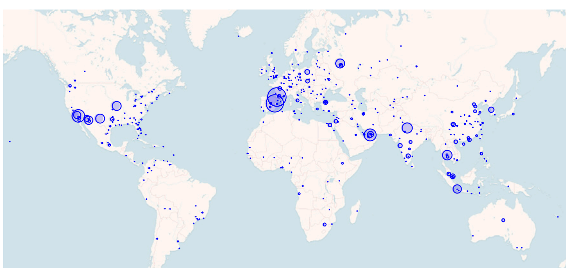

Fig. 2. Geographical distribution of the mass of titanium in stored aircraft. The circles represent the amount of titanium stored at each airport. See the supplementary material for a numerical overview. *Map lines delineate study areas and do not necessarily depict accepted national boundaries.*

The historical and future titanium inflow that was required to produce the selected commercial aircraft shows near exponential growth (Fig. 3). The historical demand trend is disrupted by crises, most strikingly the effects from the COVID-19 pandemic during 2020–2023. The future orders and assumed growth rate indicate an ongoing trend of increasing titanium demand. In addition, the historical and anticipated outflow is presented, illustrating the time discrepancy between the inflow and outflow. This phenomenon is associated with the long lifetime of an aircraft, which is approximately 25 years and corresponds with the observable delta. Consequently, the projected short-term outflow is also increasing, albeit at a rate that is not equivalent to the anticipated required inflow.

Under the assumed recycling strategy scenarios, there is low potential for meeting the required inflow (Fig. 3). Even though the total recyclable and assumed-to-be-recycled material is growing by a factor of eight between 2020 and 2040, the percentage rate of the inflow reduction potential is consistently below 10%. Even assuming a 100% recovery and recycling rate at the end-of-life of all aircraft, the hypothetical potential remains below 25% (see Fig. A.3 in Appendix A). The same observations are true if only the dataset including the B737 and A320 families is used for calculation. The reduction potential remains below 5% even in the progressive scenario, respectively under 15% for an assumed 100% recycling rate, as shown in Fig. 4.

The overall circular potential for titanium can be increased by combining the recycling-only strategy with the pure lifetime extension strategy. A pure lifecycle extension by itself, as shown in Fig. A.4 in Appendix A, shows already more potential than the recycling approach. This can be significantly increased by a combination of both strategies, as shown in Fig. 5. Although the potential changes over time, the average value of the combined base scenario is at 8.75% between 2020 and 2040, compared to 2.76% in the recycling-only and 5.22% in the pure lifetime extension-only strategies. It can also be seen that an elevation of the considered aircraft from a maximum of 18 years (conservative scenario) to 22 years (base scenario) at retirement exerts a more substantial influence than the corresponding increase to 26 years (progressive scenario).

The engine upgrade strategy is by itself less effective than the lifecycle extension strategy (see Fig. A.5 in Appendix A). However, an engine upgrade can be combined with the recycling and end-of-life extension

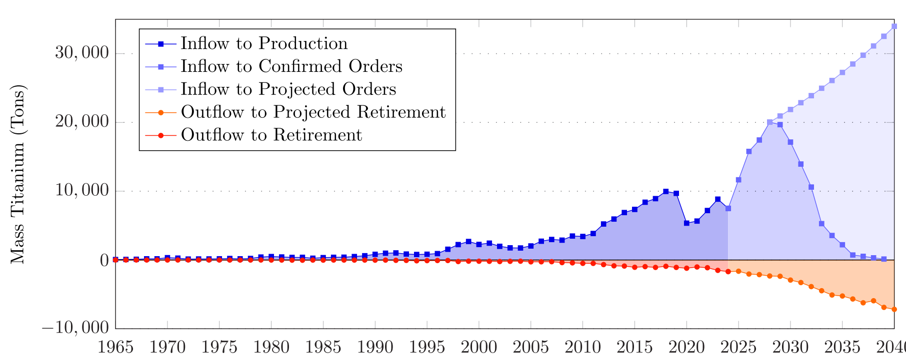

Fig. 3. Historic and future in- and outflow of titanium into civil aircraft production.

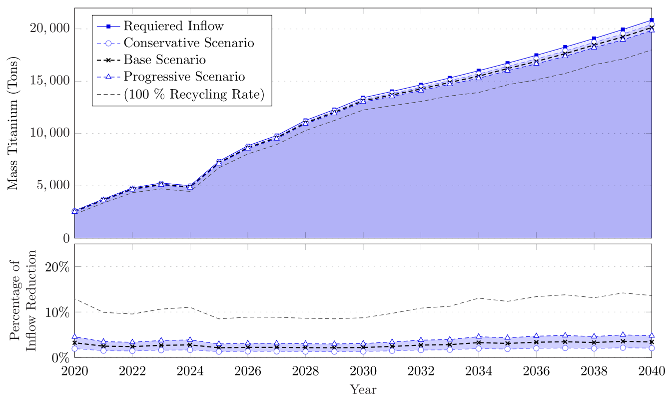

Fig. 4. Resulting inflow reduction from a recycling strategy.

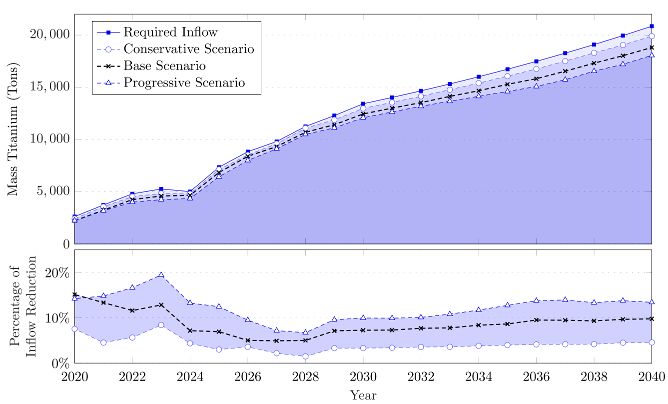

Fig. 5. Resulting inflow reduction from a combined pure lifetime extension and recycling strategy.

strategy to create synergies across these strategies. The result of 13.58% on average reduced required titanium mass in the progressive scenario is presented in Fig. 6. Concurrently, the favourable outcomes associated with a pure lifetime extension and an engine upgrade strategy are offset in the conservative scenario, thereby resulting in an average potential of 3.86% that is lower than the 4.15% observed in the pure lifetime extension strategy when combined with recycling.

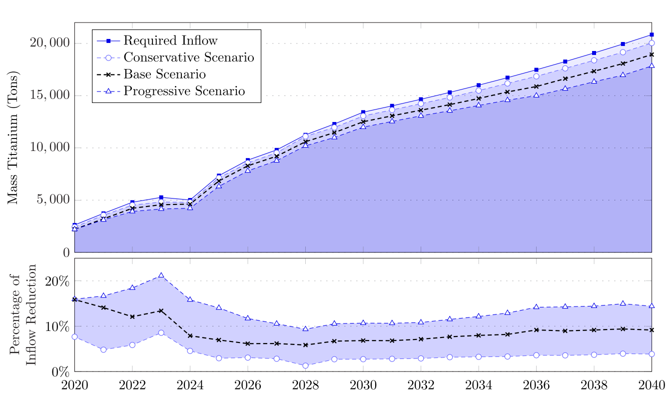

Fig. 6. Resulting inflow reduction from a combined engine upgrade, pure lifetime extension and recycling strategy.

5. Discussion

The results presented in Fig. 1 demonstrate the increasing share of titanium. However, outliers such as the J10 (3% share of titanium), the Eurofighter (7% share of titanium), or the A220 (8% share of titanium) show that increased demand for titanium in both the military and civilian applications is not unavoidable. They highlight the ability of aircraft manufacturers and designers to reduce primary demand through design choices. At the same time, the Russian MS-21 (24.5% titanium share), which is still in development, showcases that the potential for further use of titanium in the civil sector has yet to be reached. Its particularly high titanium share is partly due to the easy availability of titanium for Russian manufacturers.

The global character of the titanium and aviation value chain, together with the associated recycling facilities, is also represented in the stored aircraft represented in Fig. 2. However, a significant concentration of aircraft at select airports can be observed, many of which also host aircraft recycling and dismantling facilities. Interestingly, the distribution also shows a proximity of the stored material to the bases of the major OEMs. The global dispersion continues to present challenges, but centralising recovery activities appears to be a feasible solution and is already evident. Furthermore, the potential for recovering titanium from stored aircraft is evident since the total mass (13,639t) matches the expected demand in 2025 (11,656t).

Our results indicate that a pure end-of-life recycling strategy can only cover a small fraction of less than 10% of the demand. Even in a hypothetical scenario that does not take material dissipation during and after the remelting process into account, the potential remains below 25%. The reason being that the long service life of aircraft leads to a long time delay between the increasing demand and recyclable material becoming available. The results are in line with the publication from Buesa et al. (2024), where only minimal positive economic and environmental effects from an increased collection of aircraft end-of-life scrap could be found. However, the potential is not negligible, and its combination with other strategies would be desirable. At the same time, it must be considered that the total recycled mass must constantly increase to cover the same fraction of inflow. This, in turn, would necessitate a continuous extension of recycling activities.

The largest potential is attributed to the pure lifetime extension strategy. The main reason lies in its distinct mechanism, which, in contrast to the recycling-only strategy, reduces primarily the demand per year, respectively delays the increase in demand. However, both strategies are not opposed to each other, as they can be combined. This results in a secondary positive effect, namely a reduction of the required recycling capacity, since the outflow is decreased. Assuming constant recycling masses, opposed to the applied fixed recycling rates, the potential of a strategy combination would further increase. A third plausible benefit of both lifetime extension strategies is that, in contrast to a recycling approach, it places greater autonomy in the hands of aircraft operators and manufacturers. This is because they are not reliant on external recycling companies that are often situated far from their countries of origin and original value chains. Furthermore, these strategies reduce the potential material losses that occur during the recycling and reintroduction of titanium into the aviation sector. A potential disadvantage of the pure lifetime extension strategy is the higher reliance on individual aircraft to meet specific requirements, which results in a less predictable potential when compared with the recycling-only strategy.

The engine upgrade strategy, which in technical terms is the most drastic departure from the current status quo, was found to be less efficient in reducing titanium demand than pure lifetime extension. This is because (particularly for older aircraft generations) most of the titanium is in the engine and its subcomponents. Therefore, the majority of titanium is replaced during the upgrade (and only partially recycled), thereby limiting the strategy's demand reduction potential.

This also explains why the conservative scenario of the three combined strategies shows less potential than the same scenario with the pure lifetime extension strategy. The replacement of the engine, and therefore the requirement for a large amount of titanium for the new engine, does not outperform the less complex and less extensive pure lifetime extension strategy. As a result, while still adding to the effects of the pure lifetime extension and recycling strategy in the base and progressive scenarios, the additional effect is only marginal.

In terms of methodology, the presented approach and underlying data allowed for the evaluation of realistic circular strategies in a large real-world application. More than 55,000 individual aircraft, including 18,886 ordered and future build aircraft, enabled a retrospective analysis, a current state analysis, and an assessment of future effects. This prognostic fleet-level approach represents an advancement over the majority of other sustainability and material-related research in aviation, which, particularly in the context of conducted LCAs, predominantly focuses on singular aircraft or state of the art analyses.

Limitations of the study include its extensive utilisation of assumptions in the scenarios, which in reality are more intricate than can be addressed within this study. For example, the proposed age thresholds will also be dependent on flight cycles and flight hours. The data sets contain this information; however, the authors did not consider the data to be of a high enough quality. The absence of consideration of the component level presents a further limitation, which is attributed to the size and diversity of the data set. As a result, the study focused exclusively on strategies at the aircraft level. For future studies, there are a considerable number of circular activities that are also undertaken during the lifecycle, for instance via MRO, that could be studied. Furthermore, economic data such as associated costs or financial potential of the proposed strategies was not included in the analysis.

6. Conclusion

This paper aimed to answer the research question of what effects the implementation of circular strategies has on the demand and supply of titanium in the aviation industry. Applying a novel approach based on a large real-world data set, it was shown that circular strategies, especially a simplistic lifetime extension, can significantly reduce the demand for titanium in the aviation sector and help to enable sustainable and resilient supply chains.

Demonstrating this not only in retrospect but also in the medium-term and through geographical analysis enables further and more detailed research. The presented strategies should be verified and further detailed in cooperation with industry. Furthermore, future studies should include circular strategies that focus on the lifecycle rather than mostly the end-of-life. These analyses should incorporate trade-offs between strategies, e.g., a higher environmental impact in the operation phase due to the longer utilisation of older aircraft models. Also, a detailed economic analysis would be highly recommended by the authors.

The results from this study could be extended to other critical and non-critical raw materials or alloys. The transfer of the methodology to other sectors with similar boundary conditions represents a promising research perspective, in particular the renewable energy, automotive, or machinery sector, in which long lifetimes and strong growth perspectives are in concurrence with an increased demand for critical raw materials. Circular strategies will be essential to support aviation as well as other sectors in their transformation towards a low-carbon future.

CRediT authorship contribution statement

Tim Hoff: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Benjamin Sprecher:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Ahmad Ali Pohya:** Supervision, Resources, Methodology, Funding acquisition. **Gerko Wende:** Supervision, Resources, Funding acquisition. **David Peck:** Writing – review & editing, Validation, Supervision, Conceptualization.

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.

Appendix A

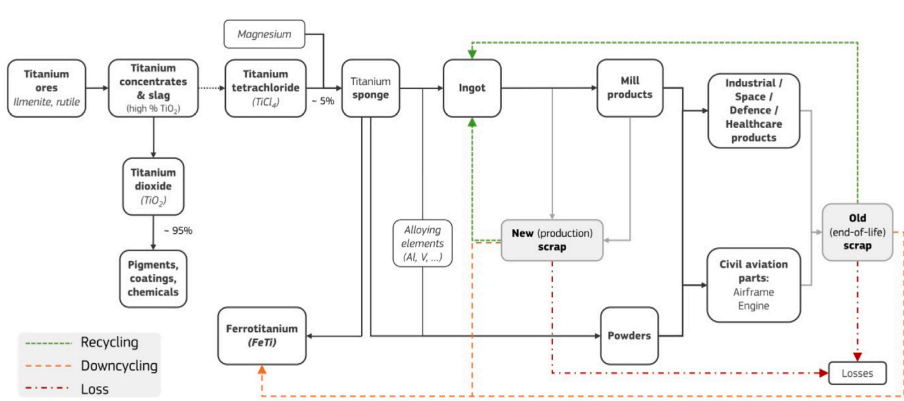

Fig. A.1. Titanium supply chain (JRC et al., 2025).

Table A.1
Share of titanium in selected civil aircraft.

Model	Origin	EIS	Titanium [%]	Reference	Conflicting data [%]
B707	USA	1957	**0.5**	Whittaker and Froes (2015) and Peters et al. (2003)	0.0 (Boyer, 2010)
B727	USA	1963	**1.0**	Whittaker and Froes (2015), Peters et al. (2003) and Boyer (2010)	
B737	USA	1966	**2.0**	Whittaker and Froes (2015) and Boyer (2010)	2.3 (Peters et al., 2003), 3.0 (Mouritz, 2012a) and 5.0 (Buesa et al., 2024)
B747	USA	1969	**2.0**	Whittaker and Froes (2015) and Boyer (2010)	2.6 (Peters et al., 2003) and 4.0 (Li, 2024; Warren, 2004)
A300/310	Europe	1972	**2.0**	Whittaker and Froes (2015)	4.0 (Woidasky et al., 2017)
B747SP	USA	1976	**3.5**	Whittaker and Froes (2015) and Boyer (2010)	3.7 (Peters et al., 2003)
MD80	USA	2016	**5.0**	Buesa et al. (2024)	
B767	USA	1981	**1.5**	Whittaker and Froes (2015) and Boyer (2010)	1.7 (Peters et al., 2003), 2.0 (Li, 2024; Warren, 2004) and 5.0 (Buesa et al., 2024)
B757	USA	1982	**5.0**	Whittaker and Froes (2015), Buesa et al. (2024) and Boyer (2010)	5.5 (Peters et al., 2003) and 6.0 (Li, 2024; Warren, 2004)
A320	Europe	1987	**4.2**	Whittaker and Froes (2015)	4.8 (Li, 2024), 5.0 (Buesa et al., 2024) and 6.0 (Airbus, 2022)
B747-400	USA	1989	**5.0**	Buesa et al. (2024)	
A340	Europe	1991	**3.5**	Whittaker and Froes (2015)	4.0 (Mouritz, 2012a) and 6.0 (Li, 2024; Buesa et al., 2024)
A330	Europe	1992	**3.5**	Whittaker and Froes (2015)	5.0 (Buesa et al., 2024) and 6.0 (Lopes, 2010)
B777	USA	1995	**7.0**	Warren (2004)	8.0 (Li, 2024; Boyer, 2010), 8.2 (Whittaker and Froes, 2015), 8.8 (Peters et al., 2003) and 10.0 (Buesa et al., 2024)
B737NG	USA	1997	**6.2**	Boyer (2010)	10.0 (Buesa et al., 2024)
A380	Europe	2005	**10.0**	Whittaker and Froes (2015) and Li (2024)	
B787	USA	2011	**15.0**	Whittaker and Froes (2015), Li (2024), Buesa et al. (2024), Boyer (2010) and Warren (2004)	14.0 (Mouritz, 2012a)
A350	Europe	2013	**14.0**	Nyamekye et al. (2023), Li (2024) and Kesarwani (2017)	13.0 (Buesa et al., 2024) and 14.1 (Whittaker and Froes, 2015)
A320neo	Europe	2016	**12.0**	Buesa et al. (2024)	
A220	Canada	2016	**8.0**	Buesa et al. (2024)	
B737MAX	USA	2017	**12.0**	Buesa et al. (2024)	
A330neo	Europe	2018	**10.0**	Buesa et al. (2024)	
B777-9/8	USA	2025	**13.0**	Buesa et al. (2024)	
B747 8-I	USA	2011	**6.0**	Assumption	
MS21	Russia	2025	**24.5**	Li (2024)	

Table A.2
Share of titanium in selected military aircraft.

Model	Origin	EIS	**Titanium [%]**	Reference	Conflicting data [%]
F4	USA	1960	**8.0**	JRC et al., 2025	
SR71	USA	1966	**85.0**	JRC et al., 2025	92.0 (Dowling, 2013)
C5	USA	1968	**6.0**	LHTi (2023)	
MiG25	USSR	1970	**9.0**	JRC et al., 2025	
F14	USA	1970	**24.0**	Baojiti (2024)	
F15	USA	1974	**25.0**	Mouritz (2012a)	10.0 (McCormack, 2007), 26.1 (Yunch Titanium, 2019), 27.0 (Baojiti, 2024)
Il76	USSR	1974	**15.0**	UAC Russia (2017)	12.0 (LHTi, 2023)
F16	USA	1978	**7.0**	McCormack (2007)	0.8 (Roskowicz et al., 2018), 2.0 (Li, 2024), 25.0 (Mouritz, 2012a)
J8	China	1980	**4.0**	Baojiti (2024)	
F/A-18 (A/B)	USA	1983	**12.0**	Li (2024)	13.0 (Baojiti, 2024)
F117	USA	1983	**25.0**	Baojiti (2024)	
MiG29	USSR	1983	**3.0**	Machines (2009, as cited in JRC et al., 2025)	
Mirage 2000	France	1983	**23.0**	Baojiti (2024) and LHTi (2023)	
Su27	USSR	1985	**18.0**	Baojiti (2024) and LHTi (2023)	
B1	USA	1986	**21.0**	Li (2024)	17.6 (Top War, 2013)
Tu160	USSR	1987	**38.0**	Latypov (2016, as cited in JRC et al., 2025)	
F/A-18 (C/D)	USA	1989	**13.0**	Mouritz (2012a) and Li (2024)	
B2	USA	1993	**26.0**	Li (2024), LHTi (2023) and Baojiti (2024)	
C17	USA	1993	**10.0**	JRC et al., 2025	
F/A-18 (E/F)	USA	1999	**15.0**	Li (2024)	
Eurofighter	Europe	2003	**7.0**	JRC et al., 2025	
F22	USA	2005	**33.0**	Mouritz (2012a)	41.0 (Li, 2024), 42.0 (JRC et al., 2025)
J10	China	2005	**3.0**	LHTi (2023)	
F35	USA	2011	**27.0**	Li (2024)	20.0 (JRC et al., 2025), 35.0 (Mouritz, 2012a)
J20	China	2017	**20.0**	LHTi (2023)	
Su57	Russia	2020	**19.0**	JRC et al., 2025	

Table A.3
Assumption table.

Number	Type	Description
1	Exclusion	Alloy compositions are not considered.
2	Assumption	The presented recycling rates include material losses/dissipation in the remelting process.
3	Exclusion	Buy to fly ratios are not considered.
4	Exclusion	Due to the exclusion of buy to fly ratios, potential material losses of the recycled material after its remelting process are neglected.
5	Exclusion	Stored aircraft are not considered for the in-/outflow calculation.
6	Exclusion	Non-commercial (e.g., private or government-owned) aircraft are not considered.
7	Assumption	After 2029 the future growth rate of titanium demand is 4.5%, equalling the average growth rate of civil aviation (Fleming and de Lèpinay, 2019).
8	Assumption	Future aircraft retirements are normal distributed ($\mu = 25, \sigma = 5$) (International Air Transport Association, 2018).
9	Assumption	The pure lifetime extension and engine upgrade strategy are only applied to an individual aircraft ones.
10	Assumption	The engine upgrade strategy requires 1750 kg of titanium for an engine exchange (Li, 2024; Mouritz, 2012a).
11	Implementation details	If there are no more aircraft of the same type available to be delayed or substituted in the lifetime extension strategies, the following pairings will be used: B737 to B737NG, B737NG to B737MAX and A320 to A320neo.

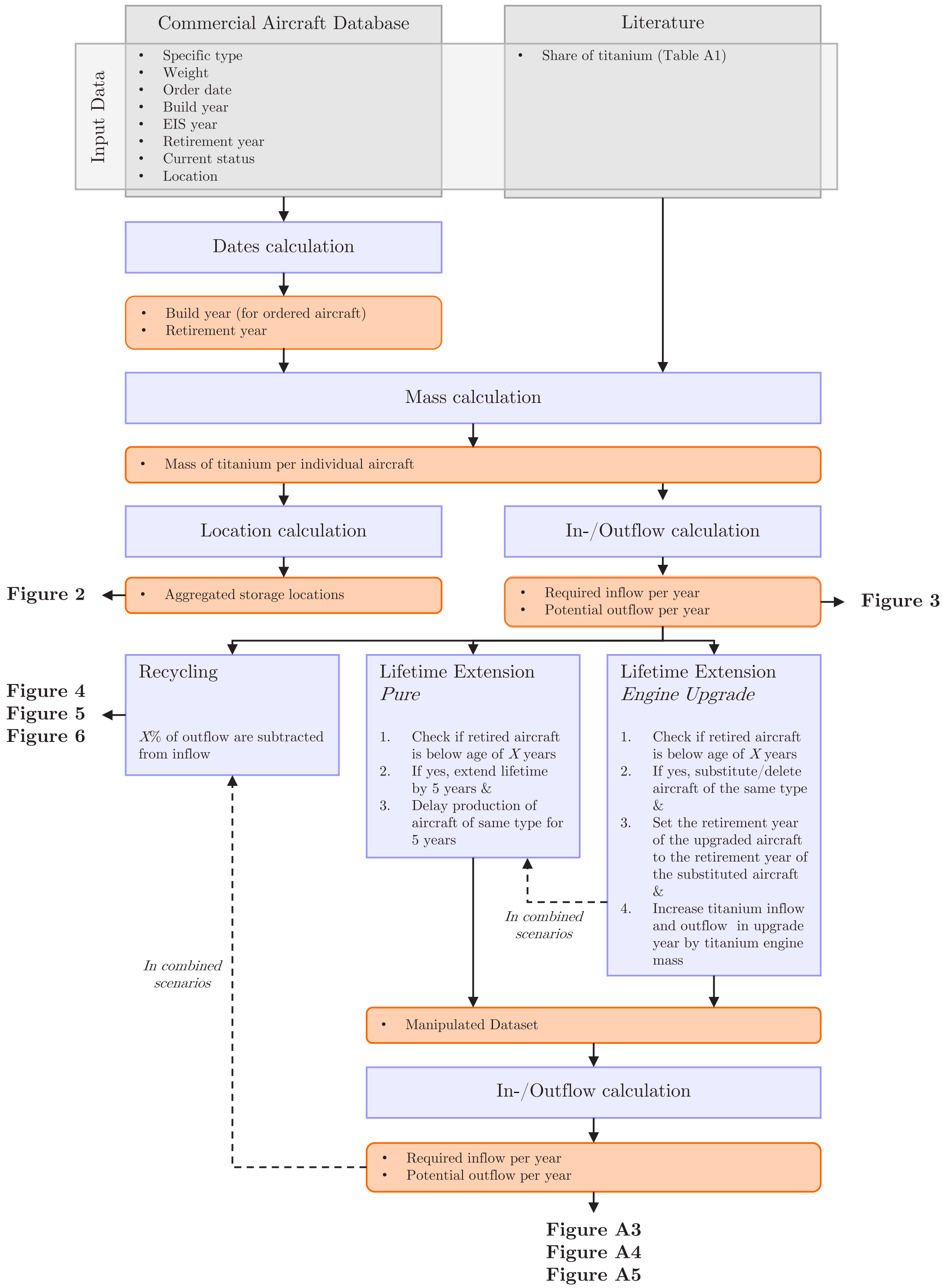

Fig. A.2. Simplified flowchart of the methodology.

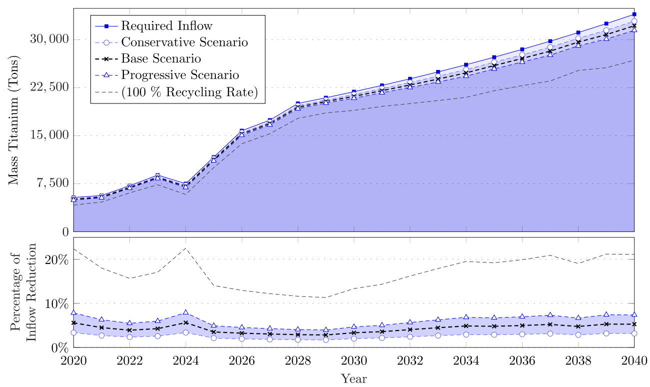

Fig. A.3. Resulting inflow reduction of the total aircraft fleet from a recycling strategy.

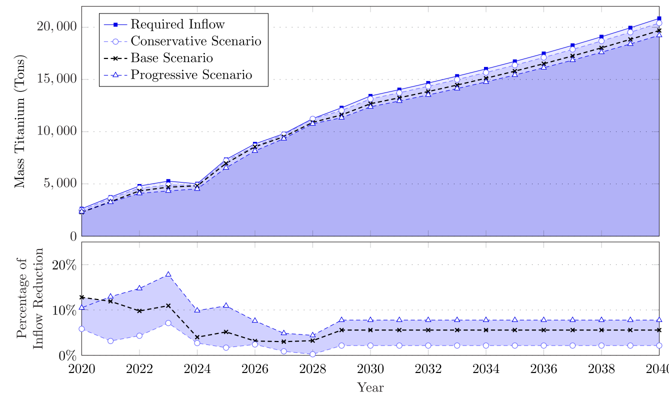

Fig. A.4. Resulting inflow reduction from a pure lifetime extension strategy.

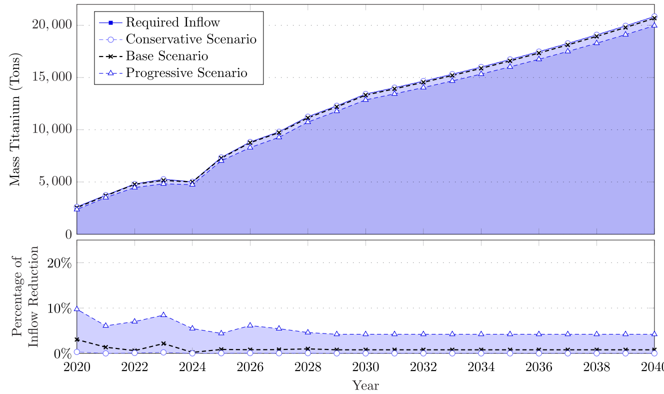

Fig. A.5. Resulting inflow reduction from an engine upgrade strategy.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resconrec.2025.108476.

Data availability

The authors do not have permission to share data.

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