

THE ROLE OF CIRCULAR ECONOMY IN RESOURCE SECURITY

A Material and Economic Analysis of
Titanium Supply in the European Union

M.Sc. Industrial Ecology

Stefano Ghirlandi

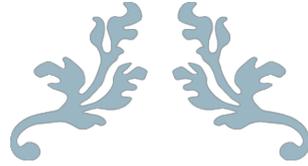


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The Netherlands



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A Material and Economic Analysis of Titanium Supply in the European Union

by

Stefano Ghirlandi



Student Number

3846474
6103871

Leiden Universiteit
TU Delft

Thesis committee

Dr. Franco Donati
Dr. David Peck
MSc Tim Hoff

Leiden University, first supervisor
TU Delft, second supervisor
DLR, company mentor

27th of February, 2026



**Universiteit
Leiden**
The Netherlands

*All'idea di quel metallo, portentoso, onnipossente,
Un vulcano la mia mente incomincia a diventar.*

Il Barbiere di Siviglia, G. Rossini

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The completion of this thesis is far more than a deliverable in the process of graduating. It marks the end of a cycle that will shape both my personal and professional life in ways I am only beginning to grasp. I remember starting this master's programme unable to explain what Industrial Ecology even was. Today, after three years, hundreds of papers, three courses as a teaching assistant, and thousands of hours spent studying complex socio-technical systems and other formidable concepts I can finally explain in... a short essay.

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Executive Summary

The European Union increasingly frames the Circular Economy as a means to advance its Open Strategic Autonomy vision. This shift is increasingly reflected in policies on the supply security of critical raw materials. Titanium metal is central to this debate given its importance for aviation and defence and the European structural reliance on external suppliers; however, two significant limitations persist in the research assessing how circular strategies contribute to its supply security. First, there is no integrated, system-wide assessment that explicitly quantifies the security gains of circular interventions in its material and economic dimensions. Second, while policy narratives increasingly link circularity to strategic autonomy, empirical assessments continue to rely on isolated indicators that are not directed by clearly defined strategic objectives. As a result, the security implications of circular economy strategies for titanium remain insufficiently operationalised.

To address these gaps, the thesis develops an analytical framework and applies it to titanium supply security adopting a national security discourse. Within this perspective, supply security is defined along two measurable dimensions of strategic autonomy, material self-sufficiency and domestic value creation, which guide the selection of indicators used to evaluate circular interventions. The framework is applied by first reconstructing the current titanium supply chain in the European Union through Material Flow Analysis, identifying key stocks, flows, and external dependencies. It then develops two scenarios in the aviation sector up to 2040, enhanced domestic recycling and aircraft lifetime extension, which are modelled using dynamic MFA to assess material effects and Multi-Regional Input–Output analysis to evaluate the corresponding impacts on domestic value creation across the economy.

The baseline analysis shows that the current titanium configuration in the European Union is characterised by two structural vulnerabilities: near-total import reliance at the midstream level and substantial losses through pre-consumer scrap generation during component manufacturing. Enhanced domestic recycling delivers the strongest improvements in both dimensions of supply security, increasing material self-sufficiency by approximately 35% and generating an estimated €43.7 million in domestic value added and around 500 jobs added. However, these gains are largely driven by the retention and reprocessing of pre-consumer scrap rather than by end-of-life recovery. Even under existing remelting capacity, secondary feedstock would be depleted within roughly a decade, limiting its structural contribution. Besides, more than half of the pre-consumer scrap produced is still bound to buyback agreements with the United States, remaining a significant constraint to strategic autonomy. On the other hand, aircraft

lifetime extension performs more modestly in static comparisons, delivering roughly half the economic gains of recycling. Yet, by slowing inflow requirements, it acts as a demand-side buffer, suggesting that strengthening maintenance, repair and overhaul capabilities represents a relevant complement to recycling efforts.

In conclusion, this thesis contributes to the understanding of how circular economy can support strategic autonomy objectives, highlighting that their effectiveness depends on a holistic, system-wide, and dynamic perspective on the supply chain. Conceptually, it situates circular interventions within a resource security framework, bridging industrial ecology with international relations considerations of critical raw materials. Methodologically, it introduces a hybrid approach combining dynamic Material Flow Analysis with Multi-Regional Input–Output modelling, enabling simultaneous assessment of material flows and economic interdependencies. Empirically, the application to titanium illustrates both the opportunities and limits of circular interventions, providing evidence to inform policy and industry strategies for strengthening domestic control and industrial capacity.

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Acronyms

- AT: Air Transport
- CE: Circular Economy
- CFRP: Carbon-fibre reinforced polymers
- CRM: Critical Raw Materials
- CRMA: Critical Raw Materials Act
- CSC: Coal and Steel Community
- CSS: Circular Security Studies
- EEIOA: Environmentally Extended Input-Output Analysis
- EEC: European Economic Community
- EU: European Union
- GFCF: Gross Fixed Capital Formation
- HHI: Herfindahl-Hirschman Index (Diversity indicator)
- IAM: Integrated Assessment Model
- IE: Industrial Ecology
- IOA: Input-Output Analysis
- IOT: Input-Output Table
- IR: International Relations
- LCA: Life Cycle Assessment
- LTE: Lifetime Extension
- MARIO: Multifunctional Assessment of Regions through Input-Output
- MFA: Material Flow Analysis
- MOT: Manufacturing of Other Transport Equipment
- MRIO: Multi-Regional Input-Output
- MRO: Maintenance, Repair, and Overhaul
- OSA: Open Strategic Autonomy
- PRC: People's Republic of China
- SRM: Strategic Raw Material
- Ti: Chemical element of Titanium
- WGI: Worldwide Governance Indicators (Political Stability indicator)
- WTO: World Trade Organization

Chapter 1 - Introduction

1.1 Background

The European Union (EU) was originally founded on the premise that shared control over strategic resources reduces conflict and strengthens collective security. (Bennett, 2022) Its direct precursor, the European Coal and Steel Community (CSC), institutionalised resource governance as a foundation of political stability: by pooling two vital resources for industrial recovery, it laid the basis for cooperation and trust (Pecchia et al., 2024; Segers, 2023). For several decades, multilateral trade regimes supported economic expansion, while transatlantic security arrangements allowed Member States to prioritise civilian investment over defence spending. Under these conditions of predictability, both deepening trade and material interdependence were largely perceived as an opportunity rather than a vulnerability (Letta, 2024). However, recent geopolitical crisis and supply chain disruptions have shifted this perception. The tension between the EU's economic, strategic, and environmental goals has reached a breaking point; as Draghi (2024) observes, "the foundations on which we built are now being shaken". Yet these foundations remain rooted in the collective governance of key resources, once coal and steel, now critical raw materials (CRM).

Against this background, a new strategic orientation emerged under the label of Open Strategic Autonomy (OSA). While maintaining a commitment to open markets, OSA reframes interdependence as a structural risk when concentrated in critical sectors. It seeks to reduce excessive dependencies in strategically sensitive value chains without reverting to protectionism (Kroll, 2024). This vision is reflected in the progressive expansion of the concept of material criticality in EU policy. Originally linked to military applications, it has been formalised through assessments combining economic importance and supply risk, thereby identifying materials essential to key industrial value chains (Schrijvers et al., 2020). The subsequent introduction of the category of Strategic Raw Materials (SRM) further politicised this approach, explicitly prioritising materials indispensable for the green and digital transitions, as well as for aerospace and defence (JRC, 2025).

This evolution culminated in the adoption of the Critical Raw Materials Act (CRMA) which sets binding targets for domestic extraction, processing and recycling, and limits dependence on single third countries (Grohol & Veeh, 2023). Crucially, the CRMA marks a shift in the positioning of the Circular Economy (CE): from an initially waste-oriented

policy (Gregson et al., 2015), to a competitiveness-driven (European Commission, 2015) and just transition agenda (Calisto Friant et al., 2021) and now to an instrument explicitly linked to resource security. While the broader sustainability framing has often struggled to generate consensus among Member States, resulting in fragmented implementation and limited transformative impact (Castillo-Díaz et al., 2024; Pinyol Alberich et al., 2023), the integration of CE into the criticality and security agenda may alter its political traction.

Further confirmation of this trajectory is provided by the Strategic Foresight Report, which states that “security has become the key vector for all EU policies” and highlights the opportunity of new civil–military synergies, particularly in dual-use materials (European Commission, 2025). Within this framing, innovation in CE practices is explicitly identified as a pathway to reduce strategic dependencies. In the same direction, Tukker (2025) argues that circular strategies such as urban mining and design for circularity are mechanisms to retain control over the supply chain of stranglehold technologies, becoming a means of safeguarding industrial sovereignty. Positioned neatly within this debate, recent research on titanium in aviation demonstrates that this metal mirrors the very tensions that currently defines the EU’s quest for securitised raw materials.

Owing to its exceptional strength-to-weight ratio, corrosion resistance and durability, titanium metal¹ is indispensable in aerospace and defence applications. In civil aviation alone, the share of titanium in aircraft structures has increased from negligible levels to approximately 15 percent of total weight over the past five decades (Hoff et al., 2025). The metal clearly embodies the so called “minerals trilemma” (Vivoda et al., 2025) as it generates high economic value, contributes to fuel efficiency through lightweighting and lacks viable substitutes in critical defence applications. At the same time though, its supply chain is characterised by high import dependence, geographically concentrated extraction and processing, and minimal domestic recycling due to binding exports agreements (Buesa et al., 2025). Despite various drivers to circularity have been already identified as pathways to enhance domestic control of the supply chain, further research is needed to model material and economic scenarios to complement existing policy recommendations (Baldassarre, 2025).

Two contributions currently provide the most comprehensive assessments of titanium circularity. A report by the Joint Research Centre (JRC) delivers an extensive examination of the titanium supply chain, its applications, and the geopolitical configuration of the

¹ The EU criticality assessment distinguish between titanium (dioxide) and titanium metal. The first is the precursor to the metal that is however used by 95% for pigment production and is therefore deemed noncritical (Buesa et al., 2025). On the other hand, titanium metal is critical mainly for its higher value added. In this thesis, titanium will be used as a synonym of titanium metal.

metal. It further develops two Input–Output Analysis (IOA) scenarios, whose results substantiate the case for both pre-consumer and end-of-life scrap recycling (Buesa et al., 2025). Yet, despite its analytical breadth and data granularity, the report does not adequately represent the underlying stock–flow structure of the system and relies heavily on unbalanced cost datasets affected by mass inconsistencies (L. Hu et al., 2022). Complementarily, Hoff et al. (2025) assess the effects of recycling and lifetime extension strategies on global titanium demand and supply in aviation up to 2040. Their results indicate that strengthening maintenance, repair, and overhaul (MRO) capabilities alleviates supply constraints more effectively than recycling alone and operates synergistically with it. However, the analysis remains confined to the use phase, excluding material stocks nor evaluating downstream supply chain ramifications, such as implications for import dependency.

1.2 Research Gap and Objective

The review of EU's resource policy and the current research on titanium highlights two interrelated gaps.

First, despite growing attention to titanium as a strategic metal, there is no integrated, system-wide quantitative assessment of how circular economy strategies affect the security of titanium supply in the EU. Existing studies offer valuable but partial insights that do not adequately show the complexity of titanium supply. As a result, the combined implications of circularity strategies for the diverse security dimensions remain unclear.

Second, a conceptual inconsistency underlies this empirical fragmentation. Key terms such as criticality, resilience, and risk are defined inconsistently across policy and academic literature, and existing frameworks oscillate between narrow, indicator-driven assessments and broader holistic interpretations (Salim et al., 2022; Schrijvers et al., 2020). A disconnect therefore emerges between discourse² and assessment: while political narratives oscillate between sustainability and sovereignty, existing analytical tools often pursue technical evaluations of supply risk or economic value without a clearly articulated strategic objective. As a result, although CE is increasingly embedded in EU resource security policy, its concrete contribution to material supply security remains insufficiently defined and operationalised.

² The thesis uses "discourse" to denote structured security framings (national, international, human, ecological) following Petelin (2024). Technically, actors *align with* discourses through socialization rather than *choosing* them. However, the framework operationalizes discourse as an explicit analytical decision: declaring which normative lens informs the assessment. Though this could alternatively be termed "framing," "discourse" captures the deeper claim that these are not simple rhetorical choices.

The objective of this thesis is to establish a consistent analytical basis for assessing titanium supply security under circular interventions. It proceeds in two steps. First, it reconstructs the current material flow structure of titanium in the European Union, identifying key stocks, flows, and external dependencies. Second, it models the impact of selected circular economy strategies on two measurable dimensions aligned with the EU's strategic autonomy agenda: material self-sufficiency and domestic value creation. By linking these dimensions to explicit quantitative indicators, the study provides a structured evaluation of how CE can contribute to titanium supply security.

1.3 Research questions

Based on the identified gaps, the research is founded on the following questions:

Main Research Question

What effect could Circular Economy have on the security of titanium supply in the European Union?

Sub-Research Questions

1. What is the current material configuration of titanium supply?
2. How might circular interventions in civil aviation affect self-sufficiency in titanium supply?
3. How might circular interventions in civil aviation affect domestic value creation of the titanium sector?

1.4 Thesis contribution and outline

This thesis contributes to Industrial Ecology (IE) by advancing both conceptual clarity and methodological integration in the analysis of critical material supply security. First, it develops a framework that systematises the ongoing shift of repositioning CE under a broader resource security umbrella, which includes but is not limited to ecological objectives. It builds a bridge between core IE analysis and political-economic considerations surrounding critical raw materials. Methodologically, the thesis integrates Multi-Regional Input-Output (MRIO) analysis with dynamic Material Flow Analysis (MFA), enabling the simultaneous assessment of physical stock-flow dynamics and economic interdependencies. Applied to titanium, this hybrid approach demonstrates how circular interventions, such as lifetime extension and recycling, can be evaluated consistently across both material and economic dimensions.

At the empirical and policy level, the thesis provides the first integrated assessment of the titanium supply chain in the EU, contributing to the ongoing debate on critical resource governance and the implementation of the CRM Act. By quantifying structural supply vulnerabilities, and the potential of circular strategies in enhancing domestic control and industrial capacity, it offers evidence directly relevant to discussions on Open Strategic Autonomy and the forthcoming Circular Economy Act in late 2026. In doing so, it translates high-level policy ambitions into system-wide modelling results, clarifying both the opportunities and the limits of circularity as a tool for strengthening material security in the European context.

The research outline is visualised in Figure 1 and described in detail in the following text. **Chapter 2** reviews the technical, conceptual, and methodological foundations of the study by examining titanium's life cycle, global and European supply chain; then presents the R ladder as framework for CE, the current EU policy on CRMs and the shift happening in resource security, followed by an analysis of the security discourses most used to present CE strategies and the epistemological gap surrounding resource security assessments; finally it reviews the main IE methods and their hybridation, specifically applied to titanium or the aviation sector.

Chapter 3 develops the *Circular Security* analytical framework and methods used in the thesis, linking security discourses to indicators, scenario design and security implications; then it presents the data and assumptions regarding static and dynamic MFA alongside MRIO with model implementation of circular interventions in aviation.

Chapter 4 presents the outcome of the indicators and the outstanding results that help tackle the sub research questions.

Chapter 5 discusses the implications of these findings for the specific case of titanium in aviation and then the broader conceptual impact of the Circular security framework. Finally it discusses the methodological novelty and limits of this thesis.

Chapter 6 concludes by summarising the main contributions of the thesis, answering the main research question, and identifying directions for future research.

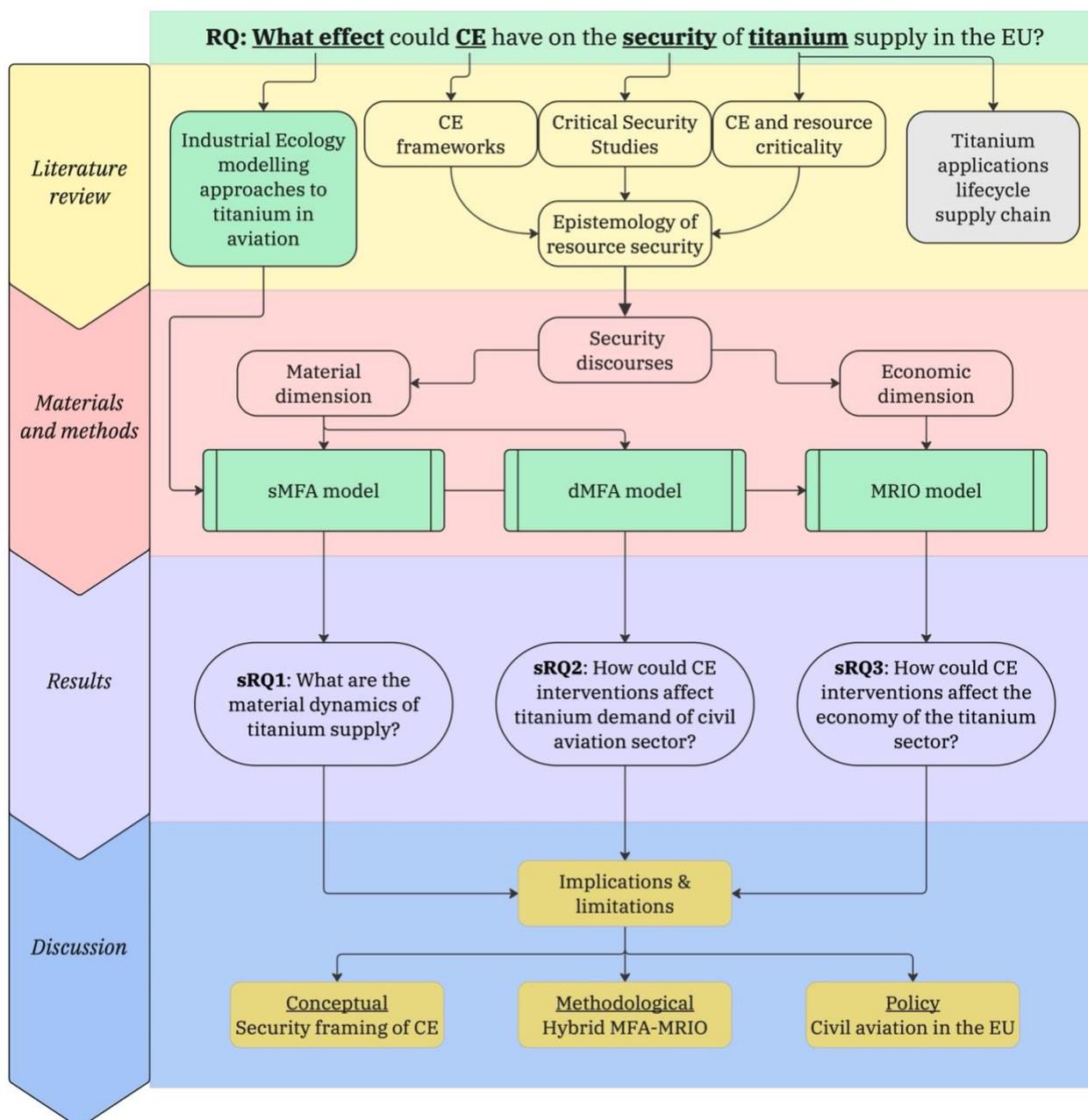


Figure 1. Research Flow Diagram

Chapter 2 – Literature review

The previous chapter outlined the shift surrounding resource security in the EU and how CE has emerged as a potential pathway to reduce supply chain risk and strengthen industrial autonomy. Titanium emerged as an ideal case: a material that is indispensable to aviation and defence, increasingly demanded by new designs, yet deeply exposed to geopolitical and structural supply constraints.

This literature review builds the foundation for any further assessment on the impact of CE on titanium supply chain security. It traces the conceptual, technological, and methodological landscape in which this thesis is situated. It begins by examining titanium itself, its properties, alloy systems, lifecycle and global supply chain, to clarify the technical and trade constraints from which risks emerge. It then turns to Circular Economy strategies through the R-Ladder framework. It reviews their conceptual evolution and the growing argument for framing circular interventions as instruments of security, particularly in the context of the EU's critical raw material agenda.

The chapter subsequently introduces the analytical approaches used to study material systems within Industrial Ecology. Material Flow Analysis (MFA) and Multi-Regional Input-Output (MRIO) analysis are presented not in their methodological detail but in their suitability in addressing the RQs. Indeed, MFA provides the material-level visibility that the aviation sector currently lacks, while MRIO captures the economic interdependencies that shape vulnerability and exposure. Their complementarities, and the potential of hybrid approaches, form the methodological backbone of this thesis. Finally, the state of the art section reviews how the two IE methods have been applied to titanium and aviation. Its purpose is to understand how earlier studies defined their system boundaries, material scope, and research logic, and why specific methods were chosen for those questions. By surveying this work, the section identifies what is already known, what remains underdeveloped and how this shapes the methodological choices of the present thesis.

These sections reveal three major gaps, namely conceptual, methodological, and sectoral policy, that motivate the present research and define its scientific contribution. They also provide the analytical and empirical foundation for the modelling work developed in Chapter 3.

2.1 Titanium Metal overview

2.1.1 Properties, Alloys, and Applications

Titanium (Ti) stands out among metals for its exceptional combination of strength, lightness, and durability, properties that make it indispensable in advanced engineering. Its alloys match the strength of steels while being roughly 40% lighter, enabling substantial weight savings in structural components (Najafizadeh et al., 2024). Titanium also offers remarkable corrosion resistance, owing to a stable and self-healing oxide layer that protects it from seawater, chlorine, and many acids. Though its melting and boiling points are among the highest of all structural metals, above about 500 °C its mechanical and chemical performance deteriorates sharply due to oxidation in reactive environments (SCREEN2, 2020). Finally, titanium is both biocompatible, bonding naturally with bone tissue without triggering immune responses, and non-magnetic, making it ideal for medical and imaging technologies such as MRI (El-Bassyouni et al., 2025).

Titanium's versatility is further enhanced through alloying with elements such as aluminium, vanadium, molybdenum, zirconium, nickel, and iron. The most widely used alloy, Titanium-Aluminium-Vanadium (Ti-6Al-4V), accounts for nearly half of global titanium consumption each year (Najafizadeh et al., 2024) and for 95% of aviation demand (Baldassarre, 2025). Besides, its alloying allows engineers to tailor properties such as strength, fatigue resistance, and corrosion behaviour to specific industrial requirements.

These unique characteristics have made titanium a cornerstone of both aerospace and biomedical technologies. In aviation, its high strength-to-weight ratio enables lighter, more fuel-efficient aircraft, while its fatigue and temperature resistance ensure long component lifespans in demanding environments (Najafizadeh et al., 2024; Nyamekye et al., 2023). Titanium is used extensively in engines, airframes, landing gear, and hydraulic systems, and its compatibility with carbon-fibre reinforced polymers (CFRP) has accelerated its substitution for aluminium in modern airframe structures (Lefevre et al., 2017).

Titanium demand is concentrated in four main application areas: civil aviation and space; industrial equipment, such as robotics, nuclear, chemical, oil and gas; medical and consumer goods; defence systems including armoured vehicles and military aircraft (Buesa et al., 2025; SCREEN2, 2020). Its dual use in both civilian and defence applications underlines its strategic importance and justifies its inclusion in the critical mineral lists of various countries.

In civil aviation, titanium components are classified according to their function and location, which determines their maintenance regime (SKYbrary, 2015). Life-limited parts, mainly rotating engine components, are subject to fixed retirement limits based on flight cycles and must be scrapped once these limits are reached. Rotables, such as landing-gear assemblies, can be periodically removed, overhauled to an as-new condition, and reintroduced into service. Structural elements, by contrast, are typically managed on an on-condition basis and remain with the airframe for most of its operational life unless damage is detected (AEM, 2025). Current safety regulation prioritises conservative hard-time limits, particularly for life-limited parts, to minimise fatigue-related failure risks. While effective for safety assurance, this approach constrains aircraft lifetime extension and circular strategies. Aviation rules prohibit the reuse of life-expired components irrespective of their residual material integrity, leading high-value titanium to be routed directly to scrap melting rather than remanufacturing. This regulatory rigidity constitutes a major barrier to the development of a more circular aerospace supply chain (KPMG, 2024).

On the resource efficiency side, the picture is equally challenging. Conventional manufacturing methods such as forging and machining have a buy-to-fly ratio of about 9:1 (Baldassarre, 2025), meaning that nine kilograms of titanium are required to produce one kilogram of finished parts, with the rest lost as scrap. Additive manufacturing using titanium powder is increasingly adopted, particularly in space and drone applications, as it allows near-net-shape production and significantly reduces material waste (Buesa et al., 2025).

2.1.2 Titanium metal life cycle

Most of the information regarding the supply chain of titanium are drawn by the extensive study carried out by the European Joint Research Centre - “Titanium metal in the EU: Strategic relevance and circularity potential” which also represents the groundwork of this thesis research (Buesa et al., 2025). Figure 2 shows a simplified diagram of the titanium metal life cycle.

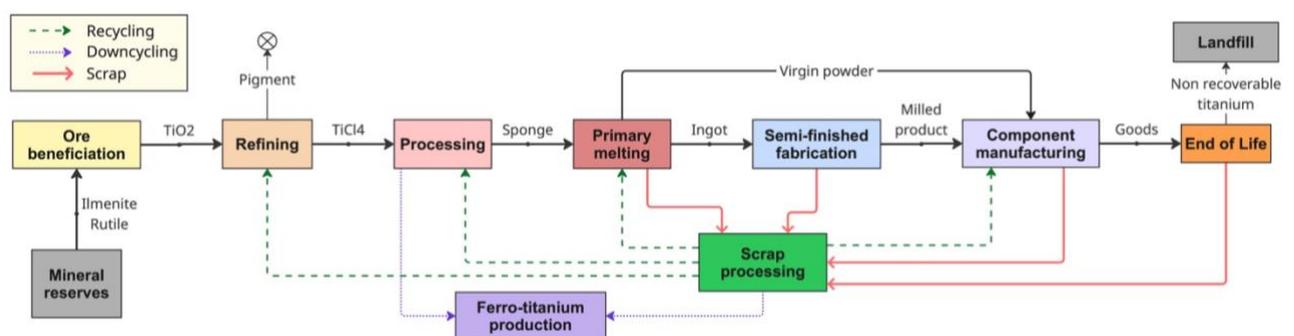


Figure 2. Life cycle of titanium metal

The life cycle of titanium metal comprises nine main stages, from extraction to end of life. Table 8 in Appendix I outlines the material inputs and outputs at each stage, along with the primary and alternative processing technologies. This detail is essential, as not all technologies can accommodate scrap feedstock, revealing both technical and financial barriers to titanium circularity. The following paragraph provides a concise overview of these stages.

1. **Ore beneficiation** - The first stage involves the extraction and concentration of titanium-bearing minerals such as ilmenite (FeTiO_3) and rutile (TiO_2). They are defined based by their purity, i.e. titanium dioxide content. Ilmenite is the most abundant mineral but has a purity of 30 to 60%, while rutile is less available but is naturally concentrate. The main output it titanium dioxide concentrate and slag as byproduct. The beneficiation process typically includes physical separation methods such as gravity, magnetic, and electrostatic separation (SCRREEN2, 2020).
2. **Refining** - In the second stage, TiO_2 concentrate is refined to produce pigments and intermediates for metal production. Approximately 95% of TiO_2 is used in the manufacture of whitening pigments, while only about 5% enters the titanium metal value chain (USGS, 2023). The same concentrate can also be chlorinated to produce titanium tetrachloride (TiCl_4), which serves as the precursor for sponge production (SCRREEN2, 2020). Though they share the feedstock, pigment and sponge production undergo very different processes for grade of purity of the input, technology required and know-how of the personnel (Takeda & Okabe, 2019).
3. **Processing** - The third stage is the Kroll process, in which TiCl_4 is reduced in a steel reactor using magnesium to form titanium sponge. The output typically consists of 80–90% high-grade sponge and 10–20% off-grade material contaminated with iron, which is then diverted to ferro-titanium production (Takeda & Okabe, 2019). Alternative technologies that employ molten salts or plasma reduction yield higher grade sponge that is destined to aerospace applications.
4. **Ferro-titanium production** - Off-grade sponge and titanium-rich scrap are alloyed with iron to produce ferro-titanium, a key additive for steelmaking. This pathway provides an important outlet for material that cannot meet the purity requirements of the aerospace or medical sectors, yet it represents a downcycling route rather than a closed circular loop (Panigrahi et al., 2010).
5. **Primary melting** - In this stage, titanium sponge, clean scrap, and alloying elements such as aluminium and vanadium are melted in vacuum furnaces to produce ingots or converted into powders for additive manufacturing. The scrap

additive ratio is estimated to be around 50% for Ti-6-4 alloy (Takeda & Okabe, 2019). The choice of the furnace is determined by the operational costs, quality of feedstock, including scrap, and desired grade of titanium ingot.

6. **Semi-finished fabrication** - The ingots are processed into mill products (blooms, billets, bars, tubes, wires, plates, sheets, and strips) through forging, extrusion, or rolling (Zhang et al., 2011).
7. **Component manufacturing** - Mill products are further shaped into finished components by casting, forming, forging, or machining. This is the costliest stage of the chain, as titanium's hardness and low thermal conductivity accelerate tool wear and slow production. Conventional processes yield a buy-to-fly ratio of about 9:1, generating large amounts of high-grade scrap and swarf (Baldassarre, 2025). Innovative additive manufacturing techniques, such as power bed fusion allow for higher yields and can handle up to 100% recovered powder from scrap (IperionX, 2023).
8. **Scrap processing** - Machining scrap and offcuts are collected, cleaned, and remelted where possible, but quality assurance requirements restrict their use in high-performance alloys. As shown in Figure 2, machining scrap and offcuts are collected, cleaned, alloys are sorted and powder is recovered. Subsequently, depending on the desired grade, the scrap can enter the supply again at any given stage. Through hydrometallurgy, titanium dioxide can be extracted for pigment production (Zhang et al., 2011); FCC Cambridge process allows for high quality sponge and powder recovery from scrap with lower energy requirements than Kroll process (D. Hu et al., 2017).
9. **End of life** - After use, titanium can be landfilled, or treated as hazardous waste in the case of medical applications (SCRREEN2, 2020). A portion remains stored in decommissioned aircraft, awaiting dismantling and eventual recycling. However, the high cost of recovery and lack of specialised infrastructure currently hinders end-of-life circularity (Hot et al., 2020).

2.1.3 Titanium Supply Chain: Global Overview

Global production of titanium metal reached 165 kilotons in 2019, continuing a decade of steady growth driven civil aerospace (45%), industrial equipment (40%), defence applications (9%), and consumer goods. Across nearly all stages of the titanium supply chain, the EU remains marginal in terms of output volume.

Below, Table 1 shows the market share for each stage of the supply chain of the main countries involved based on Buesa et al. (2025) and Louvigné (2021). The percentages in italics refer to the production of aviation grade sponge for processing, or component manufacturing destined to aviation.

Table 1. Global distribution of titanium production by region and processing stage in 2019. In italics and red font, the share of aviation grade processing and manufacturing capability.

	Mining	Processing	Melting	Fabrication	Manufacturing
EU	4%	0%	3%	4%	18% <i>(25%)</i>
China	36%	63% <i>(12%)</i>	37%	66%	40% <i>(15%)</i>
USA	1%	0%	26%	11%	30% <i>(51%)</i>
Russia	1%	11% <i>(30%)</i>	16%	10%	6% <i>(7,5%)</i>
Japan	0%	16% <i>(41%)</i>	10%	6%	4% <i>(1,5%)</i>
RoW	58%	10% <i>(17%)</i>	8%	3%	2%

As shown in Table 7 in Appendix I, the extraction of titanium-bearing minerals such as ilmenite and rutile is dominated by China, Mozambique, and South Africa. Within Europe, only Norway and Ukraine possess proven reserves and maintain active mining operations, together contributing a negligible share of global output.

At the refining and processing stages, production is concentrated in China, Japan, Russia, Kazakhstan, and Saudi Arabia. When only aerospace-grade sponge, which requires exceptional purity and microstructural consistency, is considered, Japan and Russia lead the market, followed by Kazakhstan and China (USGS, 2019). Saudi Arabia has recently emerged as a significant new entrant, investing heavily to expand capacity and integrate further along the value chain (Hughes, 2025a).

For ingots and mill products, no aerospace-specific statistics are available. However, the global pattern remains largely unchanged. China retains the largest production share, closely followed by the United States, which continues to move up the value chain through advanced processing and additive manufacturing capabilities.

At the component manufacturing stage, particularly in aerospace, the United States and the EU account for roughly three quarters of global output. This dominance reflects the strength of the industrial ecosystems surrounding Boeing and Airbus, which anchor extensive supply chains and technological networks. The pattern is mirrored in the composition of the global aircraft fleet, where Boeing, and its branch McDonnell Douglas, built around half of all active aircraft, while Airbus accounts for roughly one quarter (Woidasky et al., 2017).

2.1.4 Titanium Supply Chain in the European Union

From the previous paragraph it is clear that the EU plays a limited role in the global supply chain of titanium metal. Historically, it focused its investments on R&D and manufacturing capacity in the high value added stage of component manufacturing.

The EU consumed roughly 29,7 kilotons of titanium metal in 2019, of which civil aviation received 67%, industrial equipment 29%, Military applications 2% and consumer goods 2% (Buesa et al., 2025).

Despite holding ore reserves estimated at nearly 40,000 kilotons of TiO_2 , the EU extracts only a negligible share, entirely directed toward pigment production (SCREEN, 2020; USGS, 2023). As a result, the EU lacks domestic refining and processing capacity for titanium metal, relying almost entirely on imports to meet industrial demand. Table 2 summarises the structure of EU titanium metal trade by partner and product stage showing both import and export shares relative to total traded volumes (UN Comtrade, 2019). This breakdown highlights EU's dependence on external suppliers, particularly for intermediate and reprocessed materials. Since the nomenclature adopted by UN Comtrade and JRC differs from the one presented above, for the purpose of this thesis unwrought titanium will be considered sponge, while wrought will include ingot, milled products and components.

Table 2. EU trade in unwrought, wrought, and scrap titanium metal by main partner in 2019 (% of total imports and exports). Source: UN Comtrade

	IMPORTS			EXPORTS		
	UNWROUGHT	WROUGHT	SCRAP	UNWROUGHT	WROUGHT	SCRAP
USA	34%	37%	50%	20%	20%	60%
JAPAN	24%	16%	20%	0%	1%	1%
Russia	11%	25%	3%	2%	0%	12%
CHINA	6%	18%	1%	1%	7%	0%
RoW	26%	5%	26%	77%	72%	28%

At the primary melting stage, titanium production in the EU is concentrated in a handful of Member States, Italy, France, and Romania, whose combined annual capacity is estimated at roughly 10 kilotonnes of ingots (Buesa et al., 2025). In 2019, the majority of titanium sponge and high-grade scrap used in EU production originated from the United States, Japan, Kazakhstan, and Ukraine. The ongoing war in Eastern Europe has since disrupted trade with Russia and Ukraine, shifting import flows toward the United States and, increasingly, Saudi Arabia. Because the EU does not produce titanium sponge domestically, all sponge exports from the bloc should be considered re-exports (Rueda-Cantuche et al., 2022).

For downstream stages, including ingot conversion, mill product fabrication, and component manufacturing, available statistics provide limited clarity due to inconsistent definitions of “wrought” and “unwrought” titanium across datasets. Nonetheless, the JRC estimates that France accounts for more than half of EU wrought titanium production, followed by Germany and Italy. Import patterns largely mirror those observed for sponge, with continued reliance on the same extra-EU partners (Buesa et al., 2025).

As previously discussed, most titanium scrap generated in Europe arises from manufacturing processes rather than end-of-life collection. Since the 1980s, U.S. producers have consolidated leadership in titanium reprocessing and midstream production technologies, supported by long-term buyback agreements with European manufacturers. Under these arrangements, European firms supply production scrap in exchange for discounted wrought titanium products. Currently, no comprehensive data exist on in-use titanium stocks or the volume and location of end-of-life titanium-containing goods within the EU economy. From interviews with aviation experts, it results that end-of-life recycling is underexplored, though advances such as turbine remanufacturing and the emergence of dismantling facilities suggest growing potential (Baldassarre, 2025).

As introduced in the background section, the study “Circular Economy for Resource Security in the European Union” by Baldassarre offers an in depth qualitative analysis of the supply chain, mapping stakeholder roles, interactions, and systemic barriers to circularity (Baldassarre, 2025). The author, that contributed as well to the other groundwork study on titanium by the JRC, identifies multiple drivers and barriers across five domains, namely geopolitical, cultural, economic, regulatory, and technical all summarised in Appendix I, Figure 16. Baldassarre advances three key recommendations for EU stakeholders:

1. Foster public–private investments in recycling technologies while revising restrictive buyback agreements to enable economies of scale;
2. Establish dedicated dismantling facilities for end-of-life aircraft and defence systems within Europe, increasing the availability of high-grade secondary titanium;
3. Develop new international partnerships with upstream suppliers to diversify import sources and enable cross-border circularity loops.

The case of EcoTitanium exemplifies the practical implementation of these recommendations. Established in 2017 as a joint venture between UKAD, the French State, and Crédit Agricole, EcoTitanium operates the first European facility producing

aerospace-grade titanium ingots primarily from recycled scrap. Thanks to the installation of Plasma Arc Melter (PAM), around 80% of its feedstock originates from machining residues and offcuts generated by European aircraft manufacturers and subcontractors that were previously exported to the United States. The recovered titanium is melted into high-quality alloy ingots and further processed downstream by UKAD and Aubert & Duval into semi-finished and finished products. EcoTitanium had 30 employees and a melting capacity of 4 kt/year in 2024. The manufacturer claims that the innovative process, exemplified in Appendix I - Figure 17, emits four times less CO₂ compared to primary melting route that uses only titanium sponge (Aubert & Duval, 2025).

2.2 Circular Economy and Raw Material Supply Security

2.2.1 Circular economy overview

The circular economy is a systems framework that challenges the linear “take–make–dispose” model by promoting restorative and regenerative practices designed to retain products, components and materials at their highest value while minimising waste and pollution (Ellen MacArthur Foundation, 2017). Its guiding principles are to eliminate waste, circulate materials through strategies such as reuse, repair, remanufacturing and high-quality recycling, and regenerate natural systems. Although efforts have been made to formalise a single definition, CE remains highly context- and time-dependent, with diverse interpretations shaped by local conditions (Upadhayay et al., 2024).

The circular economy paradigm is usually represented through the R-ladder framework (Figure 3), which effectively communicate its hierarchical set of value-retention strategies.

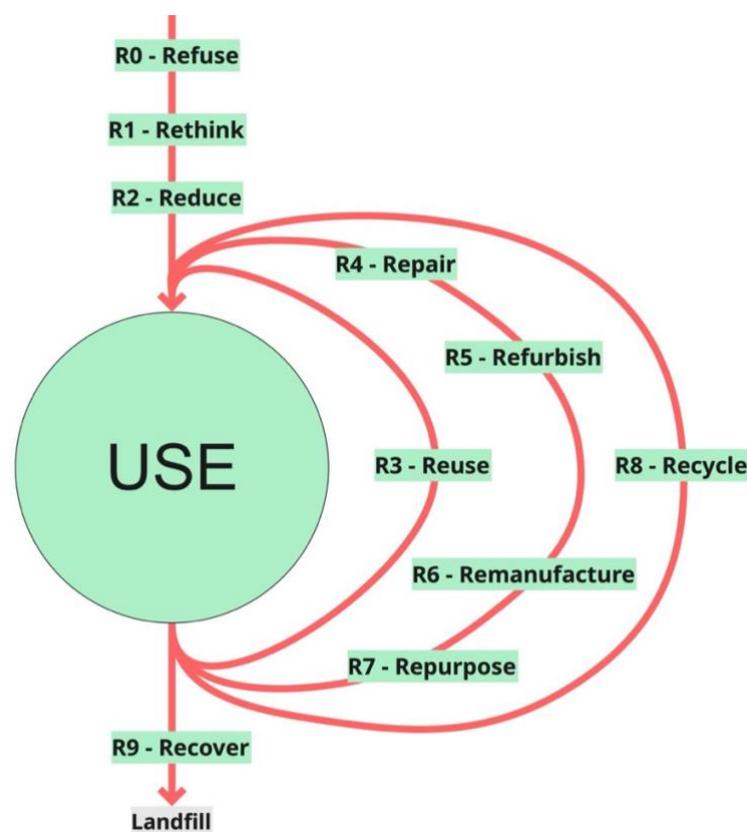


Figure 3. Schematic representation of the R-ladder of Circular Economy strategies

At the top of the ladder (R0–R2: Refuse, Rethink, Reduce), strategies act upstream by avoiding or minimising resource extraction and waste generation in the first place. These “narrowing loops” are translated into the Ecodesign and Sustainable products regulation reducing virgin material consumption at the design stage (EEA, 2025).

In the middle of the ladder (R3–R7: Reuse, Repair, Refurbish, Remanufacture, Repurpose), the focus shifts to extending the functional life of products or components, keeping them in active use and preserving embodied energy, materials and capital value. These “slowing loops” found a limited application in the broader public policy through the Extended Producer Responsibility (EPR) and Right to Repair legislations (EEB, 2024).

At the bottom (R8–R9: Recycle, Recover), the strategies intervene late in the product life cycle, recovering materials or energy from waste. Even though “Closing loops” are inherently less efficient due to entropic principle, they have been historically the most studied and promoted strategies of the ladder. For instance, Calisto Friant et al. (2021) found a dichotomy between the rather holistic EU discourse, and its policies focus on end of pipe solutions.

As mentioned above, there is no consensus on the definition of CE as it should ultimately be considered as a set of strategies that can serve different purposes. In the first place, an ecological economics approach highlights various elements: a critique of infinite growth that emphasises the preservation of natural capital, planetary boundaries and sufficiency (Wautelet, 2018). Within this “resource stewardship” perspective, circular strategies are organised through the R-ladder, a hierarchy that prioritises upstream reduction, reuse and lifetime extension before recycling, reflecting the aim of retaining value and minimising virgin extraction. Yet these same strategies can be mobilised toward a totally different end: resource autonomy. In this alternative framing, increasingly visible in EU debates on Critical Raw Materials, circular practices are adopted not for environmental regeneration but to reduce import dependence, secure strategic materials and reinforce industrial resilience (Moloney, 2025). Recognising both paradigms, stewardship and autonomy, is essential when approaching the relevant legislation, as they shape how circularity is interpreted, which strategies are prioritised and what policy objectives they ultimately serve.

2.2.2 Critical Raw Materials in the EU legislation

It is widely recognised that the origins of the EU lie in the Coal and Steel Community of 1952, created to secure and jointly govern access to essential resources (Bennett, 2022). This arrangement was shaped not only by economic reasoning but also by the pursuit of political stability and collective security (Pecchia et al., 2024; Segers, 2023). The logic that linked resource governance to peace and integration continues to inform European raw

materials policy today. While the institutional landscape has evolved in response to new technologies and political shifts, the underlying concern for shared access to strategic resources remains evident (Glencross, 2024).

Within this context, the concept of criticality has gradually expanded its relevance. Once largely confined to defence planning and national security, the notion gained broader significance after early disruptions in the rare earth market, particularly China's 2011 export restrictions. These events highlighted the extent to which modern economies depend on a small group of materials that support key industries and everyday technologies (Schrijvers et al., 2020). Across jurisdictions, assessment methods vary, yet they converge on two core dimensions: the degree to which an economy relies on a given material, and the probability that its supply could be disrupted within a relevant timeframe.

In the EU methodology, these dimensions are formalised through two indicators (Blengini et al., 2017). **Economic Importance (EI)** reflects how strongly a material underpins the economy, calculated as the sum of its contribution to major industrial mega sectors:

$$EI = \sum_s (A_s \times GVA_s)$$

where A_s is the material's share of inputs to mega sector s , and GVA_s is that mega sector's Gross Value Added. **Supply Risk (SR)** captures vulnerability to disruptions, combining the concentration of primary supply, measured through the Herfindahl–Hirschman Index (HHI), with political and governance conditions in supplier countries, followed by risk-reducing factors such as recycling and substitutability:

$$SR = HHI_{WGI} \times (1 - EOL_{RIR}) \times SI$$

where HHI_{WGI} embeds governance quality, EOL_{RIR} is the end-of-life recycling input rate, and SI is the substitution index.

While widely adopted, these formulas have been criticised for oversimplifying supply chain dynamics. Scholars argue for incorporating additional variables, such as trade barriers, import dependencies, or a more symmetrical role for substitutability, to better reflect real-world vulnerabilities (Blengini et al., 2017). Most importantly, the existing framework retains an end-of-pipe bias, reducing the circular economy to end-of-life recycling and overlooking upstream interventions that could meaningfully alter risk profiles.

Concerning the assessment outcomes, regularly updated since its launch in 2011 (European Commission, 2025b), a notable novelty was the introduction of Strategic Raw Materials (SRMs) subset in 2023. This label adds a political dimension by designating dual-use elements essential for both civilian technologies, such as renewable energy and medical equipment, and defence applications. This shift reflects what Vivoda et al. (2025) named the minerals trilemma: the challenge of balancing national security, economic feasibility, and environmental and social sustainability. Figure 4 maps all the 70 candidate materials, of which 34 critical, in the 2023 evaluation within the EU's criticality matrix (Grohol & Veeh, 2023).

Building directly on this updated framework, the Critical Raw Materials Act (CRMA) provides the EU's legislative mechanism for addressing these risks and securing a resilient and sustainable access to CRMs. The Act sets explicit 2030 targets, 10% extraction, 40% processing, and 25% recycling of annual EU demand, while limiting dependence on any single third country to 65% at each stage of the value chain. To achieve this, the CRMA accelerates permitting for Strategic Projects, requires major companies to conduct supply chain stress tests, and fosters international partnerships aimed at stabilising supply (European Commission, 2020).

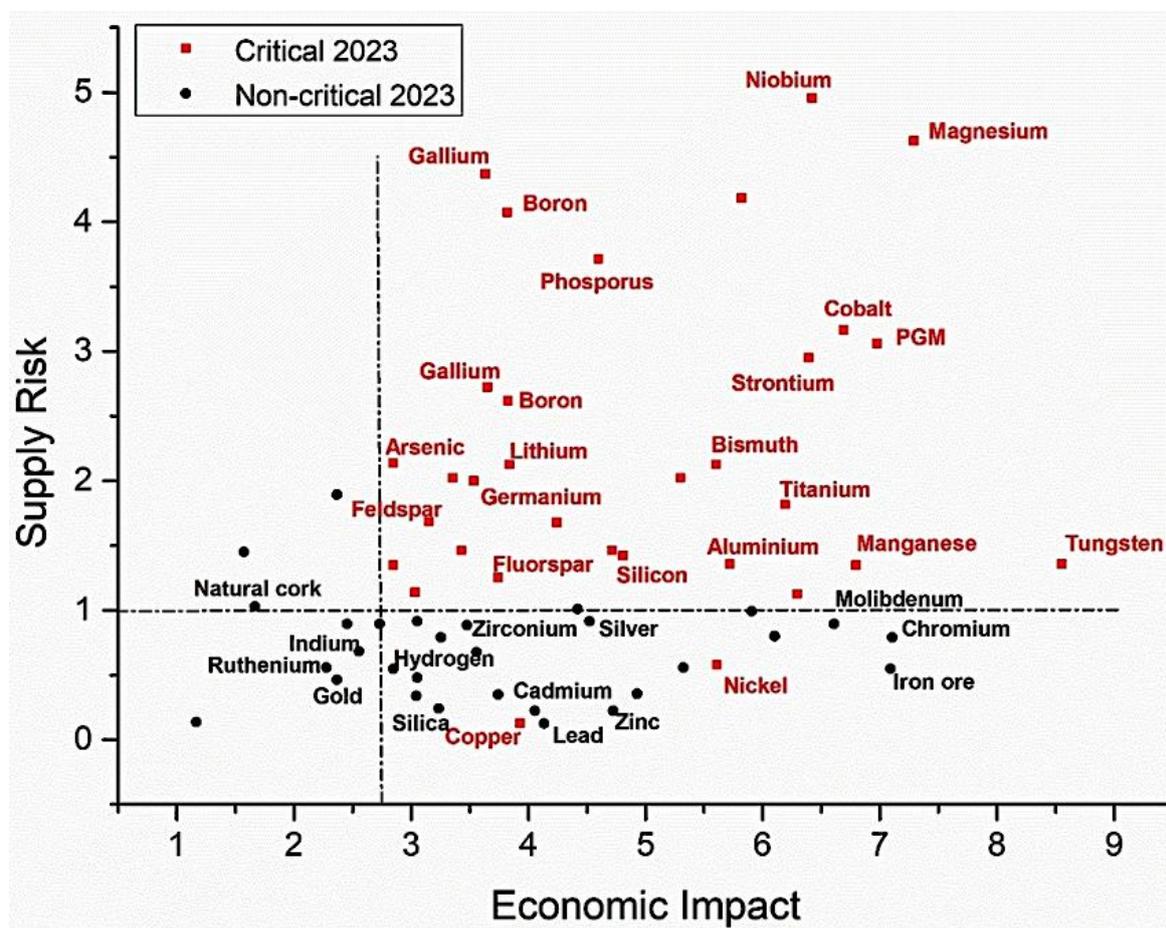


Figure 4. Results of the 2023 EU criticality assessment. In red the 34 critical materials. (Melchionna & Fornasiero, 2025)

The CRMA is a direct expression of the EU's broader commitment to OSA. Under this vision, the EU seeks to maintain openness to global trade while pursuing self-sufficiency in those strategic sectors structurally dependent on external suppliers. Contrary to autarky, OSA aims to strengthen the Union's capacity to act, produce, and secure essential inputs within its jurisdiction when external conditions become unstable, without however limiting international cooperations and partnerships (Kroll, 2024). Within this framework, CE is shifting from being primarily a resource management strategy to a structural tool for enhancing domestic capacity and reducing exposure to concentrated external supply.

This new orientation marks a shift from earlier policies. Despite the EU's long standing commitment to the CE through various action plans and legislative packages (European Commission, 2020a), implementation has remained fragmented across Member States. Circularity is often equalled to recycling, which should in fact be the loop of last resort as shown in the R-Ladder (Pinyol Alberich et al., 2023). National strategies present relevant differences in terms of expectations, justifications and priority of intervention (Arbolino et al., 2024). The lack of a common market for secondary raw materials or harmonised best practices, has led to a plateau in key performance indicators over the last ten years (Castillo-Díaz et al., 2024). The current policy landscape reflects a voluntary, bottom-up model, driven by forward-thinking enterprises and responsive states, rather than a coordinated top-down strategy (Arbolino et al., 2024).

Expanding upon this diagnosis, Tukker (2025) argues that many circular options that are technically and economically feasible remain underutilised. The bottleneck lies less in technology than in insufficient systemic coordination and integration of circular strategies into industrial and strategic policy. The alignment of the OSA vision and the CRMA, echoed in the foreword to the proposed Circular Economy Act (European Commission, 2025a), open a policy window to scale circularity beyond isolated initiatives. To support this shift, Tukker (2025) stresses the need for forward-looking, economy-wide foresights revealing industrial interlinks and dynamic MFA studies, enabling the projection of future demand, stock development, and secondary material availability.

2.2.3 Circular Economy in the Security Studies

Security is central to the survival of political communities and a persistent theme in public debate. In International Relations (IR), its meaning has shifted repeatedly depending on two variables: the referent object, who or what is to be secured, and the threat, from whom or what security is needed (Jackson-Preece, 2011).

For classical realists, security meant the protection of the state against objective military or subversive threats. This view, grounded in the logic of game theory, assumed rational, self-interested actors competing in an anarchic system. They focused merely on national and international discourses. Constructivist scholars challenged this narrow scope, treating security as a social construct and extending it to non-military challenges such as environmental degradation, health crises, and economic instability. The human security agenda went further by shifting the referent object from the state to the individual. The Copenhagen School formalised this perspective with its theory of securitisation: by shifting the referent object in the public debate any issue can be framed as an existential threat to justify extraordinary measures (Stepka, 2022).

Critical Security Studies (CSS) represents the latest turn in the debate. If security is socially constructed, then identity, values, and power must be central to its definition. Competing social interests make security an inherently ethical and therefore political question, tied to emancipation and justice. CSS encompasses feminist, post-colonial, and ecological perspectives. Unlike environmental security, which treats nature as a resource to be protected for human use, ecological security recognises ecosystems themselves as actors that require safeguarding (Aradau et al., 2014).

Independently of the assumptions behind the designation of an issue as a matter of security, the logical consequence is its prioritisation over competing concerns on the political agenda. In a world of limited resources, political actors must weigh time, budget, and consensus against other pressing demands. As Lidén (2023) argues, risk assessments embed political and ethical judgements about whose security is prioritised and whose is deferred, revealing that securitisation is as much about values and identity as it is about objective threats.

As outlined above, CE in the European context has traditionally been framed as a sustainable development agenda, implemented through a largely voluntary and fragmented bottom-up approach. A significant shift is now underway, with circularity increasingly positioned as a pivotal instrument to advance OSA vision.

The Strategic Foresight Report states that “security has become a key vector for all EU policies” (Secretariat general, 2025), linking competitiveness, autonomy, and the green transition within a single geopolitical framework. As argued by Tukker (2025), innovation in circularity, particularly applied to CRMs, constitutes a concrete pathway through which the EU can reconcile resource constraints with strategic autonomy objectives.

In academia, to the best of my knowledge the most relevant work on the topic is represented by Petelin (2024). By adopting a constructivist lense, CE is mapped onto four security discourses each with a different referent object. National security discourse

focuses on safeguarding the state from resource dependence and external shocks. International security addresses vulnerabilities at the regional or global level, linking CE to fair supply chains and geopolitical stability. Human security emphasizes protecting communities and individuals, prioritising wellbeing, equity, and resilience. Finally, ecological security takes the biosphere itself as the object of protection, pursuing systemic transformation to restore and maintain planetary balance. Under this rationale CE is no longer reduced to waste management or climate policy, rather it becomes a strategic lens through which resource flows, industrial practices, and geopolitical concerns can be aligned. Figure 5 provides a clear diagram of the relation between security threats and the subsequent responses that the relevant actors, in this case referred to as Natural Resource Management System, can put forward to achieve resource security. In the European context, Petelin’s framework would allow policymakers to recognise its multiple security implications: stabilising critical material supplies (national), strengthening international cooperation and transparency in supply chains (international), supporting jobs and livelihoods through new circular models (human), and addressing long-term planetary limits (ecological).

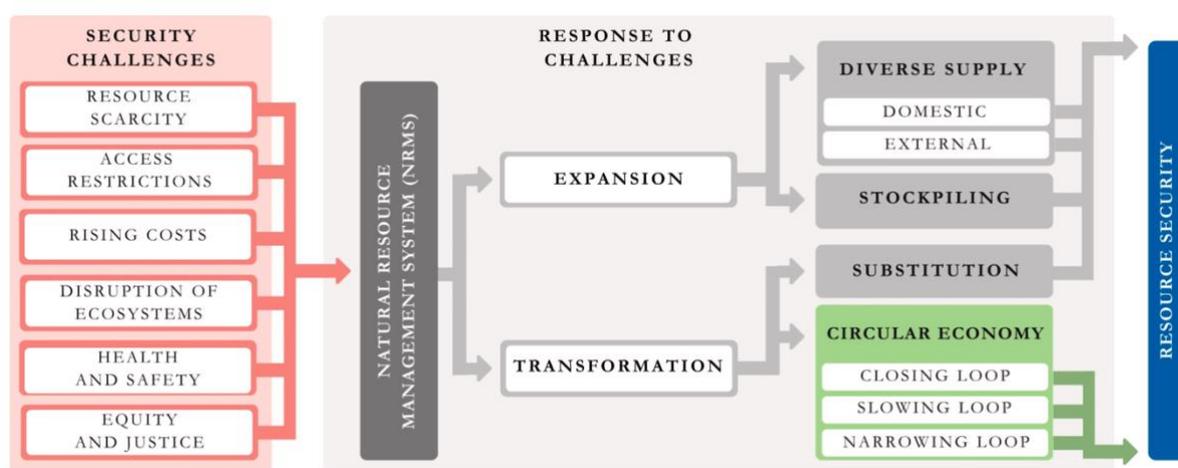


Figure 5. Security challenges and policy responses, positioning circular economy as a key strategy for achieving resource security (Petelin, 2024)

Nonetheless, already Petelin (2025) studying the Nordics’ approach to CE of critical metals recognised the insurgence of pitfalls that undermine the stated alignment to a discourse. By prioritising sovereign control over secondary raw materials and restricting exports, states risk turning CE into a zero-sum competition that weakens global cooperation, raises costs, and exacerbates inequalities between industrialised and resource-dependent countries, ultimately preventing real transformation. Patrick Schröder & Jack Barrie (2024) have named this protectionist practice “Circular Resource Nationalism”. Early examples of such practice are China’s restrictions on the export of rare earth processing technologies, British Steel’s proposed limits on scrap metal exports, and

the adaptation of CE principles within military logistics for selective fortification. Such trends highlight the need for a balanced approach. One that integrates CE into security strategies without reproducing the very vulnerabilities and rivalries it aims to overcome.

2.2.4 The Epistemology of Resource Security Assessment

This section of the literature review has shown the extent to which the definition and conceptualisation of resource security is shaped by underlying worldviews and objectives. Although a discussion on the epistemology of terms may appear trivial for the purposes of this research, it directly influences the contextualisation of the answer to the main research question. Moreover, this section provides the theoretical justification for the *Circular security* framework defined in the Methods (Section 3.1).

A key contribution to this discussion is a study by world-leading experts who reviewed the methods and data used to determine raw material criticality (Schrijvers et al., 2020). In the introduction, the authors highlight that no generic standard approach exists for conducting a criticality assessment, succinctly captured in the statement that “criticality is in the eye of the beholder.” Building on the methodological framework of Life Cycle Assessment (ISO, 2006), they developed an approach that demonstrates how goal and scope shape the outcomes of criticality assessments. Defining the nature and type of risk associated with the supply of a material, together with the availability of data, determines the selection of indicators, their evaluation, and ultimately the interpretation and communication of results.

The typical criticality matrix identified by the authors contains two quantifiable axes (Schrijvers et al., 2020): Supply Risk and Vulnerability (or Impact of Supply Restriction). Supply Risk captures the probability or likelihood of a supply disruption within current or future supply structures. Indicators central to this dimension, such as the diversity of producing countries (HHI) and their political stability (WGI), focus on external factors that could trigger a shock. Vulnerability, by contrast, assesses the impact or consequence of such a disruption on the system under study (e.g., the economy, in the case of the EU methodology, or a specific technology). Indicators such as a material’s relative economic importance and the lack of substitution possibilities directly measure the magnitude of harm if supply fails. The detailed table of indicators is presented in Appendix II – Indicators for criticality assessment. Notably, resilience does not function as an independent dimension but instead operates as a cross-cutting property embedded within existing indicators. Factors such as recycling rates, the presence of stockpiles, and substitutability are, in essence, forward-looking measures of a system’s resilience. They

illustrate the inherent ability of the system to absorb, adapt to, or recover from a supply shock, thereby acting to reduce the overall assessed Supply Risk or Vulnerability score.

On the other hand, in a review of pathways to achieve supply security for Rare Earth (RE) elements, a subset of CRMs, the three leading theories of risk, resilience, and criticality are presented as independent concepts (Salim et al., 2022). The authors observe a persistent tendency in the literature to concentrate on isolated aspects of the security challenge, thereby limiting a full understanding of the complex system dynamics of RE supply chains. Indeed, a risk-theory lens can offer mitigation options only for a static scenario, while criticality assessments lack an integrated view of interconnected production chains. The review identifies four pathways to enhance supply security, which can be generalised to all CRMs: circular economy strategies, although in this paper reduced solely to recycling; supply chain agility, referring to the ability of a business to remain responsive and flexible amid unpredictable market changes through both diversification and substitution; building domestic supplies, achieved through stockpiling in the short term and through streamlining investment and regulation in domestic mining and processing in the long term; and pursuing options beyond terrestrial mining, such as R&D in deep-sea and space mining. In summary, supply security is not merely the absence of risk, but the systemic capacity to ensure stable, sustainable and resilient access to materials over time through the interaction of these four pathways.

Both studies converge on the idea that material supply security cannot be captured by a single metric and requires a multi-dimensional assessment. They agree that supply disruptions originate from a combination of external pressures, such as geopolitical instability or production concentration, and internal system characteristics, such as substitutability or recycling performance. However, they intrinsically differ in the epistemology of resource security. Schrijvers et al. (2020) adopts a reductionist, measurement driven definition where supply security is an assessment problem that, although with limitations, can be represented through a single endpoint value. Resilience is not a separate object of inquiry but a property embedded within the indicators themselves. The result is that security becomes what can be systematically measured.

On the other hand, Salim et al. (2022) chooses a holistic definition that has risk, resilience and criticality as distinct categories, each contributing to the knowledge of resource security. Rather than collapsing resilience into a single numerical output, this view conceptualises it as an emergent property of the system that depends on adaptability, redundancy, and strategic capacity. These differing views highlight the need for a framework that can reconcile indicator-based rigour with system-level understanding, providing a more complete foundation for analysing titanium supply security in the chapters that follow.

2.3 Core Industrial Ecology approaches

Industrial ecology offers a diverse analytical toolkit for studying resource use, environmental burdens, and system-wide dynamics (Clift & Druckman, 2015). Although each core method operates at a different analytical scale, they are united by a common objective: tracking flows of materials, energy, emissions and value across systems.

At the macro level, Input–Output Analysis (IOA) is a systematic framework for quantifying the economic flows of goods and services within a defined system, typically a national or regional economy, over a specific period (Leontief, 1936). It builds on the principles of interdependence among sectors, tracing how the output of one industry becomes the input of another and how final demand drives production across the entire economy. When multiple regions engage in trade, the IO framework extends to capture interregional exchanges, forming what is termed Multi-Regional Input–Output (MRIO) analysis (Nakamura, 2023).

At meso level, Material Flow Analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2016). It builds on concepts from network analysis and life cycle analysis, as it connects the sources, the pathways, and the intermediate and final sinks of a material. Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks, and outputs of a process.

Finally, at micro level, Life Cycle Assessment (LCA) is a systematic method for evaluating the environmental impacts of a product or process across all life-cycle stages, from raw material extraction to end-of-life (ISO, 2006). It builds on systems analysis by linking material and energy inputs to emissions and wastes at each stage, forming a coherent cradle-to-grave representation. Because it applies consistent accounting rules to all unit processes, LCA ensures comparability across alternatives and allows environmental burdens to be traced transparently throughout the supply chain.

Despite these differences in scale, scope, and system boundaries, the methods are conceptually complementary. All three rely on flow-based representations of systems and share a foundation in conservation principles. This conceptual compatibility has motivated increasing interest in hybridisation approaches for those areas of research where data gaps are common and flows traverse both physical and economic domains (Hagenaars et al., 2025). As illustrated in the next section, in CRM research, an hybrid framework is particularly valuable for linking material-specific supply chains to the broader economic structure, improving both resolution and system completeness.

Appendix III – IE methods in detail provides a comprehensive, step-by-step technical reference for both MFA and MRIO. Readers unfamiliar with the technical details can consult the section for reproducibility and implementation clarity while the main text focuses on conceptual interpretation and empirical findings.

2.3.1 Hybrid MFA-MRIO approaches

Hybrid MFA–MRIO models integrate the material specificity of MFA with the system-wide economic structure of MRIO. Nakamura et al. (2007) outline two principal pathways for such integration: full physical input–output tables (PIOTs), which express all interindustry flows in mass units, and matrix augmentation through the Waste Input–Output (WIO) approach. While PIOTs offer a conceptually elegant, unit-consistent representation of material–economic systems, their construction is hindered by limited physical data. The WIO framework provides a more practical alternative by adding waste-generation and waste-treatment sectors to the existing IO structure, thereby retaining the monetary framework while embedding key material pathways alongside it.

A prominent example of matrix-augmentation hybridisation is the study by Tisserant & Pauliuk (2016), who projected long-term cobalt requirements for electromobility by coupling a dynamic stock-driven MFA of vehicles and batteries with an environmentally extended MRIO model. Their approach maps MFA-derived stocks, inflows and outflows onto concordant IO sectors and converts these physical trends into demand-side shocks that the Leontief model can propagate throughout the economy. Hybridisation is achieved by isolating cobalt mining and refining as a dedicated sector within the IO system: splitting the “Other non-ferrous metals” category in the supply–use tables and reallocating flows based on production statistics and process yields. The resulting sector is populated with MFA-based process coefficients, replacing generic IO entries and creating a physically consistent cobalt supply chain embedded within the MRIO structure. Scenario analysis, built on variations in GDP growth and mining risk, demonstrates that even a simplified hybrid model can quantify how upstream disruptions cascade across the broader economy.

More recent work illustrates the flexibility of hybridisation for analysing critical materials and circularity transitions. Della Bella et al. (2023) combine dynamic MFA with MRIO trade structures to create a multi-regional waste IO framework that estimates future demand, secondary-material availability and systemic bottlenecks under low-carbon pathways. Similarly, Meglin et al. (2022) develop an integrated assessment model that embeds physical IO representations of regional construction flows, enabling joint evaluation of material cycles, economic outcomes and environmental impacts. Despite

their advances, these studies underline enduring challenges which include the inadequate representation of industrial reality by static technical coefficients, uncertainties in sectoral disaggregation especially with CRM and limited representation of circularity in terms of quality degradation over use cycles and secondary-material technical constraints.

2.4 Industrial Ecology studies on titanium in aviation

Despite the economic weight of aviation and the risks of material bottlenecks illustrated in the background, as also noted by Baldassarre (2025), to date no study has applied hybrid Industrial Ecology methods as presented before on CRMs in aviation. Nevertheless, the reviewed literature has produced a constellation of studies that naturally outlines the boundaries of the research gap.

The most comprehensive contribution is by Hoff et al. (2025) who analysed how circular strategies affect titanium demand and supply in aviation globally. Drawing on data from over 55,000 aircraft, the study shows that end-of-life recycling offsets less than 5% of titanium inflows due to long service lives, while engine upgrades offer only limited reductions as newer models remain titanium-intensive. Extending aircraft lifetimes emerges as the most effective strategy, lowering annual demand by up to 10%, with greater effects when combined with recycling. Unlike previous studies, this work captures the sector's inflow–outflow dynamics at fleet scale, yet it omits stock evolution and upstream supply-chain interactions that a full MFA approach would reveal.

The following two subsections review the most relevant literature focusing specifically on aviation and on titanium. Although these studies do not yield results directly comparable to those of this thesis, owing to differences in system boundaries, methodological scope, and underlying assumptions, they provide valuable methodological insights. By examining how previous researchers have approached similar research questions, this literature helps contextualise the present work and informs several of the methodological choices adopted in this thesis.

2.4.1 Aviation sector applications

Regarding applications of Industrial Ecology methods to aviation, one of the most comprehensive studies is by Lefeuvre et al. (2017), who used a dynamic MFA to assess global in-use stocks of carbon fibre reinforced polymers (CFRP) and related waste flows between 2016 and 2050. Using a bottom-up approach, they estimated the number of civil aircraft currently in use, retired, and produced in the future, linking each aircraft model

to its specific CFRP content. Although the study validated its stock estimation methods through cross-comparison, it arguably oversimplifies fleet evolution and composition, focusing mainly on end-of-life waste management while neglecting upstream and midstream circular strategies.

Complementary insights are provided by Woidasky et al. (2017), who estimated the global aircraft fleet and its material composition to evaluate potential recycling stock. They offered detailed breakdowns by aircraft model, engine type, manufacturer, and region, concluding that metal alloys are well positioned for recovery due to their high intrinsic value, while CFRP recycling remains a longer-term challenge. However, the study's methodological rigor is limited, with poor data transparency and circular references undermining the robustness of its findings.

2.4.2 Titanium industry applications

In contrast to aviation, existing MFA and MRIO research on titanium focuses predominantly on national case studies, particularly China. The country occupies a central position in the upper and midstream stages of the global titanium value chain. It is therefore unsurprising that most dynamic MFA studies on titanium concentrate on the Chinese context. Notably, authors share the same stated objective of directioning Chinese policy effort toward a sustainable development of the industry rather than supply security or resilience reasons. However, they differ in scope along the value chain, examining titanium dioxide (X. Li et al., 2020), titanium sponge (X. Hu et al., 2022), and aggregated titanium products (M. Li et al., 2022). While section 3.3.2 will detail the stages of titanium's life cycle, the focus here lies on their methodological contributions. Some of the remarkable advances are the combination of spatiotemporal analysis and Shared Socioeconomic Pathways (SSPs), extending beyond historical snapshots to provide forward-looking insights and regional policy guidance. Yet, significant limitations persist: data on end-of-life scrap recovery remain highly uncertain, and scenario assumptions are often simplistic, overlooking process-level efficiencies and economic feedback. Regarding indicators, authors adopted import dependence, primary production loss and recycling rate, without though formalising them to compare scenarios.

In the context of Japan, Takeda & Okabe (2019) conducted a comprehensive review of titanium recycling technologies and processes, complemented by a simplified national MFA for 2007. Their study traced transformation losses, additive inputs, and scrap generation across the production chain, offering one of the first schematic overviews of titanium circulation in an industrialized economy. Interestingly, they were also the first to characterise aircraft models by material composition, revealing the near-complete

replacement of aluminium with titanium alloys and composites since the 1990s. The authors concluded that a substantial reduction in production costs would likely trigger a sharp rise in titanium demand and, consequently, scrap generation; making the development of advanced recycling technologies for impurity removal increasingly critical.

Lastly coming to the United States, Lamin (2024) introduced an innovative methodology to analyse the global, company-level titanium supply chain for the aerospace and defence sectors. The study integrates network analysis with flow modelling through a Network Interdiction Model. This framework enables the simulation of worst-case disruption scenarios, assessing how geopolitical shocks or targeted attacks on specific firms or trade routes could impair supply continuity. The analysis revealed a structurally fragile network, particularly vulnerable to disruptions in sponge production, and underscored the strategic importance of geographic diversification and domestic capacity restoration.

A structured attempt to model titanium metal stock and flow dynamic within the EU is yet to be developed. The most comprehensive effort to date is by the JRC, whose report *“Titanium metal in the EU: Strategic relevance and circularity potential”* represents the only instance of MRIO-based analysis in this field (Buesa et al., 2025). Using the FIGARO database, the authors evaluated two circular economy scenarios: (1) reducing EU-US buyback agreements to increase domestic scrap reprocessing, and (2) improving the collection of end-of-life aeronautical scrap suitable for remelting. To model these, they first simulated the negative effects of cutting trade with non-EU partners through the Hypothetical Extraction Method (HEM), and then applied bi-proportional adjustment methods to re-balance global supply, demand, and trade under expanded EU production capacity

The first scenario yielded about €20 million in value added, 380 new jobs, and a reduction of 16.4 kilotonnes of CO₂-equivalent emissions. While the second produced negligible impacts. The authors noted several methodological limitations:

1. Total titanium scrap flows derived from customs-level data do not perfectly align with macroeconomic statistics. This discrepancy likely arises from re-exports, mixed shipments containing multiple goods and limited geographical coverage of the micro-level dataset;
2. the disaggregation was done by hybridising FIGARO with EXIOBASE database which have different structures and aggregation assumptions, yielding noticeable deviations;
3. recycling activities are possibly misclassified in national accounts, and aggregated activities that are not always applicable to metal reprocessing.

A further, implicit limitation lies in the aggregation of all titanium types into a single product category. Given the exceptionally high value added and purity requirements of aerospace-grade titanium, which is traded between 5 to 10 times the price of ordinary consumer titanium (Lee, 2025), this simplification likely underestimates the true potential of advanced end-of-life recycling in strategic sectors. Finally, an issue that is found throughout the report is the overreliance on unbalanced costume datasets which are notoriously affected by mass inconsistencies (L. Hu et al., 2022)

Chapter 3 – Methods and Data

The chapter is divided into four parts. Section 3.1 introduces the *Circular security* Framework, which serves as the conceptual and operational link between the theoretical debates of Chapter 2 and the empirical analysis that follows. It clarifies how different interpretations of security are translated into measurable indicators and circular strategies, ensuring internal coherence in the assessment. Sections 3.2 to 3.4 then present the industrial ecology methods used to quantify titanium flows and their economic interdependencies: static Material Flow Analysis (MFA), dynamic MFA, and Multi-Regional Input-Output (MRIO) analysis.

Static MFA offers mass-balance transparency and integrates heterogeneous datasets into a consistent representation of the EU titanium system in 2019. Because of its straightforward implementation, it is treated briefly. Dynamic MFA and MRIO required more extensive data processing, restructuring, and scenario design, and therefore receive fuller elaboration. Two pairs of scenarios were developed to examine the effects of circular interventions: lifetime extension and enhanced recycling in the dMFA for the civil aviation sector, and parallel lifetime-extension and recycling scenarios in the MRIO for the whole economy. Given their distinct system boundaries and analytical purposes, scenarios are presented within each methodological section rather than consolidated in a standalone chapter.

System boundaries were defined as follows. Spatially, the EU27 is treated as a single region interacting with four external macro-regions: the United States, China, Russia, and the Rest of the World. Temporally, the static MFA and MRIO reference 2019, while the dynamic MFA spans 1970–2040, with scenarios evaluated for 2040. Sectorally, the analysis includes all titanium production and transformation stages described in Section 2.1. Materially, the study considers titanium metal only, in line with the Critical Raw Materials Act, excluding titanium dioxide pigments. Functionally, all results are expressed per kilotonne of titanium metal in final use to enable consistent comparison across methods and scenarios.

All datasets were sourced from publicly available databases and peer-reviewed studies. Detailed sources are documented in the supplementary material on Zenodo, and all Python scripts used to implement the models are openly available on GitHub to ensure full transparency and reproducibility.

3.1 “Circular security” framework

The main research question of this thesis presents an inherent challenge because the concepts it engages with do not possess stable or universally agreed definitions. As shown in Section 2.2, neither “circular economy” nor “supply security” is a fixed analytical category. Security is articulated through competing discourses, each privileging different referent objects, threat perceptions, and policy priorities, while the circular economy spans interpretations ranging from resource stewardship to strategic autonomy. This plurality has direct epistemological implications: what counts as “secure” depends on how security is framed.

The literature reveals two contrasting approaches to operationalising resource security. A reductionist approach compresses security into composite quantitative indicators, producing clear endpoint scores that facilitate benchmarking and comparison. A more holistic approach resists such aggregation and instead treats security as a multidimensional condition shaped by structural dependencies, governance arrangements, and system dynamics. While the former enhances comparability and policy communication, it risks obscuring how circular interventions reshape underlying dependencies. The latter preserves analytical nuance but can limit quantitative tractability and operational clarity.

Titanium is a useful case study because it reflects the range of considerations currently present in EU resource policy, including industrial competitiveness, environmental objectives, and defence concerns. At the same time, existing material flow and economic analyses of titanium are often conducted independently of explicit policy framing, which makes it difficult to translate technical findings into concrete decision-making guidance. The way security is defined shapes which risks are examined, which indicators are selected, and which circular interventions are modelled.

In order to navigate this ambiguity, the present thesis develops an explicit analytical framework that links debates on resource security to categorisation of circular strategies and subsequent translation into interventions. This structure ensures coherence throughout the analysis and enables a more robust assessment of titanium supply in the chapters that follow. Below are the five stages of the framework.

Stage 1: Security discourse selection

The framework begins by identifying the security discourse that frames the analysis. This first step anchors the assessment within a clear normative position, recognising that different policy actors define security in different ways. National security discourses view

circular strategies as instruments of resource autonomy and defence; international security discourses align CE with geopolitical stability; human security discourses emphasise just transitions; and ecological security discourses foreground stewardship of natural capital. Making this choice explicit enables transparent comparison across scenarios rather than assuming a single, universal understanding of security.

Stage 2: Indicator Selection and dashboard presentation

Once a discourse is selected, indicators are drawn systematically from the criticality, resilience and risk literature. These can encompass various dimensions, for instance material, economic, social or environmental. Aligning indicators with the discourse ensures that the assessment remains internally consistent rather than applying a uniform indicator set across fundamentally different security objectives. Some examples of indicators and their framing in each supply chain security theory are available in Table 9 - Appendix II.

Instead of collapsing indicators into a single composite score, the framework adopts a midpoint dashboard format inspired by LCA standard. This approach retains the multidimensional character of security and makes explicit how circular strategies shape different facets of the system. The dashboard enhances transparency by clarifying which dimensions improve or deteriorate under each scenario. It reveals trade-offs that would be obscured by an aggregated index.

Stage 3: Circular Strategy Selection

Once discourse-specific indicators are established, this stage identifies which circular economy strategies are most aligned with the chosen security discourse. Using established CE frameworks (e.g., the R-ladder presented in Section 2.2.1), strategies are evaluated for their compatibility with discourse priorities. Some examples can be: national security emphasises domestic recycling infrastructure and retention of material ownership; international security favours cross-border recycling networks and diversified secondary suppliers; human security foregrounds fair labour conditions and community-based recovery systems; ecological security prioritises dematerialisation, design optimisation and high-value material cycles.

Stage 4: Circular Intervention Modelling

The fourth stage translates abstract circular strategies into concrete, context-specific interventions for the titanium supply chain. Using methods such as the IE ones, discourse-aligned strategies are operationalized as quantifiable scenarios. For example, a "domestic recycling infrastructure" strategy (national security discourse) becomes a modelled

intervention specifying collection rates, processing capacity, and secondary titanium output within EU borders.

Baseline and intervention scenarios are then compared across the dashboard indicators established in Stage 2. This stage directly answers the research question in its discourse-specific form: *What effect could [discourse-aligned CE strategies] have on [discourse-specific security indicators] for [material] supply?* Each discourse yields different intervention priorities, which are evaluated against different indicator sets, producing a systematic yet pluralistic answer to how CE affects titanium supply security.

Stage 5: Security implications

The results are read through the security lens chosen at the outset. Changes in indicators are translated into concrete security implications according to the priorities defined in Stage 1. This final step ensures that a numerical improvement in one indicator is not automatically treated as a security gain, it must first be assessed against what the chosen framing actually values.

3.1.1 Framework implementation

This section explains the choices made while applying the framework in this thesis, and it is depicted in

Figure 6.

Stage 1, National security discourse is chosen in line with the Open Strategic Autonomy vision and the latest EU resource security policies; the supply of titanium is the referent object to be secured.³

Stage 2, two dimensions are chosen to align with the resource autonomy goal:

- The **material dimension** reflects the physical structure of the supply system. Based on JRC indicators used in its Material System Analysis (Oko-Institut e.V., 2020):
 - *Self-sufficiency*, defined as the share of Share of intermediate flows between stages that are domestically produced. It is effectively the inverse of import dependency, but better highlights the domestic capacity framing;

³ While the European Union is a supranational entity and not a traditional nation-state, the 'National Security' discourse is applied here to the Union as a whole. This methodological choice reflects the EU's delegated competence to enact systemic industrial and trade policies. Because the titanium supply chain is a cross-border industrial system, addressing vulnerabilities at the level of individual Member States would be analytically insufficient.

- *Recycling input rate*, measuring the share of secondary metal in total production input (adding the various manufacturing stages);
- *CRMA targets*, share of final material demand covered by domestic processing or recycling across the supply chain (Grohol & Veeh, 2023). The indicator relates domestic output to total EU demand, distinguishing it from self-sufficiency measures based on the specific manufacturing stages.
- The **economic dimension** captures the capacity of the titanium sector to sustain industrial and social stability, and in turns national security. It includes
 - *Value added* generated by the titanium supply chain, measured in million euros per year;
 - *Employment* it supports across interlinked sectors, measured in thousands people.

The indicators are linked to the methods chosen for the analysis. MFA will represent the material dimension, while MRIO will take the economic one.

Stage 3, the circular strategies chosen are enhanced domestic recycling and aircraft lifetime extension. The former because of its centrality in EU policies about autonomy and the potential to lower imports along the titanium supply chain, while the latter for the particular importance it has in the civil aviation sector (Hoff et al., 2025). Under the national-security framing adopted in this study, the hierarchical ordering of loops in the R-ladder is not a guiding principle, since avoiding material use does not necessarily confer greater security benefits than end-of-life recovery. Instead, circular strategies are judged by their ability to strengthen domestic control over material flows.

Stage 4 concerns the translation of these strategies into quantitative scenario design. The concrete interventions implemented in the models are detailed in section 3.3 for the MFA and section 3.4 for the MRIO, where they are operationalised through specific assumptions, system boundaries and parameter choices that determine the results.

Stage 5, Under the national security lens adopted in this thesis, supply security is understood as strategic autonomy. The selected indicators are therefore interpreted according to their effect on external exposure and domestic industrial capacity.

Material indicators capture the structural dependence of on external titanium supply. Increases in these indicators are interpreted as reductions in import reliance and thus as strengthening strategic autonomy.

Economic indicators capture the strength of the domestic production base sustaining titanium supply. Increases in these indicators are interpreted as reinforcing industrial capacity within the EU and therefore enhancing supply security.

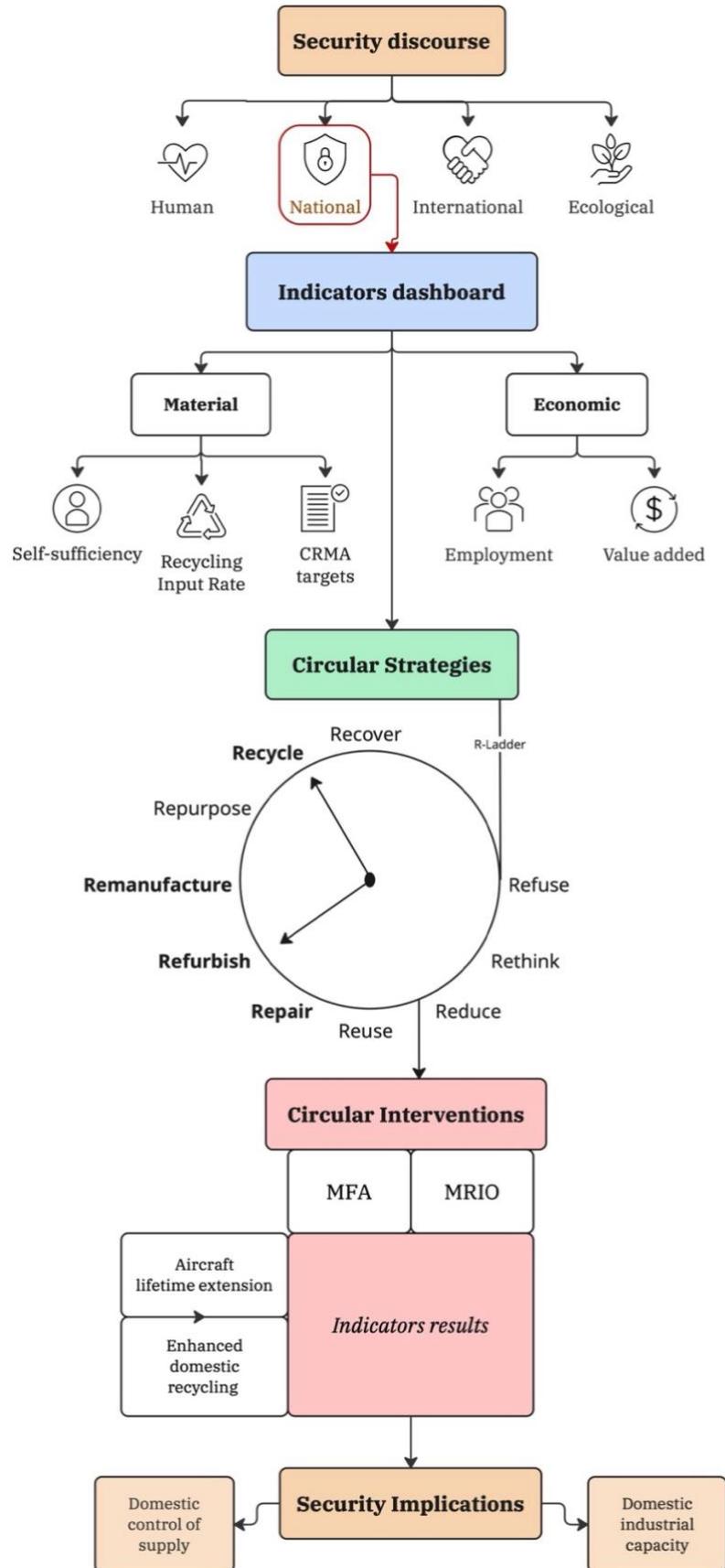


Figure 6. "Circular security" framework applied to titanium case study

3.2 Static Material Flow Analysis

The static MFA was developed to integrate the known life cycle of titanium metal with the structure of the European supply chain in 2019. It began as an accounting framework that consolidated all available raw data into a single model. Through mass balancing and a set of documented assumptions, the complete European titanium supply chain for 2019 was reconstructed. This static representation was then linked to the dynamic MFA by applying transfer coefficients that map aircraft-related inflows, stocks and outflows onto the economy-wide titanium system. Under the assumption that the sectoral pathways of titanium in aviation follow the same transformation chain as the overall economy, this coupling enabled subsequent scenario analysis.

3.2.1 Data

The data for this section come directly from the literature review section 2.1. In particular, it yields on the findings of Buesa et al. (2025) as well as raw figures from UN Comtrade and Eurostat Prodcom.

3.3 Dynamic Material Flow Analysis

The dynamic MFA was applied in this study to quantify the titanium metal embedded in the fleet of aircraft operating within the EU between 2000 and 2040. This exercise provides a bottom-up validation of the titanium inflows to civil aerospace estimated by the static MFA and directly contributes to answering Research Question 3. The modelling approach draws on the framework of Fishman & Graedel (2019), who applied it to analyse neodymium flows in wind turbine systems.

As discussed in Appendix III – IE methods in detail, a stock-driven dMFA begins from observed or projected in-use stocks and uses a survival function to estimate the corresponding inflows and outflows over time. The basic relationship between stock and flow is expressed as:

$$inflow_{plane}(t) = stock_{plane}(t) - \sum_{\tau=t_0}^{t-1} [inflow_{plane}(\tau) \times Survival(t - \tau)]$$

The model uses essentially four exogenous set of variables, for creating the yearly distribution of the survival vintages and the correspondent inflows and outflows:

1. **Fleet of planes** - number of planes registered in the EU between 2000 and 2023 (Eurostat, 2024)

2. **Fleet by class** - breakdown of the fleet in five classes: Passenger (1-50 seats; 51 – 150; 151 – 250; 250+) and Cargo (max weight 1e6 lbs; max 1e6 + lbs) (Eurostat, 2024)
3. **Weight by class** – For each class a representative model is chosen and its manufacturer’s empty weight (MEW) applied to the whole fleet (Aadharsh Viswanath, 2024)
4. **Titanium by vintage** – based on historical data showing an increase in titanium share per aircraft generation (Buesa et al., 2023; Nyamekye et al., 2023). Each new model year is assumed to have a uniform titanium intensity, and this trend is extrapolated to 2040.

3.3.1 Data

The number of aircraft registered in the EU between 2000 and 2023, core input data of this model, was obtained from Eurostat (Eurostat, 2024). The years 2020–2022 show an anomalous dip in the number of aircraft, followed by a sharp rebound in 2023. These fluctuations, drawn directly from Eurostat, reflect the exceptional conditions of the COVID-19 pandemic, during which airlines temporarily grounded or stored aircraft to cut operating costs. Since most of these aircraft were not permanently decommissioned, it was assumed that no significant retirements occurred. Therefore, a regression was applied between the 2019 and 2023 observed values to smooth the anomaly and ensure continuity in the fleet trend. Additional information is available in Appendix IV – MFA model implementation.

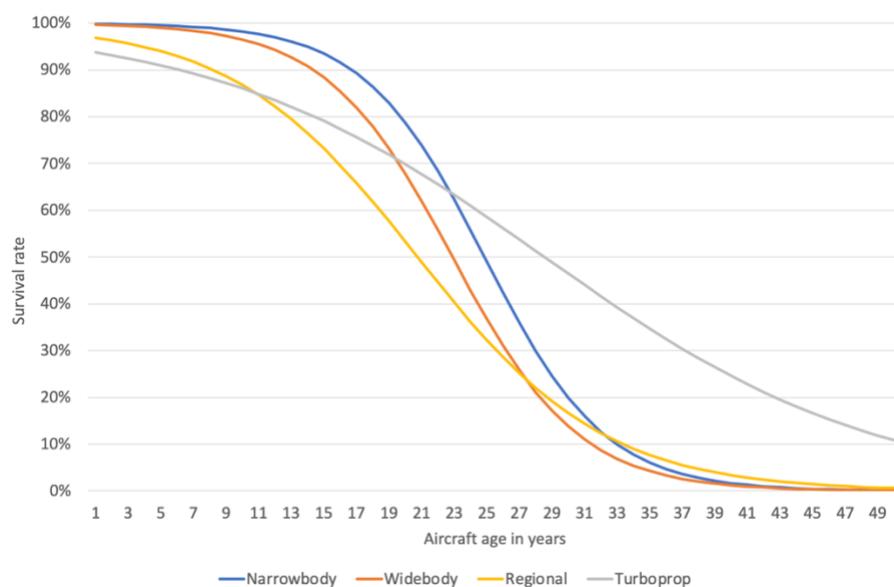


Figure 7. Retirement curves employed in the DLR flagship model (Baier et al., 2024)

As in Figure 7, aircraft lifetimes follow a normal distribution with a mean of 25 years and a standard deviation of 10 (Baier et al., 2024). To ensure a realistic evolution of the in-use stock, the model backcasts the fleet to 1970, assuming an initial near-zero number of aircraft, and projects it forward to 2040, targeting approximately 7000 aircraft in operation. Within the European Civil Aviation Conference (ECAC) area, encompassing 44 countries, air traffic is projected to grow by 1.9% annually until 2040. For this study, it is assumed that such growth translates into a more moderate 0.5% yearly increase in the EU aircraft fleet (Eurocontrol, 2021). At present, the EU accounts for approximately 15% of the global fleet (Cirium, 2025). Maintaining this share constant and considering forecasts of a global fleet reaching 45,000 aircraft by 2040, the EU would represent between 6,750 and 7000 aircraft by that year (Airbus, 2025).

The resulting dataset provides yearly values for inflows, outflows, and net additions to stock (NAS) over the 70-year period. The stock is further divided into vintages that gradually deplete over time, each characterised by class and converted from aircraft mass to titanium mass using class-specific material intensities. This allows the estimation of titanium embedded in the EU fleet over time.

Regarding titanium intensity, as shown by Hoff et al. (2025), it varies significantly over time as a result of technological and design evolution. The share of titanium in total aircraft weight has increased from nearly zero in the 1970s to around 12% in the most recent models. Table 3 summarises the assumed titanium content by aircraft class and decade, showing a consistent upward trend in titanium use projected to continue through 2040. This progression reflects the growing reliance on titanium alloys in modern airframes and engines, driven by the shift toward composite materials and the pursuit of higher fuel efficiency.

Table 3. Evolution of titanium content by aircraft class, 1970–2040.

Aircraft class	1970– 1980	1981– 1990	1991– 2000	2001– 2010	2011– 2020	2021– 2030	2031– 2040
P-aircraft (1–50 seats)	0.00	0.00	0.00	0.03	0.03	0.05	0.05
P-aircraft (51– 150 seats)	0.0275	0.036	0.0535	0.0535– 0.08	0.08	0.10	0.12
P-aircraft (151– 250 seats)	0.0275	0.036	0.0535	0.08	0.13	0.15	0.17
P-aircraft (250+ seats)	0.0275	0.036	0.0535	0.08	0.13	0.15	0.17
Cargo (<1e6 lbs)	0.0275	0.036	0.0535	0.0535– 0.08	0.08	0.10– 0.12	0.12
Cargo (>1e6 lbs)	0.0275	0.036	0.0535	0.08	0.13	0.13– 0.15	0.17

Uncertainty remains regarding two key assumptions: first, all newly registered aircraft are assumed to be produced within the EU, implying all inflows of titanium are of EU origin; and second, MRO operations are simply translated in elongation of the mean lifetime, but in fact they would introduce secondary inflows and outflows of titanium prior to end-of-life.

3.3.1 Lifetime extension scenario

The survival curve governs the flow dynamics in the model. In the baseline scenario, an average aircraft lifetime of 25 years with a standard deviation of 10 years is assumed. The lifetime extension (LTE) scenario explores the effect of enhanced MRO operations that prolong service life. Here, the mean lifetime increases to 30 years and the standard deviation to 12.5, reflecting greater variability in aircraft longevity due to differences in maintenance quality. This modification shifts the survival function, reducing outflows and delaying the demand for replacement aircraft, thereby altering the temporal profile of titanium inflows and embedded stock within the EU fleet. Any lifetime extension strategy, be it MRO, takes time to yield considerable results at scale. Therefore, the LTE scenarios were set to forecast the inflow-outflow dynamics till 2060 instead of baseline 2040. Table 4 shows the parameters chosen in the four scenarios. The stock goal is set at 8000 as to approximate a trend continuing the one identified in section 3.3.1.

Table 4. Lifetime Extension scenario modelling parameters

	Stock goal	Mean (year)	Deviation (years)	Mean	Deviation
Baseline 2060	8.000	2040	10	25	12,5
LTE 2060	8.000	2040	10	30	15

3.3.2 Recycling scenario

The recycling scenario explores how much titanium Europe could recover domestically if current trade practices were partially altered while technological limits remained unchanged. The scenario keeps buyback agreements with the United States intact, meaning that the portion of pre-consumer scrap contractually tied to US remelters continues to be exported. However, the remaining 40% of pre-consumer scrap, currently traded on open markets, is assumed to be retained within the EU and directed to domestic reprocessing rather than export.

Two sets of technical constraints determine how this domestically retained scrap translates into effective secondary production. First, aerospace-grade metallurgy restricts the amount of recycled scrap that can be blended into primary melting. Due to

oxygen and iron specifications in titanium alloys, the practical scrap additive ratio is taken as 55%, which reflects the maximum share of secondary inputs that can be introduced without compromising alloy quality (Takeda & Okabe, 2019). This parameter does not act as a cap on total recycling, but simply defines the proportion of recovered scrap that can re-enter the aviation-grade production loop.

Second, end-of-life recovery efficiencies determine how much titanium can be recovered from the aircraft fleet. Based on dismantling studies such as Airbus' PAMELA project, 90% of the titanium collected at end-of-life is assumed to be directed to recycling (Scheelhaase et al., 2022), and sorting yields an 80% conversion into aviation-grade feedstock, while the rest is downcycled (Airbus, 2022). Together, these parameters define the technical recovery potential from post-consumer flows.

By combining these structural and technical elements, the scenario derives the effective recovery rate used in the MFA model. The retained pre-consumer scrap flow represents the main source of secondary titanium, adjusted by the 55% blending ratio, while post-consumer material contributes an additional stream scaled by the 0.9 collection rate and 0.8 remelting yield.

3.4 Multi-Regional Input Output Analysis

Section 2.3.1 presented the state of the art of hybridisation of Input Output analysis. Matrix augmentation results to be the most suitable approach for addressing the research questions of this thesis research. Indeed, the main limitation to the use of pure MRIO was the aggregation of nearly all critical raw materials under the broad category "*Other non-ferrous metals*," within the Exiobase database (see section 3.3.1). As a result, the specific industrial structure and economic value of titanium remain untraceable within the standard dataset. Following the steps outlined by Tisserant & Pauliuk (2016), the new sector "*Manufacturing of Titanium and Articles Thereof*" was incorporated into the MRIO framework following the detailed procedure and assumptions described in Appendix V – MRIO model implementation.

Concerning circularity scenarios, the methodology builds on Donati et al. (2020). In their framework, the overarching objective of achieving a Circular Economy (CE) is articulated through four strategies: Product Lifetime Extension, Closing Supply Chains, Resource Efficiency, and Residual Waste Management. Each strategy can be operationalised through case-specific interventions that are, in turn, translated into modifications of the Input-Output Table (IOT). Depending on the strategies these modifications are implemented either on the final demand vector (Y) or the technical coefficients matrix

(A). As discussed, the A matrix describes the production “recipe” of each sector, tracing its upstream suppliers by column and downstream customers by row, while the final demand vector (Y) represents the consumption of outputs by households, government, and capital investment. In particular, Gross Fixed Capital Formation (GFCF), capturing sectoral investment, serves as the only proxy for stock within the static IO framework.

The analytical foundation relies on the fixed-price Leontief model, where total output required to satisfy final demand is given by:

$$X = L^{-1} Y$$

Where X is the vector of total outputs and $L = (I - A)^{-1}$ is the Leontief inverse, capturing all direct and indirect effects of changes in demand or production structure.

Once circularity interventions are implemented in the IOT, the difference of total output represents the change between the baseline (X) and counterfactual (X') scenarios

$$\Delta X = X' - X$$

This change is then propagated through the satellite accounts S, allowing the estimation of variations in Value Added (in million €) and Employment (in thousand people) across sectors and regions.

Finally, since the model is multiregional, each entry in A, Y, and X refers not only to an economic sector or demand category but also to its corresponding region (e.g., EU, USA, China, Russia, or Rest of the World), enabling an integrated analysis of both domestic interlinkages and international trade dependencies.

3.4.1 Data

EXIOBASE 3 provides the monetary input–output table covering 163 industries across 44 countries (the EU27 plus 17 major economies) and five aggregated rest-of-the-world regions, with satellite accounts for emissions, materials, resources, and employment. All matrix manipulations were performed using the *Multifunctional Assessment of Regions through Input–Output* (MARIO v0.3.1) Python package. More specific assumptions and data are available in Appendix IV – Model implementation and in the supplementary Excel “Supplementary MRIO” in Zenodo.

3.4.2 Lifetime extension scenario

The product lifetime extension scenario aims to simulate how extending aircraft lifetimes reduces the need for new production while increasing maintenance and repair activities throughout the use phase.

Three sectors are directly affected:

- *Manufacturing of Other Transport Equipment (MOT)*, representing aircraft manufacturing and component production;
- *Air Transport (AT)*, corresponding to the operational use phase;
- *Supporting and Auxiliary Transport Activities (MRO)*, which capture maintenance, repair, and overhaul operations during service life.

Based on the results of the dynamic MFA, the inflow of aircraft required by the civil aviation sector decreases by approximately 20% under a lifetime extension scenario. Assuming a direct relationship between aircraft demand and expenditure, the input coefficient from non-EU - MOT to EU - AT is therefore reduced by 20%. To maintain the balance of the table, the coefficient representing EU - MRO activities is proportionally increased within the same column, reflecting higher demand for maintenance services.

At the level of Gross Fixed Capital Formation (GFCF), the following adjustments are applied:

1. a 5% decrease in GFCF for non-EU MOT, to reflect reduced European demand for imported aircraft;
2. a 5% decrease in GFCF for EU Air Transport, as fewer aircraft entering service require fewer operational investments;
3. a negligible decrease (0.007%) in GFCF for EU MOT, accounting for slightly lower domestic aircraft production;
4. an 8% increase in GFCF for EU MRO services, corresponding to the reinvestment of savings from avoided aircraft purchases into repair infrastructure and spare parts inventories.

This increase in MRO investment is justified by the need to expand maintenance capacity and replace components over longer service lives. It reflects a shift from capital-intensive aircraft production toward service-intensive maintenance activities, embodying the circular principle of value retention through extended product use.

3.4.3 Recycling scenario

The recycling scenario aims to simulate how the EoL recycling of titanium-containing aircraft components can reduce the EU's dependence on imports of primary titanium from third countries. Building on the outcomes of the dynamic MFA, the scenario assumes that approximately 15% of the total input to the European titanium manufacturing sector

is replaced by reprocessed waste sourced domestically, rather than by imported materials.

Five sectors are directly affected by this change:

- *Manufacturing of Other Transport Equipment (MOT)* – representing aircraft manufacturing and component production;
- *Air Transport (AT)* – corresponding to the operational use phase of aircraft;
- *Manufacturing of Titanium and Articles Thereof (Ti)* – the newly added titanium industry;
- *Other Non-Ferrous Metal Production (ONF)* – representing upstream non-ferrous metal producers;
- *Reprocessing of Other Non-Ferrous Metal (RM)* – representing the recycling industry.

The implementation of the scenario follows a structured series of steps within the Input–Output framework:

1. A new domestic input coefficient is introduced for EU RM → EU Ti, set to 16%, representing the share of titanium input now derived from reprocessed and recycled scrap. The percentage derives from the MFA related to civil aviation where it was 26% but in this context the system boundaries comprise all sectors therefore the coefficient has to be scaled. The existing input shares from electricity, ONF, and value added are maintained at their baseline levels to preserve production functionality.
2. To maintain the column-sum constraint ($\sum \text{inputs} = 1$), all other intermediate input coefficients from non-EU sectors to EU Ti are proportionally reduced. This adjustment effectively captures the decline in import dependency for titanium feedstock, reflecting a circular substitution of primary imports with secondary domestic supply.
3. Because EXIOBASE lacks a pre-defined structure for Reprocessing of Other Non-Ferrous Metals, its output is modelled such that 15% flows to the EU titanium manufacturing sector, while the remainder remains unallocated, keeping the circularity intervention local to the EU system. The input structure of the RM sector is assumed to mirror that of the titanium manufacturing sector's output, under the realistic assumption that the same industries supplying titanium products (e.g., MOT, ONF, Electricity) also generate the corresponding scrap streams.
4. The employment and value-added satellites of the RM sector are assumed to be identical to those of the Reprocessing of Copper industry, given the technological and labour-intensity similarities between non-ferrous metal recycling processes.

This configuration ensures that the recycling scenario captures the material circularity achieved through domestic reprocessing while preserving the balance of monetary flows within the Input–Output framework. The result is a modelled reduction in external dependence and a strengthened domestic recycling capacity, allowing for a direct comparison with the baseline scenario in terms of self-sufficiency, value added, and employment.

Chapter 4 – Results and Scenario Outcomes

The following sections present the results of the modelling framework developed in the preceding chapter and summarised in the research flow diagram (Figure 1). It addresses the sub-research questions by progressively moving from a system-wide representation of titanium flows to sector-specific dynamics and economy ripple effects of circular interventions.

The chapter first reconstructs the 2019 titanium metal supply chain of the EU through a Sankey diagram, highlighting the structure of production, use and trade, and documenting the shifts in import patterns that have emerged following recent geopolitical disruptions. It then examines the stock–flow dynamics of titanium in the civil aviation sector, quantifying baseline trends and the effects of aircraft lifetime extension and enhanced recycling scenarios. Finally, the chapter assesses the economic dimension of circular economy interventions, reporting their implications for value added and employment in the EU.

4.1 What is the current material configuration of titanium supply?

Figure 8 is the Sankey diagram of titanium metal flowing in the EU economy in 2019⁴. It results that there was no domestic upstream titanium supply, relying entirely on foreign imports of sponge and scrap. Much of this material was downcycled into ferro-titanium, roughly half of it, or titanium powders for additive manufacturing. Domestic fabrication met only a quarter of the EU's total demand for milled titanium, estimated at 29,7 kilotonnes, with the remainder primarily imported from the United States, China, Russia, and Japan. Around 67% of titanium metal demand was represented by civil aviation, meaning 19,9 kilotonnes. Due to the extremely high buy-to-fly ratio of around 9:1 in downstream sectors such as aerospace, only about 6 kilotonnes of titanium effectively entered the use phase. Hence, roughly 4,5 kt ended up as net addition to stock (NAS) while 1,4 kt reached end of life waste management. Of the resulting outflows, roughly 80% were collected and stored, while the remainder was simply landfilled or unaccounted for (Oko-Institut e.V., 2020).

⁴ 2019 is selected as the baseline year as it precedes the major trade disruptions and geopolitical realignments that significantly altered global supply chains, thereby avoiding distortions associated with exceptional volatility. It also ensures consistency and comparability with the JRC's foundational material system analyses, which rely on pre-2020 data.

Interestingly, concerning the bulk of pre-consumer titanium scrap, only 4,8 kt was reprocessed domestically, while 27,2 kt was exported: over 60% to the United States under long-term buyback agreements, and the rest to Russia and Ukraine.

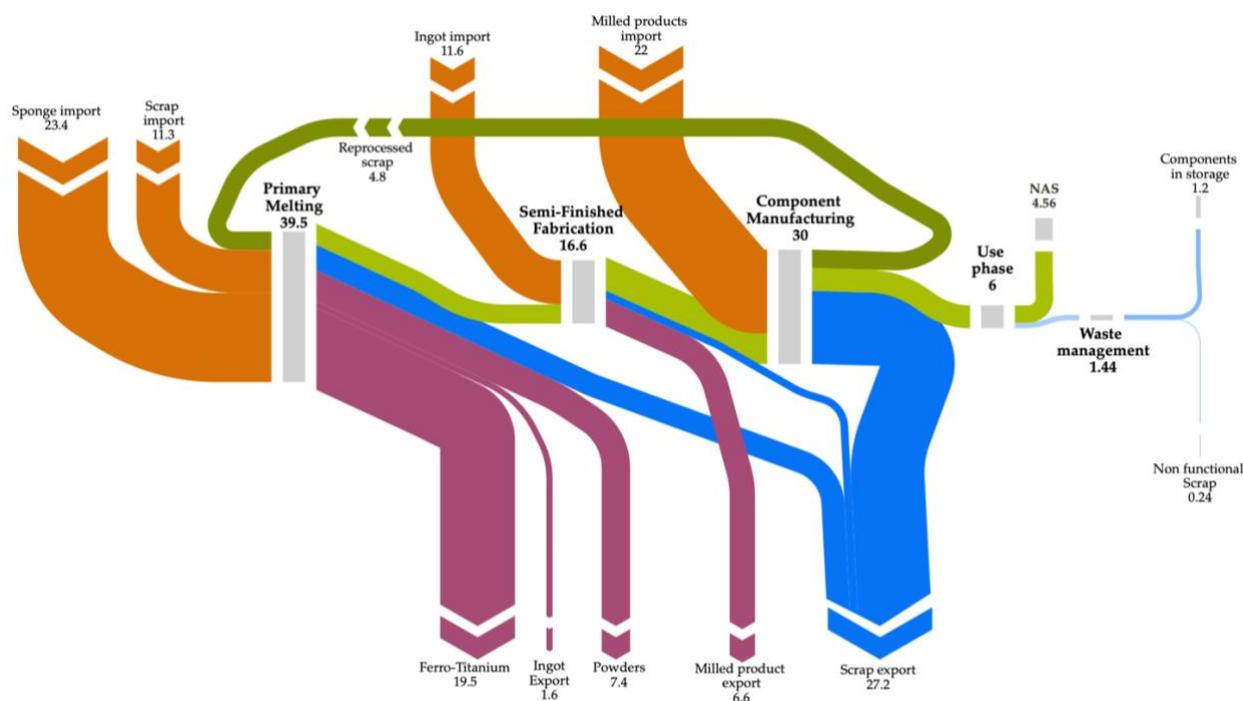


Figure 8. Static Material Flow Analysis of Titanium metal in the EU in 2019. Values are in kilotonnes. Flow colours denote imports (orange), domestic flows (light green), exports (purple), scrap exports (blue), end-of-life management (light blue), reprocessing (dark green) and recycling (cyan).

Since 2019, two major disruptions have reshaped this supply chain: the COVID-19 pandemic and the Russo-Ukrainian war. The pandemic primarily affected downstream demand, with civil aviation activity recovering to 2019 flight levels only by 2024, forcing manufacturers to delay or cancel aircraft orders and to decommission older models. The war, instead, disrupted trade and halted several mining operations in Ukraine, triggering both a contraction in total titanium trade and a profound restructuring of international partnerships. As a result, EU titanium trade volumes contracted across all product categories, while their geographical composition shifted markedly. In addition, the officialization of Brexit in 2020, distorts the dataset as the United Kingdom now results as a new emergent trade partner when it has actually always engaged within the EU. Wrought titanium imports declined slightly from 33 to 31 kt, with the United States as dominant supplier at around one third, while Russia almost halved in favour of a greater quota from China. More pronounced changes occurred in unwrought titanium, where total imports fell from 23 to 18 kt and supplier concentration increased. Kazakhstan became the leading source, providing about 37% of unwrought imports in 2024, while the shares of Japan and the United States dropped to 18% and 14%, respectively, and Saudi Arabia entered the market with a non-negligible share. Scrap trade experienced the strongest contraction: imports declined from 11 to 9 kt, with the United States still supplying the largest share at 28 percent, but with greater diversification across partners,

while exports more than halved, remaining heavily oriented toward the United States, signalling the persistence of buyback agreements. These shifts indicate a reconfiguration rather than a reduction of external dependence. Against this backdrop, and in light of the collapse of Russian titanium production capacity (Moscow Times, 2025), the continued exemption of titanium from EU sanctions has become increasingly contested, prompting renewed debate over the Union’s strategic trade posture and resource security objectives (Banks, 2025).

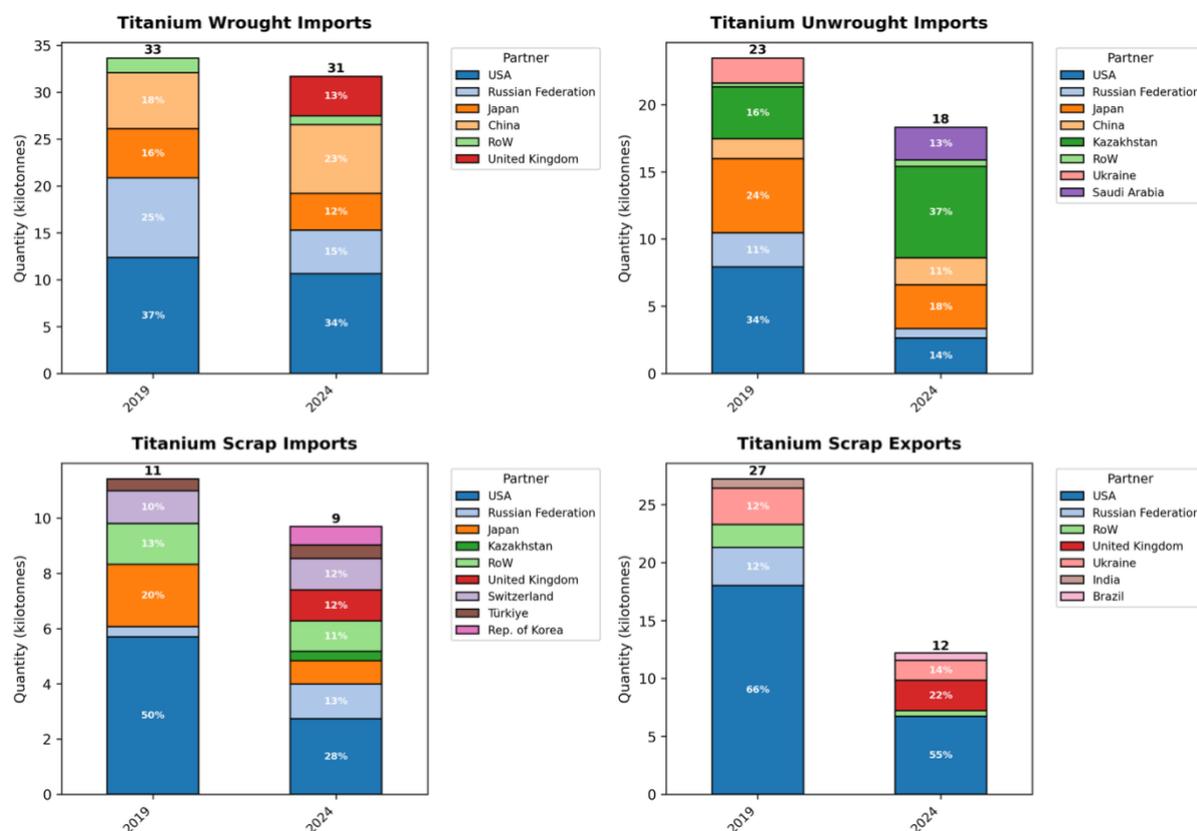


Figure 9. Structure and evolution of EU titanium trade by product category and trading partner in 2019 and 2024 (data: UN Comtrade)

4.2 How might circular interventions in civil aviation affect self-sufficiency in titanium supply?

Under the modelling assumptions described in Section 3.3, Figure 10 illustrates the aircraft survival matrix for the European fleet. The shows the evolution of aircraft in operation from 1970 to 2040. Each coloured band represents a vintage, or cohort, of aircraft entering service in a given year, gradually declining over time according to the assumed lifetime distribution of 25 years. The model backcasts the early fleet growth, reproduces the observed data from Eurostat, and projects forward to a total stock of approximately 7,000 aircraft by 2040.

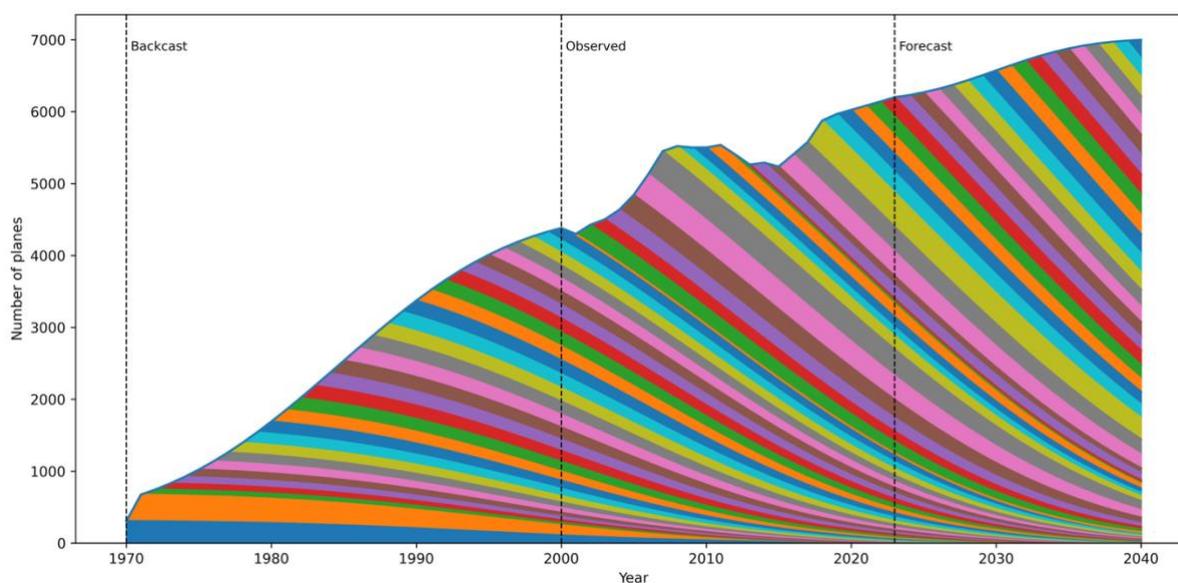


Figure 10. Aircraft survival matrix for the EU fleet (1970–2040). Each colour represents a vintage of aircraft entering service and depleting over time according to the assumed normal lifetime distribution.

The projected inflow of aircraft between 2021 and 2040 amounts to approximately 6,500 units, which is deemed consistent with Boeing’s forecast of 8,700 new aircraft deliveries across the broader Eurasia region (Boeing, 2021).

Using the established stock–flow model, aircraft data were converted into titanium tonnage, representing the metal embedded in the EU fleet. Figure 11 shows both the annual inflows and outflows of titanium, as well as the cumulative evolution of the in-use stock by vintage. As detailed in the methods chapter, the pronounced fluctuations between 2000 and 2023 reflect Eurostat’s observed data. The sharp rise in titanium inflows from 2011 to 2019 stems from the abrupt drop and subsequent recovery in aircraft numbers during that period. Under the model’s assumptions, this translates into a surge of newly introduced aircraft featuring higher titanium content per unit weight. By 2025, nearly half of the titanium embedded in the fleet originates from aircraft entering service after 2018. This pattern highlights that titanium demand in aviation is fundamentally a design-driven phenomenon, shaped by the shift toward more fuel-efficient and cost-effective aircraft architectures that replace aluminium with composite polymers, thereby necessitating a higher share of titanium for material compatibility.

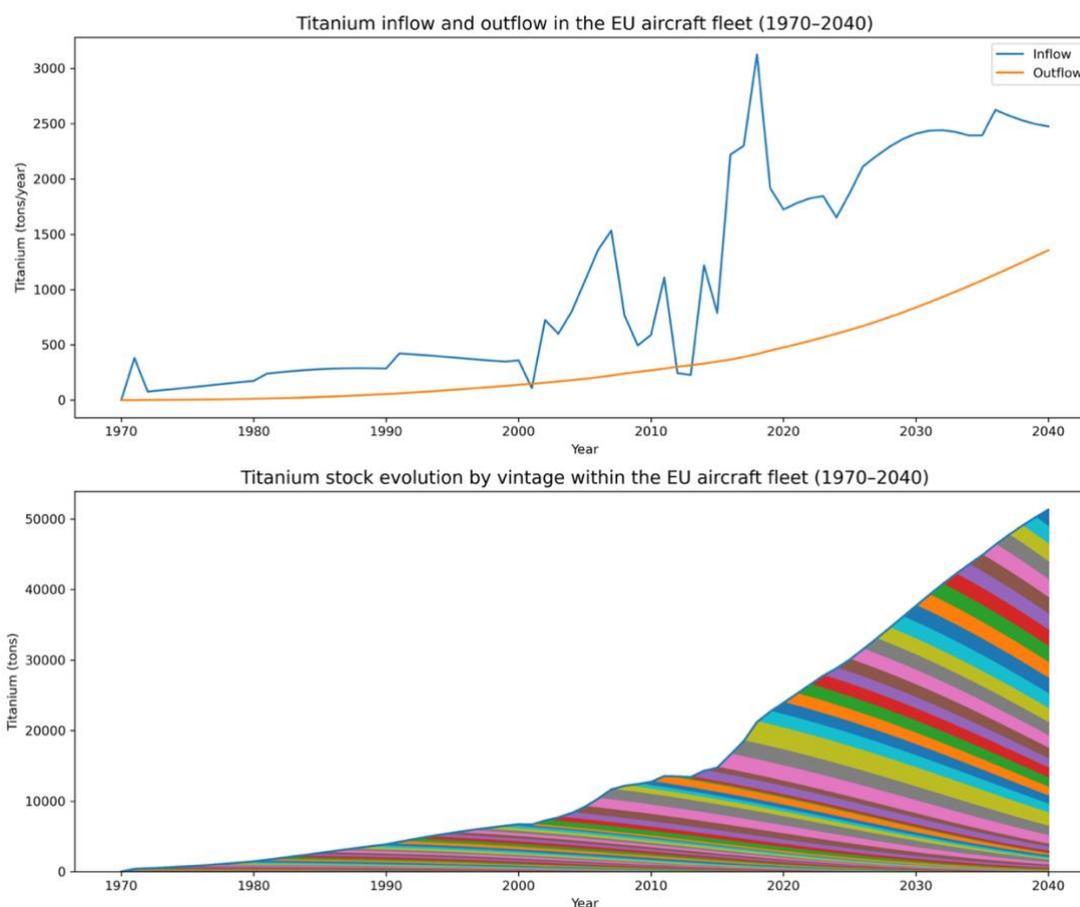


Figure 11. Titanium inflows, outflows, and in-use stock in the EU aircraft fleet (1970–2040). The top panel shows annual flows, while the bottom panel illustrates stock evolution by aircraft vintage.

In 2019, the model estimates an inflow of 1,991 kt of titanium into the use phase, which closely matches JRC estimates (19,9 kt) once the buy-to-fly ratio of the baseline scenario is applied. This convergence validates the model, demonstrating consistency between top-down estimates derived from macroeconomic and trade data and bottom-up calculations based on material intensities.

Figure 12 presents the static MFA for civil aviation in 2040, showing an inflow to the use phase of 2,5 kt. The supply chain configuration is assumed unchanged from the 2019 baseline and serves as the reference case for the two circular scenarios. Two figures stand out: the in-use stock reaches 51,3 kt, while the storage stock of decommissioned aircraft amounts to approximately 20 kt. By summing all outflows between 2000 and 2040 and applying the collection rate, it is possible to estimate the quantity of retired aircraft that theoretically still contain recoverable titanium components suitable for recycling. Such storage of end of life scrap is insufficient to sustain even part of the yearly demand of at primary melting stage (31,8 kt). However, as assessed in the following section, it might contribute to lowering the import dependency of titanium sponge.

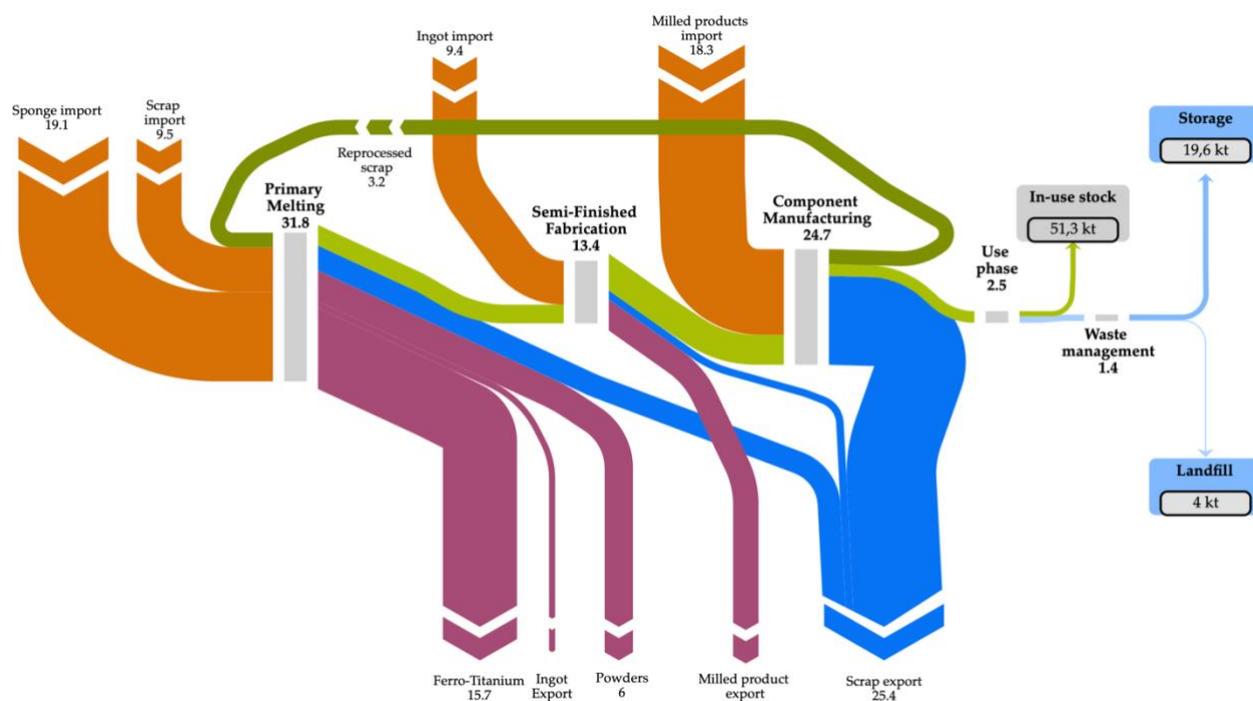


Figure 12. Titanium metal stock-flow diagram in the EU aviation sector in 2040. Values are in kilotonnes; stocks are cumulative from 2000. Flow colours denote imports (orange), domestic flows (light green), exports (purple), scrap exports (blue), end-of-life management (light blue), reprocessing (dark green) and recycling (cyan).

4.2.1. Recycling in 2040

The recycling scenario builds on two core assumptions. First, current remelting technologies can sustain a maximum scrap additive ratio of around 55%, constrained by the purity requirements of aerospace-grade titanium. Second, only 40% of the scrap generated during component manufacturing is not subject to buyback agreements with the United States and thus can be retained within EU borders.

In the baseline, 19 kt of titanium scrap are exported and 3.2 kt are reprocessed domestically. By retaining 40% of the exported quantity (7.6 kt) and adding it to the existing domestic reprocessing, total reprocessed scrap rises to 10.8 kt, while exports fall to 11.4 kt.

By 2040, the in-use and storage stocks remain comparable to the baseline. Through disassembly operations, it is assumed that roughly 4 kt of titanium are recovered from decommissioned aircraft, with an additional 1.3 kt sourced from imported aircraft reaching end-of-life, assuming the EU develops into a regional hub for recycling operations. Nearly 90% of this recovered material is assumed to re-enter the primary melting process (cyan inflow of Primary melting), while the remainder is downcycled into industrial or ferrotitanium products.

Consequently, the share of domestic scrap feeding the melting stage increases from 10% in the baseline to about 45%, significantly reducing import dependence across subsequent production stages. However, the model also highlights a limitation: with an annual inflow of 1.2 kt and an outflow of 4 kt from storage, the available stock would be exhausted within a decade, leaving the recycling sector undersupplied. Still, this figure aligns with the current capacity of facilities like Ecotitanium, which alone can process up to 4 kt per year, suggesting that such a transition remains technically feasible in the medium term.

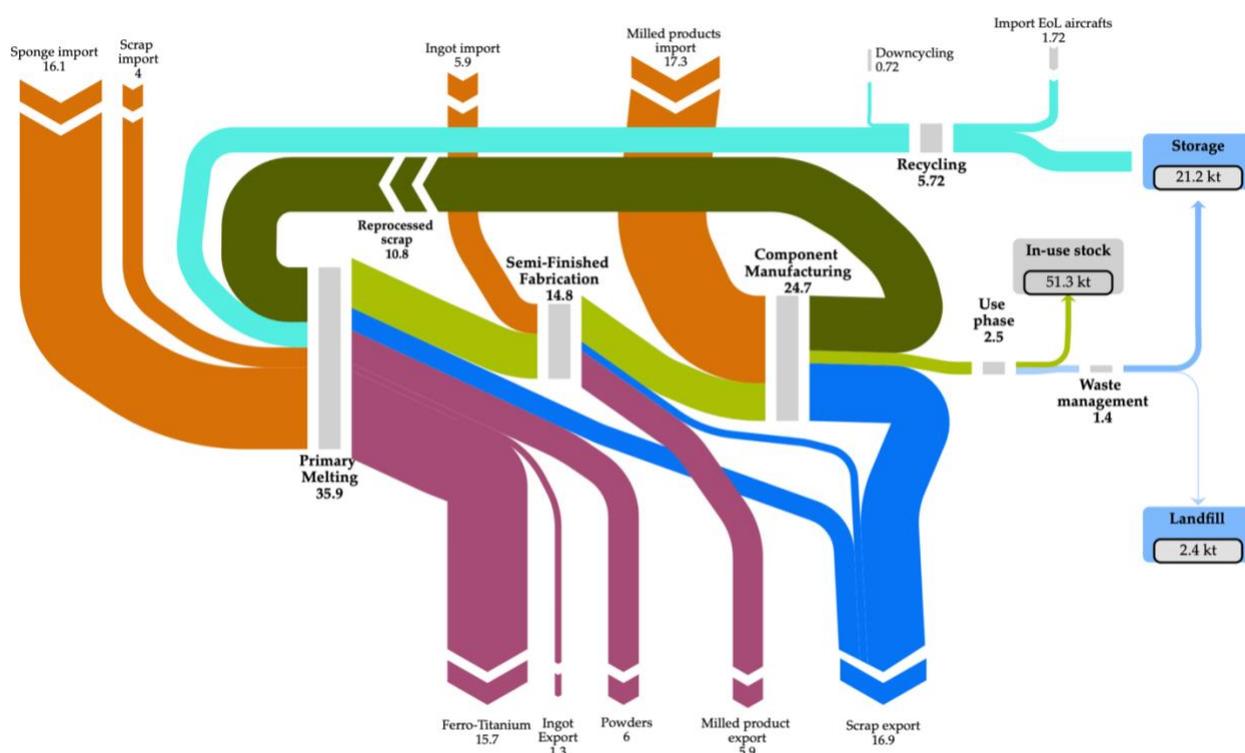


Figure 13. Recycling scenario of titanium stock-flow dynamics for the EU civil aviation sector in 2040. Values are in kilotonnes; stocks are cumulative from 2000. Flow colours denote imports (orange), domestic flows (light green), exports (purple), scrap exports (blue), end-of-life management (light blue), reprocessing (dark green) and recycling (cyan).

4.2.2 Lifetime extension

The lifetime extension scenario assumes that enhanced MRO operations increase the average aircraft lifespan from 25 to 30 years. As observed in similar studies on the automotive sector, the benefits of this strategy unfold gradually, becoming significant only in the long term (Nakamoto & Kagawa, 2022; van Keeken et al., 2024). Figure 14 illustrates the divergence between baseline and LTE scenarios for annual titanium inflow and outflow from 2024 to 2060. While yearly differences remain modest, explaining the limited variation in the indicator results presented later, the effects compound over time. For each additional year added to the average aircraft lifetime, approximately 1.5

kilotonnes of titanium inflow are avoided by 2060 compared with the baseline. Although this may appear limited relative to the 2.4 kilotonnes of inflow projected for 2040, it represents an effective smoothing of demand peaks and a strategic buffer against supply disruptions.

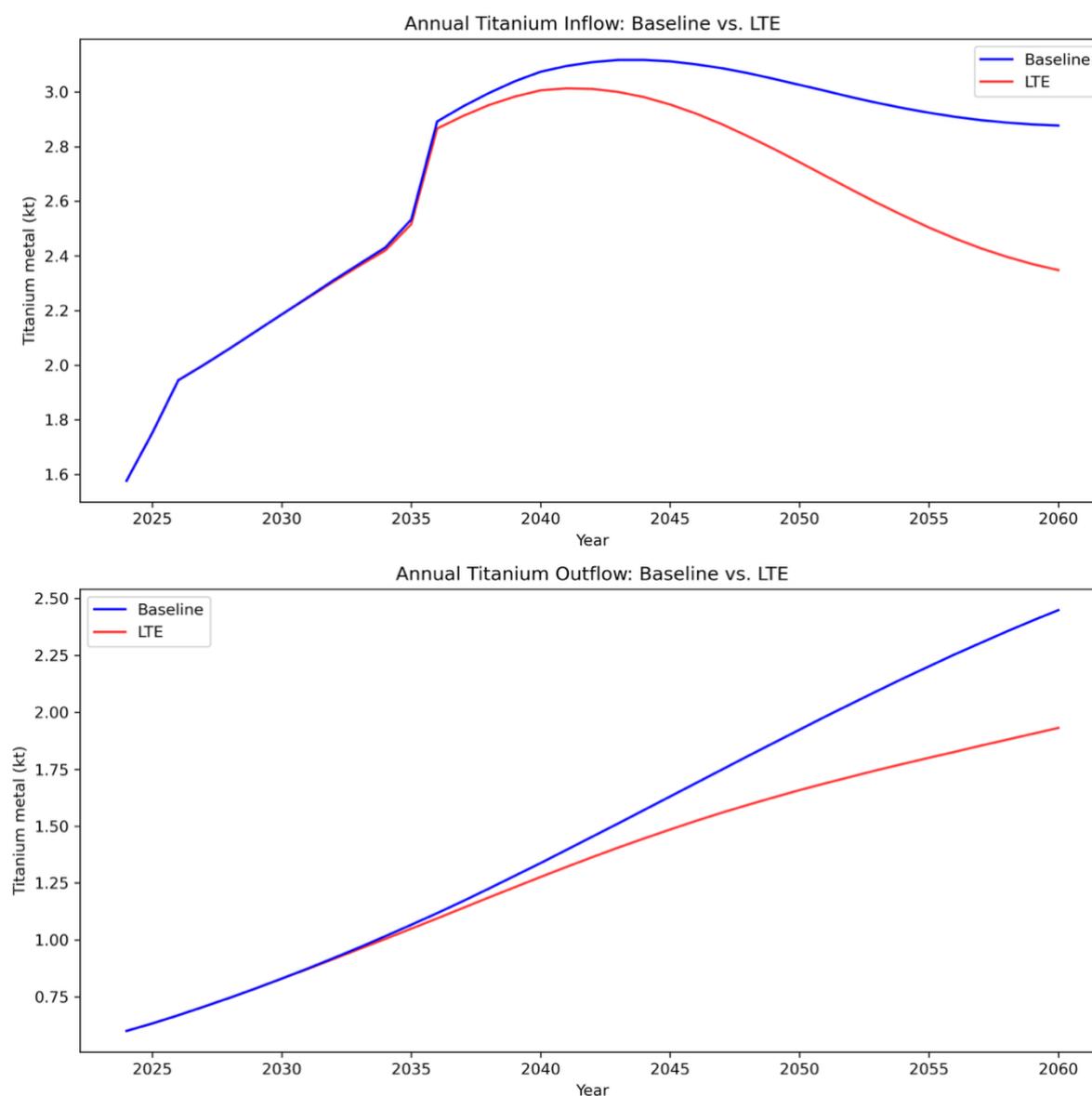


Figure 14. Comparison of annual titanium (kt) inflow and outflow between the baseline and lifetime extension (LTE) scenarios (2024–2060).

4.2.3 Material indicators for the scenarios

Under the national security discourse, as explained in section 3.1.1, the material dimension of the indicator dashboard was built to reflect the priority of gaining resource autonomy. Indeed, the two circular scenarios are now assessed and compared on their impact on self-sufficiency and recycling rate. The full set of formulas and calculations for the indicators used here is available in the supplementary material in Zenodo. Notably,

the indicators do not include the upstream stages of extraction and processing since they were not included in the system boundaries of the study.

Among the two circular strategies tested, the recycling scenario delivers the strongest improvement in titanium supply security (Figure 15). With a recycling input rate (RIR) of 35%, it demonstrates that, even when maintaining existing buyback agreements, the EU could significantly increase its autonomy from extra-EU suppliers. Under current CRMA definitions, this scenario would nearly triple the 25% recycling target and substantially raise domestic processing capacity, as measured by the share of titanium ingot production relative to demand for milled products.

The LTE scenario, as expected, has limited short-term effects on supply security by 2040. Over the longer term to 2060, it slightly reduces the availability of secondary feedstock, due to lower inflows to the use phase, but marginally enhances self-sufficiency in component manufacturing by reducing the need for imported titanium mill products.

Overall, the recycling scenario clearly outperforms lifetime extension across the tested indicators, while the latter's benefits appear marginal in the current modelling framework and time horizon.

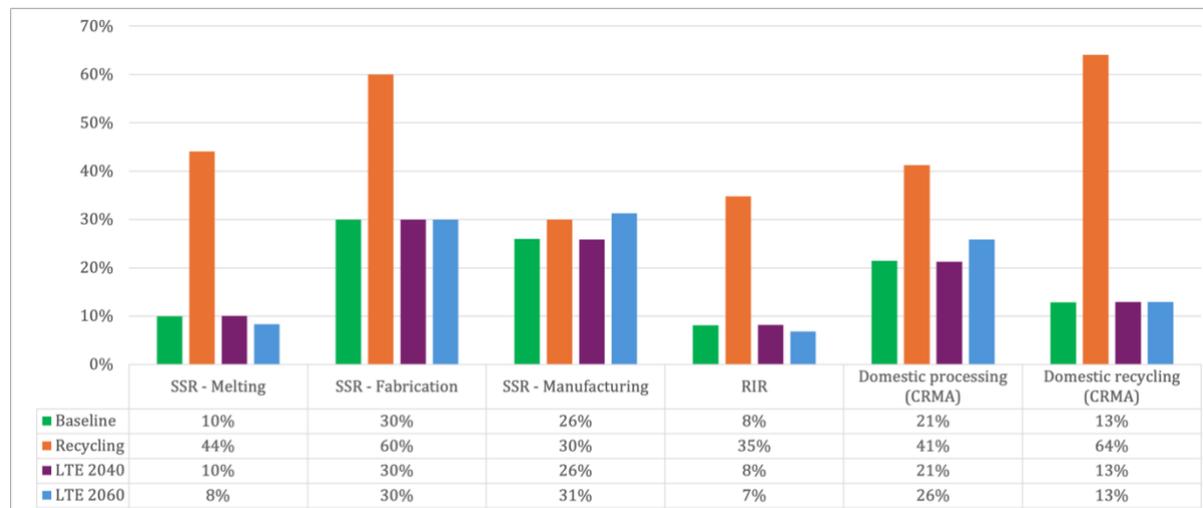


Figure 15. Comparison of titanium supply security material indicators under baseline, recycling, and lifetime extension (LTE) scenarios.

4.3 How might circular interventions in civil aviation affect domestic value creation of the titanium sector?

Based on the MRIO analysis, the *Manufacturing of Titanium and Articles Thereof* sector generated an estimated total output of €340 million in the EU in 2019, contributing €30.4 million in value added and employing approximately 341 people. These figures are consistent with external estimates supporting the reliability of the model within expected uncertainty. Indeed, Buesa et al. (2025) report that the four main titanium ingot producers in Europe collectively employ around 200 workers.

Scenario analysis indicates that circularity measures could yield measurable macroeconomic effects. Under the Recycling scenario, the European economy would gain an estimated €43.7 million in additional value added and around 500 new jobs across the supply chain, while the LTE scenario would generate a more modest increase of €6.6 million and approximately 250 jobs. These changes reflect economy-wide adjustments rather than direct employment within the titanium sector itself, showing the broader systemic impact of circular strategies.

Despite the different assumptions in the modelling of the recycling scenario, the trend is similar to what registered by Buesa et al. (2025). In this case the buyback agreements were left untouched and still considerable economic gains were obtained. In addition, the aircraft lifetime extension scenario has a lower contribution to employment and value added as expected by the increase in services by lower capital intensive industry of MRO.

Table 5. Comparison of titanium supply security economic indicators under baseline, recycling, and lifetime extension (LTE) scenarios.

	<i>Value added (Million €)</i>		<i>Employment (People)</i>	
	Sector	Economy	Sector	Economy
Baseline	30,41	14.018.388	341	202.048.000
Recycling	-0,054	+43,67	0	+495
LTE	-0,046	+6,58	-1	+245

Chapter 5 – Discussions and limitations

The previous chapter answered the three sub research questions that guide the present thesis work. The results call for a three front discussion touching the gaps exposed through the literature review. The following sections will in good order contextualise the findings in the broader picture of research on the impact of CE strategies on titanium supply security in the EU; discuss the conceptual implications of the proposed *Circular Security* framework on the broader EU policy environment; and finally comment the impact and limitation of the methodological hybridisation.

Table 6. Dashboard of material and economic indicators with percentage changes of recycling and LTE scenarios compared to baseline

	<i>Recycling</i>	<i>LTE</i>
SSR - Melting	+34%	-2%
SSR - Fabrication	+30%	0%
SSR - Manufacturing	+4%	+5%
RIR	+27%	-1%
Domestic processing (CRMA)	+20%	+4%
Domestic recycling (CRMA)	+51%	0%
Value added (Million €)	+43,67	+6,58
Employment (People)	+495	+245

5.1 Results discussion

The 2019 baseline confirms two structural vulnerabilities long identified in titanium criticality assessments. The EU remains almost entirely dependent on imports at the primary melting stage, while simultaneously generating extraordinary volumes of pre-consumer scrap during component manufacturing, most of which is exported. This configuration reflects a structural asymmetry of concern under a national security perspective: high-value downstream activities are retained, but control over primary and secondary feedstock remains externalised.

Recent trade reconfigurations suggest a more diversified supply structure, seemingly aligned with the logic of Open Strategic Autonomy. Yet this diversification conceals persistent geopolitical fragilities. Firstly, the substitution of direct Russian imports with flows from Kazakhstan and Türkiye is unlikely to reflect sudden capacity expansion and

more plausibly indicates indirect routing of sanctioned material. Secondly, the rapid rise of Saudi Arabia as a supplier of unwrought titanium illustrates how diversification can quickly generate new concentration patterns. Finally, a complete decoupling from Russia could prompt a similar pattern seen in the oil and gas sector, where its trading balance would be filled by China (Tan, 2025). This scenario would mean that the PRC would not only have a dominant position in low grade titanium sponge global supply, as assessed in the literature review, but also stockpile aviation grade material contributing to its civil and military compartments.

Against this backdrop, CE scenarios yielded insightful security implications regarding domestic control of supply and industrial capacity. On a static basis, Table 6 shows that enhanced domestic recycling preforms strongly, with consistent increase in self-sufficiency rates, accomplishment of CRMA targets and substantial creation of value added. However, this growth is primarily driven by the retention of pre-consumer scrap rather than end-of-life aircraft dismantling. At the point of self-sufficiency in melting, the reprocessing of manufacturing scrap accounts for three-quarters of the total increase. Consequently, these gains represent a tactical redirection of existing material outflows rather than a fundamental structural transformation of the EU's production base. In fact, practical constraints limit the scalability of this pathway: buyback agreements with the United States restrict domestic scrap retention, and renegotiation would likely carry geopolitical risks. Even under current proven capacities (Buesa et al., 2025), plants such as EcoTitanium would exhaust available scrap stocks within roughly a decade, revealing that end-of-life recycling cannot serve as a stable long-term foundation for supply security. In addition, as noticed in similar complex system case studies (Iacovidou et al., 2020), an “end-of-pipe” focus arguably risks locking the system into managing waste instead of addressing inefficiencies embedded in high buy-to-fly.

Lifetime extension, although weaker in static indicators, exhibits important dynamic effects. Each additional year added to average aircraft lifetime avoids approximately 1.5 kilotonnes of titanium inflow by 2060 relative to the baseline, while delaying outflows and therefore the availability of end-of-life scrap. Interestingly, this shows that recycling and lifetime extension operate in tension rather than in synergy, in contrast with previous results (Hoff et al., 2025). The same research though, proved that lifetime extension performs better than recycling in alleviating long-term titanium scarcity. At the same time, remanufacturing and component-level repair in titanium remain economically attractive, reinforcing their relevance within a security-oriented circular strategy (Baldassarre, 2025). Furthermore, current employment projections likely underestimate the labour potential of lifetime extension; for instance, a single hangar dedicated to heavy

MRO typically sustains a workforce of 150 to 300 personnel, depending on aircraft complexity and shift structures (AAR, 2024; Memon, 2022; Sharjah Airport, 2021).

Overall, under the choices of the *Circular Security* framework, the results imply that no single loop of the R ladder can be privileged in isolation for achieving domestic supply control and enhancing industrial capacity. Recycling and lifetime extension each reduce exposure, but neither alone solves the structural dependence. The research suggests that the largest security leverage lies upstream, where excessive pre-consumer scrap is generated by subtractive manufacturing. Reducing the buy-to-fly ratio through additive manufacturing simultaneously lowers primary sponge demand, expands domestic reprocessing capacity and creates more capacity for recycling scrap (Airbus, 2026). Moreover, narrowing strategies, such as reducing titanium content in future aircraft, may lower material exposure but potentially at the cost of higher fuel use and emissions. Closing-loop strategies, including downcycling of end-of-life titanium into non-aerospace applications, still representing roughly 30% of titanium metal demand, could relieve pressure on primary sponge without competing for aviation-grade material. In conclusion, security-oriented circularity therefore emerges not as a preference for recycling, but as a portfolio of interventions that must be evaluated against hybrid constraints over time.

On the limitations side, this thesis research deliberately excludes interventions in primary ore extraction and beneficiation. The choice is justified by the fact that upstream mining and refining activities are currently absent from the EU titanium supply chain and fall outside the defined system boundaries. However, circular strategies, regardless of their effectiveness, cannot substitute entirely a stable inflow of primary metal. Although titanium-bearing ores exist within Europe (Table 7), decades of limited investment in mining, refining, and metallurgical processing have generated a substantial technological and skills gap. As noted by Buesa et al. (2025), rebuilding upstream capacity within a meaningful policy horizon would require long lead times, capital intensity, and coordinated industrial strategy, making rapid reindustrialisation implausible. They recommended to strengthen partnerships with Ukraine, in order to benefit from its high-quality deposits. Yet this option has become more complex in light of the 2025 U.S.–Ukraine minerals agreement (Baskaran, 2025).

From a national security perspective, the titanium supply chain once again reflects the broader recalibration of the geopolitical landscape. As Ukrainian mineral development becomes increasingly aligned with U.S. interests, it intersects, and potentially conflicts, with the EU's own pursuit of strategic autonomy, precisely at a moment when several

Member States have begun to openly frame the United States itself as a potential security risk (Roussi, 2025).

5.2 Conceptual implications

The literature review demonstrated that neither “circular economy” nor “supply security” is a neutral or self-standing category. The EU’s criticality framework enables cross-material comparison, yet its technocratic logic abstracts from the prior political act that defines what counts as “secure.” As Petelin (2024) argues, security begins with the selection of a discourse; this choice determines which risks are prioritized and which policy instruments are legitimized. In parallel, circular economy strategies do not possess intrinsic normative value, rather their meaning depends on the security logic within which they are embedded.

The *Circular Security* framework adopted here resolves this epistemological gap by restoring political agency to the centre of analysis. As Lidén (2023) notes, risk assessments encode ethical and political judgements about whose security is protected and whose is deferred. Once a security is selected, it becomes possible to derive appropriate indicators, analytical methods, and policy objectives. The titanium case illustrates the analytical advantage of this approach. The dashboard method makes visible trade-offs that a composite index would conceal: recycling scenario meets swiftly the CRMA targets but rapidly depletes end-of-life stocks, whereas lifetime extension enhances self-sufficiency but delays scrap availability for recycling. Rather than collapsing these tensions into a single aggregate score, the framework exposes their temporal and systemic incompatibilities, forcing explicit political prioritisation.

For analytical simplicity, this thesis equates national security with Open Strategic Autonomy, a move that entails clear limitations. National security conventionally includes defence, which lies outside the present scope. Indeed, defence procurement and military capabilities remain largely under Member State control, a step below the chosen boundaries, current debates on a European army and common debt-financed rearmament suggest that this division is becoming increasingly blurred (Clapp et al., 2025). In the titanium case, the material’s dual use in civil aviation and defence applications introduces the risk of intra-European competition for constrained supply. Despite objective difficulties in data gathering regarding defence industry, a framework that excludes defence considerations cannot fully account for such distributional tensions.

A second limitation concerns the dual nature of OSA itself. Such vision is not purely inward-looking, but it combines internal capacity-building with continued international engagement. As Kroll (2025) cautions, pursuing autonomy through reduced external linkages would be economically counterproductive. Furthermore, prioritising national security can generate international insecurity if circularity becomes a zero-sum contest over secondary resources. The titanium recycling scenario demonstrates this tension concretely. Retaining 40% of currently exported pre-consumer scrap would raise the recycling input rate to 35% and generate €43.7 million in additional value added within the EU. However, this outcome presupposes the continued functioning of buyback agreements with the United States. If EU capacity expansion were perceived as a competitive threat, these arrangements could be restricted. The “security gain” is therefore contingent on geopolitical tolerance rather than structurally guaranteed.

This dynamic aligns with what Patrick Schröder and Jack Barrie (2024) term “Circular Resource Nationalism”: the strategic retention of secondary materials to enhance domestic resilience. Similar patterns are visible in China’s export controls on rare-earth processing technologies, Nordic approaches to critical metal circularity (Petelin, 2025), and the growing integration of circular practices into defence logistics (EDA, 2025). Within the EU, this shift corresponds to a broader project of “refortifying” European capitalism (Glencross, 2024), reinforced by a hybrid-warfare framing in which economic and technological dependencies are treated as vectors of vulnerability (European Commission, 2025c). The proposed RE-Source EU Act exemplifies this trajectory: circularity is elevated alongside, and in some cases ahead of, traditional resilience instruments such as stockpiling and supplier diversification (European Commission, 2025e).

Regardless of the specific choices operated in this thesis, the framework's structure reveals alternative pathways that remain latent. A human security framing, for instance, would ask whether titanium governance enhances material sufficiency and community resilience rather than simply import substitution. It would foreground secure employment in regional processing hubs and reduced exposure of workers and nearby residents to the social and health costs of extraction and refining. It could also question the social externalities of highly centralised, capital-intensive production systems, where economic concentration may erode community cohesion and contribute to social dislocation. An ecological security framing would foreground dematerialization and design optimization (R0-R2 strategies), treating end-of-life recycling as a symptom of overconsumption rather than a solution. The framework thus continues to operate in that trilemma of resources explained in the introduction. The 2026 Circular Economy Act will force a choice: either circularity serves national competitiveness, in which case ecological

and human goals are subordinated, or it serves wellbeing and planetary boundaries, in which case strategic autonomy must be pursued through other means. However, it cannot be excluded that contingent side gains can be achieved on one discourse even when pursuing another, but only continuous measurement can reveal the true extent.

5.3 Methodological implications and limitations

Beyond the conceptual contribution of the *Circular Security* framework, this thesis advances methodological hybridisation within IE. It represents the first integration of MFA and MRIO analysis applied to the aviation sector, combining dynamic stock–flow insights with an economy-wide representation of intersectoral linkages. This joint perspective reveals dynamics that neither method could capture in isolation and build directly on the recommendations of Tukker (2025). For example, MRIO results indicate that titanium recycling could generate approximately €43.6 million in value added in a single year, while the dynamic MFA shows that secondary feedstock would be depleted over the long term, constraining scalability and ultimately leading to declining recycling capacity. The application of the MARIO Python package to the analysis of critical raw materials further demonstrates the flexibility and potential of this novel open-source tool.

Methodologically, the EXIOBASE input–output table was augmented by disaggregating titanium manufacturing from the aggregated “*Other non-ferrous metals*” sector and populating it with coefficients derived from the MFA, following the approach proposed by Tisserant & Pauliuk (2016). Unlike earlier work, however, the table was not projected into future scenarios using GDP-driven forecasts. Instead, the augmented matrix was used to assess the directional economic effects of selected circular interventions on the titanium sector, maintaining a transparent link between material constraints and economic outcomes.

Despite these innovations, several limitations inherent to current data and modelling frameworks remain. First, the fixed production recipes embedded in the MRIO technical coefficients prevent the representation of technological change, such as reductions in buy-to-fly ratios enabled by additive manufacturing. Second, the inclusion of gross fixed capital formation and inventory changes can only partially mitigate the static nature of MRIO models. While national accounts represent depreciation through the consumption of fixed capital in monetary terms, MRIO frameworks do not capture asset vintages, decommissioning processes, or the physical stock–flow feedback that link capital accumulation to material release over time. Third, as already noticed by Buesa et al. (2025), all titanium types are aggregated into a single sector despite large value-added differentials between aerospace-grade and industrial titanium. The assumed average

price of €20 per kilogram masks market realities in which aerospace-grade material can exceed €100 per kilogram, and defence aviation cannot be isolated as it remains embedded within the aggregated “*Other transport equipment*” sector.

Additional limitations concern the representation of circular strategies. Lifetime extension is modelled solely as an increase in average service life and therefore does not explicitly capture MRO flows that may significantly affect material demand. Besides, the extension is applied only to new inflows of aircraft, not to the one already in stock, which is the reason why it takes much time to yield results. Similarly, the recycling scenarios assume a uniform scrap input ratio of 55% at the melting stage for both pre- and post-consumer scrap. In practice, recycling performance depends on alloy composition, contamination levels, remelting cycles, and certification constraints, which are substantially more stringent for aviation-grade titanium than for industrial applications.

Finally, an important limitation affects the satellite accounts. The investments made in automatization of recycling processes, additive manufacturing and augmented reality in MRO operations are all factors of uncertainty for the creation of jobs in the circular scenarios.

Chapter 6 – Conclusions and future research

This concluding chapter draws together the conceptual and empirical threads developed throughout the thesis, situating the titanium case within the broader challenge of securing critical material supply in an era of geopolitical volatility. It reflects on how different understandings of security shape the evaluation of circular strategies, and on how the integration of material flow and economic modelling can support more transparent and policy-relevant decision making. By returning to the analytical framework introduced earlier, the chapter answers to each sub research question, culminating in identifying the implications of the results for both Industrial Ecology research and European resource governance.

6.1 SubRQ1: What is the current material configuration of titanium supply?

The static MFA confirms the structurally weak position of the European Union within the titanium metal supply chain. The EU lacks infrastructure for both mineral extraction and ore beneficiation, although this stages are characterised by unconstrained global supply and relatively low value added. More critically, it has no domestic capacity for titanium sponge and is therefore fully dependent on imports of both virgin material and high-quality scrap from USA, Japan, China and Russia. Owing to the stringent purity requirements of civil aviation, the dominant end-use sector for titanium metal, approximately half of the sponge produced is diverted to the ferro-titanium industry, introducing an additional structural vulnerability.

Despite relatively modest titanium demand at the use phase of 6 kt, the exceptionally high buy-to-fly ratios, associated with conventional subtractive manufacturing, constitute the single most significant weakness in the supply chain. Buyback agreements with the United States account for roughly 60% of EU pre-consumer scrap exports and imply that any meaningful intervention would require political negotiation rather than purely technical adjustments. Trade patterns have been reshaped over the past five years largely due to COVID-19 shock and the Russo-Ukrainian war, yet the United States continues to dominate the EU's titanium trade balance. At the same time, new actors have entered the midstream segment, notably Saudi Arabia, while other countries have increasingly functioned as transit hubs for Russian wrought titanium exports.

6.2 SubRQ2: How might circular interventions in civil aviation affect self-sufficiency in titanium supply?

In light of the *Circular Security* framework developed in the methods section, this research question addressed the material dimension of a national security framing, with the explicit objective of reinforcing the domestic control of EU titanium supply chain. System boundaries were therefore restricted to the civil aviation sector, which allowed to identify, through a dynamic MFA, the in-use and end-of-life stocks. Following an assessment of baseline self-sufficiency and CRMA indicators, two circular interventions were evaluated in the medium future.

By 2040, enhanced domestic recycling, combining increased retention of pre-consumer scrap with end-of-life aircraft dismantling, yielded substantial improvements across all material indicators. Self-sufficiency at the melting and fabrication stages increased by approximately 30 percentage points relative to the baseline, while domestic recycling targets under the CRMA were met and exceeded. However, the dynamic stock assessment revealed a critical limitation: the available pool of end-of-life aircraft would be depleted within a decade, even when supplemented by imported decommissioned fleets. Absent significant technological change at the melting and component manufacturing stages, or a renegotiation of existing buyback agreements, large-scale investments in recycling infrastructure would therefore act as a short-term remedy to a more structural vulnerability.

By contrast, the aircraft lifetime extension scenario performed weakly across the static indicator dashboard and introduced tensions with recycling by reducing annual pre-consumer scrap generation and delaying outflows to waste management. This outcome is largely an artefact of static representation. Lifetime extension is an incremental strategy whose effects accumulate over time through increased in-use stock retention. While MRO activities do not create an alternative material supply route capable of rapidly reducing import dependence, they progressively build a buffer against demand shocks and supply disruptions.

Overall, these results highlight the necessity of a dynamic and system-wide perspective when assessing circular strategies for supply security. In particular, greater emphasis should be placed on narrowing loops through more efficient manufacturing processes and the explicit integration of material criticality into design choices, where long-term synergies across circular interventions are most likely to emerge.

6.3 SubRQ3: How might circular interventions in civil aviation affect domestic value creation of the titanium sector?

The economic dimension of circular interventions further reinforces the national security argument. The recycling scenario, modelled in the MRIO as a 15% increase in end-of-life scrap displacing primary imports, generates an additional €43.7 million in value added and approximately 500 new jobs across the EU economy. By contrast, the lifetime extension scenario, where demand shifts from new aircraft procurement to MRO services, produces more modest gains of €6.6 million in value added and roughly 250 jobs. In both cases, substituting imported primary material or new aircraft with domestic circular activities, allows the EU to retain capital that would otherwise accrue to extra-EU suppliers, notably in the United States and China. The security implications of these gains in value and employment are interpreted as increased domestic industrial capacity.

However, the static nature of MRIO limits the analysis to a snapshot of economic effects and cannot capture their evolution over time. When interpreted alongside the material results, it becomes apparent that recycling-driven value added and employment would decline as the stock of decommissioned aircraft is depleted, constraining the scalability of the sector. Lifetime extension, by contrast, delivers smaller but more stable economic returns concentrated in the MRO industry. As also observed by Hoff et al. (2025), this pathway enhances airlines operational autonomy by reducing reliance on external recycling facilities, which are often geographically and institutionally detached from original aircraft value chains.

6.4 Main RQ: What effect could Circular Economy have on the security of titanium supply in the European Union?

The titanium case study demonstrates that the aviation sector, and by extension the broader European economy, can benefit substantially from the large-scale implementation of transformative circular economy strategies. The *circular security* framework developed in this thesis clarifies the relationship between security discourses, circularity interventions and the expected implications for the various dimensions of the complex system under study.

Within the assumptions of the modelling framework, both recycling and lifetime extension contribute positively to enhancing self-sufficiency while generating additional

value and employment across the EU economy. These findings indicate that CE policies can meaningfully support national resource security objectives. At the same time, the titanium supply chain must be understood as a complex socio-technical system whose transformation requires a dynamic and holistic perspective. No single industrial actor can reshape the system in isolation. Instead, it is the political sphere that ultimately determines the direction of change by defining priorities, incentives, and the understanding of security itself. Public–private partnerships will therefore be central to translating circularity from an emerging policy objective into an operational industrial regime.

The Draghi Report’s warning that “the foundations on which we built are now being shaken” (Draghi, 2024) signals more than economic turbulence. It marks a structural shift in the geopolitical order that underpinned European integration for decades, and the titanium case fully mirrors this transformation. Buyback agreements that once reinforced the EU’s industrial competitiveness are now revealed as systemic vulnerabilities, yet abandoning them outright would simultaneously dismantle the scrap streams that make domestic circularity possible. This tension encapsulates a core dilemma facing European resource policy as autonomy cannot be strengthened without first confronting the legacies of interdependence on which the Union was built.

In this light, the reconfiguration of the titanium supply chain can capture the spirit of a broader systemic shift. The European project itself was born from the collective governance of critical materials, a mechanism designed to rebuild economies and secure peace through shared prosperity. Revisiting and reshaping that original pact is therefore not merely a technical adjustment, but a defining act of renewal. The outcome will not only determine the future of some strategic metal, but will also speak to the endurance of the European integration model in an increasingly fragmented world.

6.5 Recommendations for future research

Future research should address both the conceptual and methodological boundaries of the *Circular Security* framework while broadening its empirical scope. The framework’s current categorisation of security outcomes could be refined to distinguish more explicitly between defence-oriented applications, civil–industrial uses, and alternative understandings of security that are not necessarily derived from the constructivist school. In this sense, further studies could understand the synergies between the discourses, because as argued in the discussions, already in the OSA vision the national and international ones are closely associated.

Likewise, the selection of indicators should be expanded beyond the given material and economic metrics to include also regulatory, governance and financial variables. For instance, on the regulatory side, certification requirements for aviation-grade titanium remain a significant barrier to recycling; examining and scoring how these standards could be safely reformed would therefore be essential for enabling higher recovery rates. On the financial side, emerging instruments such as the tokenization of CRMs, which promises greater liquidity and traceability through blockchain-based systems, warrant closer scrutiny (Hughes, 2025b). While such mechanisms could support supply transparency and investment flows without the need of public subsidies, they may also intensify financial speculation and systemic risk, with implications comparable to those observed in commodity derivatives markets (Boehm, 2024).

Extending the framework to other domains, such as food or energy systems, would further test its analytical robustness and reveal whether similar trade-offs and synergies emerge across different material metabolisms.

Resilience, treated here as an emergent property proper of the holistic performance review of the indicators, warrants deeper conceptual elaboration. Future work should define resilience more explicitly in terms of absorptive, adaptive and transformative capacities, and engage with the quest to capture the system's ability to withstand, reorganise and evolve under disruption. This would allow the framework to move beyond outcome-based assessment towards a more dynamic understanding of systemic stability and change.

Empirically, greater attention should be devoted to circular strategies that narrow and slow material loops, particularly at the design and manufacturing stages. Assessing the effects of refuse, rethink and reduce strategies on titanium demand, and linking these to technological shifts such as additive manufacturing, would clarify how upstream interventions reshape both material throughput and supply vulnerability. In parallel, modelling approaches should evolve beyond the combined MFA–MRIO architecture. While these tools remain powerful for structural analysis, complementary methods would enable a more comprehensive exploration of systemic disruptions and policy interventions. In particular, Computable General Equilibrium models may capture price adjustments and substitution effects, while Agent-Based Models allow exploring nonlinear shocks, rationing, stockpiling or behavioural responses.

Bibliography

- Aadharsh Viswanath. (2024). *Investigating Aircraft Weight and Balance Metrics*. MIT. <https://www.kaggle.com/datasets/aadharshviswanath/investigating-aircraft-weight-and-balance-metrics>
- AAR. (2024, August 18). *RFD Agreement with International MRO Provider, AAR, to Bring Jobs, Offer Expanded Service Capabilities to Rockford*. <https://www.aarcorp.com/en/newsroom/press-releases/2014/rfd-agreement-with-international-mro-provider-aar-to-bring-jobs-offer-expanded-service-capabilities-to-rockford/>
- AEM. (2025, June 13). *Titanium in Aerospace: Strength, Speed & Reliability*. <https://www.aemmetal.com/news/titanium-for-aerospace.html>
- Airbus. (2022, November 7). *End-of-life Reusing, recycling, rethinking*. <https://aircraft.airbus.com/en/newsroom/news/2022-11-end-of-life-reusing-recycling-rethinking>
- Airbus. (2025). *Global Market Forecast 2025-2044*. <https://www.airbus.com/en/products-services/commercial-aircraft/global-market-forecast>
- Airbus. (2026, January 22). *Aircraft manufacturing with Titanium 3D printing*. Newsroom. <https://www.airbus.com/en/newsroom/stories/2026-01-how-airbus-is-pioneering-aircraft-manufacturing-with-titanium-3d-printing>
- Aradau, C., Huysmans, J., Neal, A., & Voelkner, N. (2014). *Introducing critical security methods*. <https://research.rug.nl/en/publications/introducing-critical-security-methods/>
- Aubert & Duval. (2025). *A full titanium offer for stringent markets*.
- Baier, F., Gelhausen, M., Leipold, A., Pabst, H., Berster, P., Chatterjee, S., & Junior, A. (2024, June 12). Long-term impact of limited airport capacity on passenger demand and fleet development worldwide up to 2050. *ODAS 2024*.
- Baldassarre, B. (2025). Circular economy for resource security in the European Union (EU): Case study, research framework, and future directions. *Ecological Economics*, 227. <https://doi.org/10.1016/j.ecolecon.2024.108345>
- Banks, M. (2025, September). *Pressure for Sanctions on Russian Titanium*. EU Political Report. <https://eupoliticalreport.com/pressure-for-sanctions-on-russian-titanium/>
- Baskaran, G. (2025). *Six Months Since the U.S.-Ukraine Minerals Deal Was Signed—What Now?*
- Bennett, S. (2022). Mythopoetic legitimation and the recontextualisation of Europe's foundational myth. *Journal of Language and Politics*, 21(2), 370–389. <https://doi.org/10.1075/JLP.21070.BEN>

- Blengini, G. A., Nuss, P., Dewulf, J., Nita, V., Talens Peirò, L., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., & Ciupagea, C. (2017). EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. *Resources Policy*, 53, 12–19. <https://doi.org/10.1016/j.resourpol.2017.05.008>
- Boehm, A. (2024, October 22). *The Hidden Dangers of Tokenization: What You Need to Know*: By Alexander Boehm. Finextra. <https://www.finextra.com/blogposting/27065/the-hidden-dangers-of-tokenization-what-you-need-to-know>
- Boeing. (2021). *Commercial market outlook 2012 - 2040*. https://www.boeing.com/content/dam/boeing/boeingdotcom/market/assets/downloads/CMO-2021-Report_13Sept21-A.pdf?utm_source=chatgpt.com
- Brunner, P. H., & Rechberger, H. (2016). Practical handbook of material flow analysis. In *Practical Handbook of Material Flow Analysis*. CRC Press. <https://doi.org/10.1007/BF02979426>
- Buesa, A., Georgitzikis, A., Jakimów, K., Piñero, M., Maury, P., Latunussa, T., Pedauga, C., Samokhalov, L., Baldassarre, V., Mathieux, B., Rueda-Cantuche, F., Manuel Stijepic, J., Reys, D., Bilous, A., Notom, A., & Tercero, P. (2025). *Titanium metal in the EU: Strategic relevance and circularity potential*. <https://doi.org/10.2760/5871804>
- Buesa, A. ; Piñero, P. ; & Pedauga, L. ; (2023). *Can circularity in Titanium metal improve EU strategic autonomy? Scenario modelling with heterogeneous data*. <https://joint-research-centre.ec.europa.eu>
- Calisto Friant, M., Vermeulen, W. J. V., & Salomone, R. (2021). Analysing European Union circular economy policies: words versus actions. *Sustainable Production and Consumption*, 27, 337–353. <https://doi.org/10.1016/J.SPC.2020.11.001>
- Castillo-Díaz, F. J., Belmonte-Ureña, L. J., Diáñez-Martínez, F., & Camacho-Ferre, F. (2024). Challenges and perspectives of the circular economy in the European Union: A comparative analysis of the member states. *Ecological Economics*, 224. <https://doi.org/10.1016/j.ecolecon.2024.108294>
- Cirium. (2025). *Cirium – The world's most trusted source of aviation analytics*. <https://www.cirium.com/>
- Clapp, S., Höflmayer, M., Lazarou, E., & Pari, M. (2025). *ReArm Europe Plan/Readiness 2030*. [https://www.europarl.europa.eu/RegData/etudes/BRIE/2025/769566/EPRS_BRI\(2025\)769566_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2025/769566/EPRS_BRI(2025)769566_EN.pdf)
- Clift, R., & Druckman, A. (2015). Taking stock of industrial ecology. *Taking Stock of Industrial Ecology*, 1–362. <https://doi.org/10.1007/978-3-319-20571-7>
- Della Bella, S., Sen, B., Cimpan, C., Rocco, M. V., & Liu, G. (2023). Exploring the Impact of Recycling on Demand-Supply Balance of Critical Materials in Green Transition: A

- Dynamic Multi-Regional Waste Input-Output Analysis. *Environmental Science and Technology*, 57(28), 10221–10230. <https://doi.org/10.1021/acs.est.2c09676>
- Donati, F., Aguilar-Hernandez, G. A., Sigüenza-Sánchez, C. P., de Koning, A., Rodrigues, J. F. D., & Tukker, A. (2020). Modeling the circular economy in environmentally extended input-output tables: Methods, software and case study. *Resources, Conservation and Recycling*, 152. <https://doi.org/10.1016/j.resconrec.2019.104508>
- Draghi, M. (2024). *The Draghi report on EU competitiveness*. https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en#paragraph_47059
- EDA. (2025). *Incubation Forum for Circular Economy (IF CEED)*. European Defence Agency. <https://eda.europa.eu/what-we-do/eu-policies/if-ceed>
- EEA. (2025). *Circular Economy requirements in Ecodesign*. Circularity Metrics Lab. https://www.eea.europa.eu/en/circularity/thematic-metrics/enabling/circular-economy-requirements-in-ecodesign?utm_source=chatgpt.com
- EEB. (2024). *Right to Repair Europe*. <https://www.ecologic.eu/18226>.
- El-Bassyouni, G. T., Mouneir, S. M., & El-Shamy, A. M. (2025). Advances in surface modifications of titanium and its alloys: implications for biomedical and pharmaceutical applications. *Multiscale and Multidisciplinary Modeling, Experiments and Design*, 8(5), 1–47. <https://doi.org/10.1007/S41939-025-00823-1/TABLES/3>
- Ellen MacArthur Foundation. (2017). *The Circular Economy | Definition & Model Explained* / . <https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview>
- Eurocontrol. (2021). *EUROPEAN AVIATION IN 2040 Annex1 Flight Forecast to 2040*.
- European Commission. (2015). *First circular economy action plan*. https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en
- European Commission. (2020). *Critical Raw Materials Act*. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en
- European Commission. (2025a). *Circular Economy Act: CALL FOR EVIDENCE FOR AN IMPACT ASSESSMENT*. European Commission. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14812-Circular-Economy-Act_en
- European Commission. (2025b). *Critical raw materials - European Commission*. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
- European Commission. (2025c). *Hybrid Threats - Defence Industry and Space* - . Defence Industry and Space. https://defence-industry-space.ec.europa.eu/eu-defence-industry/hybrid-threats_en

- European Commission. (2025d). *Strategic Foresight Report, Resilience 2.0: Empowering the EU to thrive amid turbulence and uncertainty*. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL. <https://doi.org/10.2760/635528>
- European Commission. (2025e, December 3). *RESourceEU Action Plan - Accelerating our critical raw materials strategy to adapt to a new reality*. <https://doi.org/10.2760/5665594>
- Eurostat. (2024, November 15). *Commercial aircraft fleet by aircraft category and country of registration*. Air Transport Equipment. https://ec.europa.eu/eurostat/databrowser/view/avia_eq_arc_tyreg/default/table?lang=en&category=avia.avia_eq
- EUROSTAT. (2025). *Titanium wrought - PRODVAL & PRODQNT*. PRODCOM. <https://ec.europa.eu/eurostat/databrowser/view/ds-056120/legacyMultiFreq/table?lang=en&category=prom>
- Fishman, T., & Graedel, T. E. (2019). Impact of the establishment of US offshore wind power on neodymium flows. *Nature Sustainability*, 2(4), 332–338. <https://doi.org/10.1038/s41893-019-0252-z>
- Glencross, A. (2024). The geopolitics of supply chains: EU efforts to ensure security of supply. *Global Policy*, 15(4), 729–739. <https://doi.org/10.1111/1758-5899.13388>
- Gregson, N., Crang, M., Fuller, S., & Holmes, H. (2015). Interrogating the circular economy: the moral economy of resource recovery in the EU. *Economy and Society*, 44(2), 218–243. <https://doi.org/10.1080/03085147.2015.1013353>
- Grohol, M., & Veeh, C. (2023). Study on the critical raw materials for the EU 2023 – Final report. In *Publications Office of the European Union*. <https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1/language-en>
- Hagenaars, R. H., Heijungs, R., Tukker, A., & Wang, R. (2025). Hybrid LCA for sustainable transitions: principles, applications, and prospects. In *Renewable and Sustainable Energy Reviews* (Vol. 212). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2025.115443>
- Hoff, T., Sprecher, B., Pohya, A. A., Wende, G., & Peck, D. (2025). The impact of circular strategies on titanium supply and demand in the aviation industry. *Resources, Conservation and Recycling*, 222, 108476. <https://doi.org/10.1016/J.RESCONREC.2025.108476>
- Hot, J., Dasque, A., Topalov, J., Mazars, V., & Ringot, E. (2020). Titanium valorization: From chemical milling baths to air depollution applications. *Journal of Cleaner Production*, 249. <https://doi.org/10.1016/j.jclepro.2019.119344>
- Hu, D., Dolganov, A., Ma, M., Bhattacharya, B., Bishop, M. T., & Chen, G. Z. (2017). Development of the Fray-Farthing-Chen Cambridge Process: Towards the

- Sustainable Production of Titanium and Its Alloys. *Jom* (Warrendale, Pa. : 1989), 70(2), 129. <https://doi.org/10.1007/S11837-017-2664-4>
- Hu, L., Song, C., Ye, S., & Gao, P. (2022). Spatiotemporal Statistical Imbalance: A Long-Term Neglected Defect in UN Comtrade Dataset. *Sustainability* 2022, Vol. 14, 14(3). <https://doi.org/10.3390/SU14031431>
- Hu, X., Luo, F., Lin, J., Wang, M., & Li, X. (2022). Dynamic material flow analysis of titanium sponge in China: 2000–2019. *Journal of Cleaner Production*, 371, 133704. <https://doi.org/10.1016/J.JCLEPRO.2022.133704>
- Hughes, T. (2025a, May 28). *Titanium's Spotlight Moment: Why a Once-Niche Metal Now Sits at the Center of Global Critical Minerals Diplomacy* . InvestorNews. <https://investornews.com/critical-minerals-rare-earths/titaniums-spotlight-moment-why-a-once-niche-metal-now-sits-at-the-center-of-global-critical-minerals-diplomacy/>
- Hughes, T. (2025b, July 18). *From Desert Oxides to Digital Tokens—The Week Critical Minerals Broke the Policy Sound Barrier* - InvestorNews. Critical Minerals Report. https://investornews.com/critical-minerals-rare-earths/critical-minerals-report-07-18-2025-from-desert-oxides-to-digital-tokens-the-week-critical-minerals-broke-the-policy-sound-barrier/?print=print&utm_source=chatgpt.com
- Iacovidou, E., Hahladakis, J. N., & Purnell, P. (2020). A systems thinking approach to understanding the challenges of achieving the circular economy. *Environmental Science and Pollution Research* 28:19, 28(19), 24785–24806. <https://doi.org/10.1007/S11356-020-11725-9>
- IperionX. (2023). *Life Cycle Assessment* - IperionX. <https://iperionx.com/sustainability/lca/>
- ISE. (2019). *Current prices of strategic metals* | Institute for Rare Earths and Metals. Institut Für Seltene Erden Und Metalle AG. <https://en.institut-seltene-erden.de/aktuelle-preise-von-strategischen-metallen/>
- ISO. (2006). *ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework*. <https://www.iso.org/standard/37456.html>
- Jackson-Preece, J. (2011). *Security in international relations* (London School of Economics, Ed.). https://www.london.ac.uk/sites/default/files/uploads/ir3140-security-international-relations-study-guide.pdf?utm_source=chatgpt.com
- JRC. (2025). *RMIS - Critical and strategic materials*. European Commission. https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials?utm_source=chatgpt.com
- KPMG. (2024). *Aviation 2030 series Circularity in Flight*. <https://link.springer.com/article>
- Kroll, H. (2024). *Assessing Open Strategic Autonomy*. 1–40. <https://doi.org/10.2760/767279>
- Lamin, A. T. (2024). *Vulnerability Analysis on the Titanium Supply Chain: A Network Analysis Approach* [Master of Science]. Northeastern University.

- Lee, K. (2025). *The Cost of Titanium Per Pound: Main Price Drivers*. Shengen Metal. https://shengenfab.com/en_gb/the-cost-of-titanium-per-pound/?utm_source=chatgpt.com#Primary_Factors_That_Influence_Titanium_Cost
- Lefeuvre, A., Garnier, S., Jacquemin, L., Pillain, B., & Sonnemann, G. (2017). Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050. *Resources, Conservation and Recycling*, 125, 264–272. <https://doi.org/10.1016/j.resconrec.2017.06.023>
- Leontief, W. W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics*, 18(3), 105. <https://doi.org/10.2307/1927837>
- Letta, E. (2024). *Enrico Letta - Much more than a market*.
- Li, M., Geng, P. Y., Liu, G., Gao, Z., Rui, X., & Xiao, S. (2022). Uncovering spatiotemporal evolution of titanium in China: A dynamic material flow analysis. *Resources, Conservation and Recycling*, 180, 106166. <https://doi.org/10.1016/J.RESCONREC.2022.106166>
- Li, X., Lin, J., Zhang, D., Xiong, Z., He, X., Yuan, M., & Wang, M. (2020). Material flow analysis of titanium dioxide and sustainable policy suggestion in China. *Resources Policy*, 67, 101685. <https://doi.org/10.1016/J.RESOURPOL.2020.101685>
- Lidén, K. (2023). A better foundation for national security? The ethics of national risk assessments in the Nordic region. *Cooperation and Conflict*, 58(1), 3–22. <https://doi.org/10.1177/00108367211068877>
- Louvigné, P-F. (2021). *Etude de veille sur le marché du titane 2018 – 2020* (S. Ghirlandi, Tran.).
- Meglin, R., Kytzia, S., & Habert, G. (2022). Regional circular economy of building materials: Environmental and economic assessment combining Material Flow Analysis, Input-Output Analyses, and Life Cycle Assessment. *Journal of Industrial Ecology*, 26(2), 562–576. <https://doi.org/10.1111/jiec.13205>
- Melchionna, M., & Fornasiero, P. (2025). What Is to Be Expected from Heterogeneous Catalysis in the Pipeline to Circular Economy? *ChemSusChem*, 18(5). <https://doi.org/10.1002/CSSC.202402064>
- Memon, O. (2022). *How Many Engineers Are Required To Carry Out A C-Check?* Simple Flying. <https://simpleflying.com/how-many-engineers-required-for-c-checks/>
- Moloney, P. (2025, November 11). *Is resource autonomy the new circular economy?* - Ramboll. Ramboll. <https://www.ramboll.com/insights/resource-management-and-circular-economy/is-resource-autonomy-the-new-circular-economy>
- Moscow Times. (2025, October 20). *Крупнейший производитель титана ввел 4-дневную рабочую неделю вслед за автозаводами - Русская служба The Moscow Times*. <https://www.moscowtimes.ru/2025/10/20/krupneishii-proizvoditel->

- titana-perevedet-chast-sotrudnikov-nachetirehdnevnuyu-rabochuyu-nedelyu-a177634
- Najafizadeh, M., Yazdi, S., Bozorg, M., Ghasempour-Mouziraji, Mehran., Hosseinzadeh, M., Zarrabian, M., & Cavaliere, P. (2024). Classification and applications of titanium and its alloys: A review. *Journal of Alloys and Compounds Communications*, 3, 100019. <https://doi.org/10.1016/J.JACOMC.2024.100019>
- Nakamoto, Y., & Kagawa, S. (2022). A generalized framework for analyzing car lifetime effects on stock, flow, and carbon footprint. *Journal of Industrial Ecology*, 26(2), 433–447. <https://doi.org/10.1111/JIEC.13190>
- Nakamura, S. (2023). A Practical Guide to Industrial Ecology by Input-Output Analysis: Matrix-Based Calculus of Sustainability. In *A Practical Guide to Industrial Ecology by Input-Output Analysis: Matrix-Based Calculus of Sustainability*. Springer International Publishing. <https://doi.org/10.1007/978-3-031-43684-0>
- Nakamura, S., Nakajima, K., Kondo, Y., & Nagasaka, T. (2007). The waste input-output approach to materials flow analysis: Concepts and application to base metals. In *Journal of Industrial Ecology* (Vol. 11, Number 4, pp. 50–63). <https://doi.org/10.1162/jiec.2007.1290>
- Nyamekye, P., Rahimpour Golroudbary, S., Piili, H., Luukka, P., & Kraslawski, A. (2023). Impact of additive manufacturing on titanium supply chain: Case of titanium alloys in automotive and aerospace industries. *Advances in Industrial and Manufacturing Engineering*, 6. <https://doi.org/10.1016/j.aime.2023.100112>
- Oko-Institut e.V. (2020). *Update of the 2015 Material System Analyses Final report*. <https://op.europa.eu/en/publication-detail/-/publication/69212057-e737-11ee-9ea8-01aa75ed71a1/language-en>
- Pakshal Steel. (2025). *Titanium Metal Price Per Kg - (Latest 2025 Price List)*. <https://www.pakshalsteel.com/titanium-metal-price.html>
- Panigrahi, M., Paramguru, R. K., Gupta, R. C., Shibata, E., & Nakamura, T. (2010). An overview of production of titanium and an attempt to titanium production with ferro-titanium. *High Temperature Materials and Processes*, 29(5–6), 495–513. <https://doi.org/10.1515/HTMP.2010.29.5-6.495>
- Patrick Schröder, & Jack Barrie. (2024, June 10). What is Circular Resource Nationalism? *Chatham House*.
- Pecchia, L., Maccaro, A., Matarrese, M. A. G., Folkvord, F., & Fico, G. (2024). Artificial Intelligence, data protection and medical device regulations: squaring the circle with a historical perspective in Europe. *Health and Technology*, 14(4), 663–670. <https://doi.org/10.1007/S12553-024-00878-Z/FIGURES/2>
- Petelin, E. (2024). Security priorities in circular economy: A conceptual review. In *Sustainable Production and Consumption* (Vol. 47, pp. 655–669). Elsevier B.V. <https://doi.org/10.1016/j.spc.2024.05.004>

- Petelin, E. (2025). Effects of resource security concerns on Nordic countries' approach to the circular economy of metals. *Sustainable Production and Consumption*, 55, 420–433. <https://doi.org/10.1016/J.SPC.2025.03.008>
- Pinyol Alberich, J., Pansera, M., & Hartley, S. (2023). Understanding the EU's circular economy policies through futures of circularity. *Journal of Cleaner Production*, 385, 135723. <https://doi.org/10.1016/J.JCLEPRO.2022.135723>
- Roussi, A. (2025, December 11). Danish intelligence classifies Trump's America as a security risk. *Politico*. <https://www.politico.eu/article/danish-intelligence-classifies-donald-trump-america-as-security-risk/>
- Rueda-Cantuche, J. M., Pedauga, L., & Mandras, G. (2022). The relevance of re-exports for identifying strategic dependencies. In *Science for Policy Brief*.
- Salim, H., Sahin, O., Elsayah, S., Turan, H., & Stewart, R. A. (2022). A critical review on tackling complex rare earth supply security problem. *Resources Policy*, 77. <https://doi.org/10.1016/j.resourpol.2022.102697>
- Scheelhaase, J., Müller, L., Ennen, D., & Grimme, W. (2022). Economic and Environmental Aspects of Aircraft Recycling. *Transportation Research Procedia*, 65(C), 3–12. <https://doi.org/10.1016/j.trpro.2022.11.002>
- Schrijvers, D., Hool, A., Blengini, G. A., Chen, W. Q., Dewulf, J., Eggert, R., van Ellen, L., Gauss, R., Goddin, J., Habib, K., Hagelüken, C., Hirohata, A., Hofmann-Antenbrink, M., Kosmol, J., Le Gleuher, M., Grohol, M., Ku, A., Lee, M. H., Liu, G., ... Wäger, P. A. (2020). A review of methods and data to determine raw material criticality. In *Resources, Conservation and Recycling* (Vol. 155). Elsevier B.V. <https://doi.org/10.1016/j.resconrec.2019.104617>
- SCREEN. (2020). *Titanium supply chain in the EU*. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html
- SCRREEN2. (2020). *Titanium supply chain in the EU*. https://screen.eu/wp-content/uploads/2024/01/SCRREEN2_factsheets_TITANIUM_V1.pdf
- Segers, M. (2023). The Origins of European Integration: The Pre-History of Today's European Union, 1937–1951. *The Origins of European Integration*. <https://doi.org/10.1017/9781009379380>
- Sharjah Airport. (2021). *Hangarage – Sharjah Airport*. <https://www.sharjahairport.ae/en/business/working-with-sharjah-airport/hangarage/>
- SKYbrary. (2015). *Maintenance Steering Group-3 (MSG-3)*. <https://skybrary.aero/articles/maintenance-steering-group-3-msg-3>
- Stępką, M. (2022). The Copenhagen School and Beyond. A Closer Look at Securitisation Theory. *IMISCOE Research Series*, 17–31. https://doi.org/10.1007/978-3-030-93035-6_2

- Takeda, O., & Okabe, T. H. (2019). Current Status of Titanium Recycling and Related Technologies. In *JOM* (Vol. 71, Number 6, pp. 1981–1990). Minerals, Metals and Materials Society. <https://doi.org/10.1007/s11837-018-3278-1>
- Tan, H. (2025, December 17). *Russia's Reliance on China Deepens in "Embarrassing Reversal"*. Business Insider. <https://www.businessinsider.com/russia-economy-china-reliance-oil-exports-embarrassing-reversal-2025-12>
- Tisserant, A., & Pauliuk, S. (2016). Matching global cobalt demand under different scenarios for co-production and mining attractiveness. *Journal of Economic Structures*, 5(1). <https://doi.org/10.1186/s40008-016-0035-x>
- Tukker, A. (2025). The role of circularity in European strategic autonomy. In *JRC Working Paper Series For a Fair, Innovative and Sustainable Economy*. European Commission. <https://publications.jrc.ec.europa.eu/repository/handle/JRC142613>
- UN Comtrade. (2019). *Titanium international trade*. <https://comtradeplus.un.org/TradeFlow>
- Upadhayay, S. ;, Alqassimi, O. ;, Khashadourian, E. ;, Sherm, A. ;, Jordaan, J. A., Upadhayay, S., Alqassimi, O., Khashadourian, E., Sherm, A., & Prajapati, D. (2024). Development in the Circular Economy Concept: Systematic Review in Context of an Umbrella Framework. *Sustainability 2024, Vol. 16, Page 1500, 16(4), 1500*. <https://doi.org/10.3390/SU16041500>
- USGS. (2019). *Mineral Yearbook 2019*.
- USGS. (2023). *TITANIUM AND TITANIUM DIOXIDE*. <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-titanium.pdf>
- van Keeken, M., Dullaert, W. E. H., Inghels, D. A. M., & Wissink, P. L. J. (2024). The effects of product lifetime extension on short- and long-term supply chain circularity: A case study of the European aluminum automotive supply chain. *Resources, Conservation and Recycling*, 211, 107836. <https://doi.org/10.1016/J.RESCONREC.2024.107836>
- Vivoda, V., Matthews, R., & Andresen, J. (2025). Securing defense critical minerals: Challenges and U.S. strategic responses in an evolving geopolitical landscape. *Comparative Strategy*, 44(2), 281–315. <https://doi.org/10.1080/01495933.2025.2456427>
- Wautelet, T. (2018). The concept of circular economy - its origins and its evolution. *Positive Impakt*. <https://doi.org/10.13140/RG.2.2.17021.87523>
- Woidasky, J., Klinke, C., & Jeanvré, S. (2017). Materials stock of the civilian aircraft fleet. *Recycling*, 2(4). <https://doi.org/10.3390/recycling2040021>
- World Bank. (2019). *Doing Business - Electricity prices by country*. <https://databank.worldbank.org/Electric-Prices-by-Country/id/7b12e700>
- Zhang, W., Zhu, Z., & Cheng, C. Y. (2011). A literature review of titanium metallurgical processes. *Hydrometallurgy*, 108(3–4), 177–188. <https://doi.org/10.1016/J.HYDROMET.2011.04.005>

Appendix I – Titanium supply chain

Table 7. World mine production and reserves of ilmenite and rutile. Data in thousand metric tons, titanium dioxide (TiO₂) content (USGS, 2023)

COUNTRY	MINE PRODUCTION 2024 (ILMENITE)	RESERVES (ILMENITE)	MINE PRODUCTION 2024 (RUTILE)	RESERVES (RUTILE)
UNITED STATES	100	2000		
AUSTRALIA	400	180000	200	35000
CANADA	350	51000		
CHINA	3300	110000		
INDIA	210	15000	12	670
MADAGASCAR	240	30000		
MOZAMBIQUE	1900	NA	8	720
NORWAY	360	37000		
SENEGAL	300	NA		
SOUTH AFRICA	1300	28000	100	6100
UKRAINE	120	5900	10	NA
OTHER COUNTRIES	330	>54000	20	>540
WORLD TOTAL (ROUNDED)	8900	>510000	450	>46000
WORLD TOTAL (ILMENITE + RUTILE, ROUNDED)	9400	>560000		

Table 8. Titanium metal supply chain with relevant inflows, outflows and technologies at each stage. Recycling flows and technologies are indicated in italics (D. Hu et al., 2017; Takeda & Okabe, 2019; USGS, 2019, 2023).

STAGE	INPUT	OUTPUT	MAIN TECHNOLOGY	ALTERNATIVE TECHNOLOGY
ORE BENEFICIATION	Ilmenite, Rutile	Concentrates	Physical separation (gravity, magnetic, flotation)	Synthetic rutile (ilmenite upgrading), slagging (smelting ilmenite to Ti slag)
REFINING	Concentrates (Ilmenite, Rutile, Ti Slag) + <i>contaminated scrap</i>	TiO ₂ / TiCl ₄ (feedstock), pigments	<i>Chlorination (to TiCl₄)</i> or Sulfate route (for pigments)	<i>Alternative chlorination processes (fluidized bed, plasma chlorination, hydrometallurgy)</i>
PROCESSING	TiO ₂ / TiCl ₄ + <i>oxidized scrap</i>	High-purity and off-grade Ti sponge	Kroll Process (Mg reduction)	Hunter process (Na reduction), <i>FFC Cambridge process (molten salt electrolysis), Armstrong process (plasma, Na reduction), SOM process (Mg reduction, variant)</i>
PRIMARY MELTING	Sponge + alloying additions (Al, V, etc.) + <i>alloyed scrap</i>	Ingot and powders (CP and alloys) + <i>scrap and offcut</i>	<i>Vacuum arc remelting (VAR), Electron beam melting (EB), Plasma arc melting (PAM)</i>	Induction skull melting (ISM), <i>cold hearth melting, powder metallurgy consolidation</i>
SEMI-FINISHED FABRICATION	Ingots	Billets, slabs, plates, forgings, mill products + <i>scrap and offcut</i>	Forging, casting, rolling, extrusion	
COMPONENT MANUFACTURING	Mill products + <i>recovered powders</i>	Aerospace, medical, industrial components + <i>swarf and machining scrap</i>	Traditional subtractive machining (5-axis CNC, forging-to-shape)	<i>Additive manufacturing</i> (Directed Energy Deposition, Powder Bed Fusion, Powder metallurgy (HIP), near-net-shape forming)
FERRO-TITANIUM PRODUCTION	Off-grade sponge + <i>off-grade alloyed scrap</i>	Ferro-titanium	Induction melting with Fe/steel	
SCRAP PROCESSING	Mixed EoL scrap, swarf, off-cuts	Various grades of scrap and powders	Dismantling, laser/optical alloy sorting, powder recovery	

TITANIUM METAL SUPPLY CHAIN

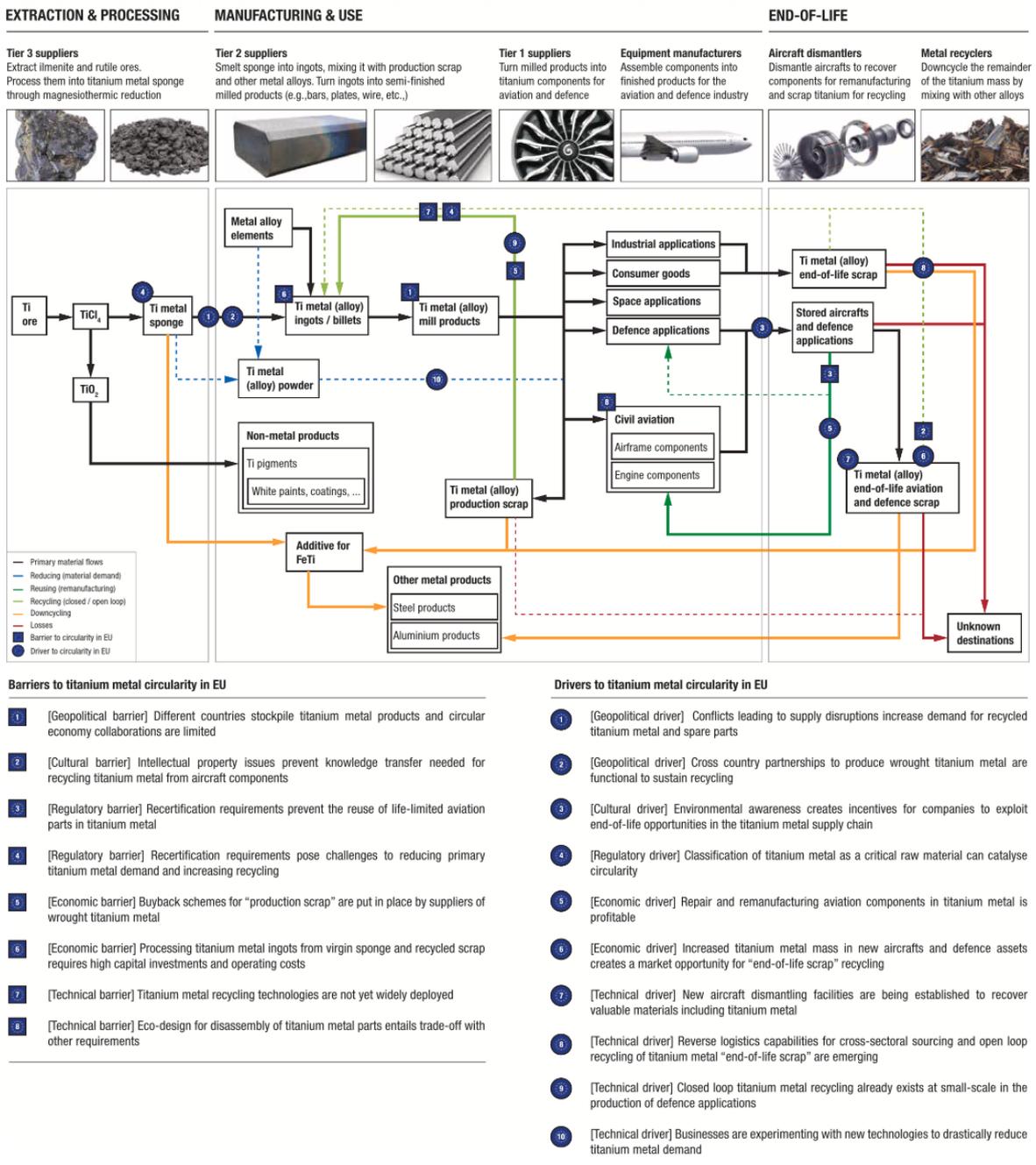


Figure 16. Titanium metal supply chain with identification of drivers and barriers to circularity in the EU (Baldassarre, 2025)

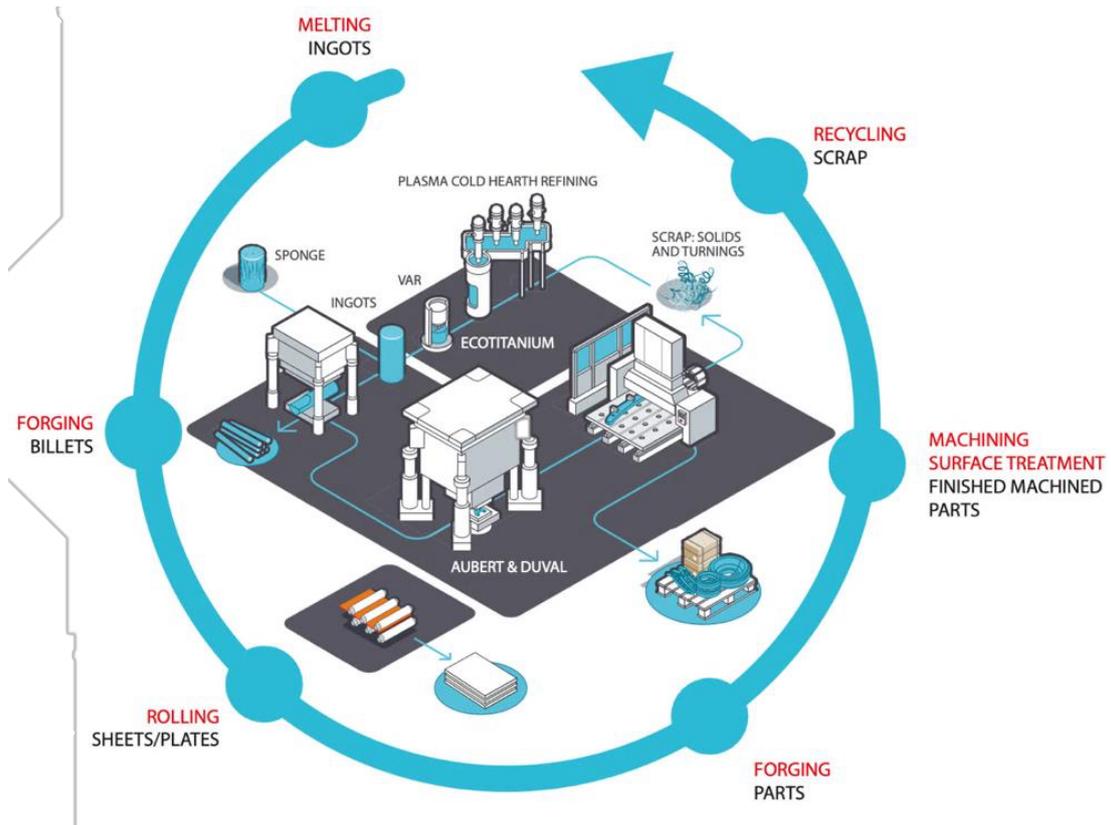


Figure 17. The cycle of titanium metal within EcoTitanium ecosystem (Aubert & Duval, 2025)

Appendix II – Indicators for criticality assessment

Table 9. Typology of Critical Raw Material (CRM) indicators and their functional roles across the dimensions of Supply Risk, Vulnerability, and Systemic Resilience.

<i>Indicator</i>	<i>Supply Disruption (Risk)</i>	<i>Vulnerability (Impact)</i>	<i>Resilience</i>
<i>Diversity (HHI)</i>	High: Low diversity (high HHI) implies concentrated supply, increasing the probability of disruption.	Low/Indirect	Low/Indirect (High concentration means low system adaptability).
<i>Political Stability (WGI)</i>	High: Instability in producing countries increases the probability of disruption.	Low/Indirect	Low/Indirect (A stable system is more resilient to political shocks).
<i>Depletion Time / Availability</i>	High: Lower depletion time increases long-term probability of supply limitations.	Low/Indirect	Low/Indirect (A long-term lack of resource necessitates major system change).
<i>Trade Policy/Restrictions</i>	High: Active trade policy (e.g., export quotas) directly increases the probability of disruption.	Low/Indirect	Low/Indirect (System is non-resilient to trade shocks).
<i>Internal Demand/Consumption</i>	Low/Indirect	High: High usage by the system under study means a disruption will have a higher impact (vulnerability).	Low/Indirect
<i>Relative Economic Importance (GDP/Revenue Impact)</i>	Low/Indirect	High: High potential economic loss means the system is highly vulnerable to disruption.	Low/Indirect
<i>Substitutability</i>	Inverse Risk: High substitutability can decrease the probability of a	Inverse Impact: Low substitutability makes the system highly vulnerable to disruption.	High: Key measure of the system's ability to adapt and recover

	market-level disruption.		
Recycling Rates	Inverse Risk: High rates reduce reliance on primary supply, decreasing the probability of disruption.	Low/Indirect	High: Reflects the system's ability to utilize secondary sources, increasing supply chain resilience .
Environmental/Social Factors	Risk Source (Perspective 1): Regulations/impacts can cause a supply disruption .	Impact Source (Perspective 2, 3): Material use causes impact/vulnerability on the environment/society.	Low/Indirect
By-product Dependency	High: Supply is dependent on another material's demand, increasing supply uncertainty/risk .	Low/Indirect	Low/Indirect

Appendix III – IE methods in detail

Material Flow Analysis

Material Flow Analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2016). It builds on concepts from network analysis and life cycle analysis, as it connects the sources, the pathways, and the intermediate and final sinks of a material. Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks, and outputs of a process.

Even though MFA is not standardised through a specific ISO, it broadly follows these steps:

1. Define the goal and scope of research – for instance just quantifying and monitoring material flows and stocks or evaluating the effects of policies on those flows and stocks will require different data and steps to reach conclusions
2. System definition and design of the model – the practitioner must choose one material and functional unit, temporal and spatial system boundaries, optionally include subsystems and choose the resolution of processes, flows and stocks. Indeed, MFA treats transformative processes as black boxes and the various elements are often aggregated. A further distinction is made at this stage
 - a. Static MFA – Time is not a modelling variable, hence the model is a snapshot;
 - b. Dynamic MFA – Time is a modelling variable and the model can be used to determine stocks and development of stocks and flows over time.
3. Quantification of the model – Once the life cycle of the material is understood and qualitatively drawn, the practitioner can proceed to entering data effectively creating an Accounting model. The main distinction here is between a top down approach, that draws data from government or global statistics, and bottom up, that obtains them by directly interviewing actors of the supply chain or derives them through material intensities. The model is then mass balanced and transfer coefficients are calculated for each process.
4. Modelling counterfactual scenarios – different scenarios, policy representations, circular transformations can be modelled and compared.
5. Interpretation of models results – usually done through indicators.

In dynamic MFA, two distinct approaches are used depending on the model's temporal logic. Flow-driven models take historical inflows as inputs and, using a lifetime

distribution (the survival curve), estimate in-use stocks and outflows. These models are suitable for retrospective analyses. Stock-driven models, instead, start from observed or projected in-use stocks and use the survival curve to calculate the corresponding inflows and outflows, making them particularly suitable for forecasting scenarios. The modelling choice depends strongly on data quality and availability.

In summary, MFA provides a robust framework for analysing the life cycle of a material, its supply chain, and the stock-flow dynamics that define its metabolism within a given system. However, it operates purely in physical terms and does not account for the economic value created at different stages of the supply chain.

Multi-Regional Input Output Analysis

Input–Output Analysis (IOA) is a systematic framework for quantifying the economic flows of goods and services within a defined system, typically a national or regional economy, over a specific period (Leontief, 1936). It builds on the principles of interdependence among sectors, tracing how the output of one industry becomes the input of another and how final demand drives production across the entire economy. Unlike material flow analysis, which measures physical quantities, the IO framework adopts monetary units, enabling a harmonised view of intersectoral linkages across the whole economy. It can represent a single region, typically a national economy, or multiple regions, capturing trade flows and economic interdependencies at a global scale (Nakamura, 2023).

The IO table is structured as a balanced matrix where rows and columns represent the same set of industries. At its core lies the interindustry transaction matrix (Z), which records the flow of goods and services used as intermediate inputs in production. Each row represents an industry's total output distributed to other industries, while each column represents the inputs that an industry purchases from others. To the right of this central block lies final demand (Y), which records sales to end users rather than to other industries. These include household consumption, government expenditure, non-profit institutions serving households, gross fixed capital formation (GFCF), changes in inventories, and exports. Together, these categories account for all goods and services that leave the production system and contribute directly to gross domestic product. The GFCF represents the investments made within a sector and serves as the only proxy for stock accumulation in Input–Output tables, which are inherently static and do not capture past or evolving capital dynamics. Below the interindustry matrix lies value added (V), which represents each sector's contribution to the economy. It is the difference between total output and intermediate consumption and includes compensation of employees,

taxes less subsidies on production, consumption of fixed capital, and operating surplus (profits). The total of these elements equals the total input (x') of each sector, which by accounting identity must match its total output (x).

Input-output analysis thus enables the measurement of total economic impacts, identification of key sectors with strong upstream and downstream linkages, and support for macroeconomic planning and policy evaluation. When extended with environmental data such as energy use or emissions, the IO framework becomes an environmentally extended input-output analysis (EEIOA), a central tool in industrial ecology for assessing the material and environmental footprints of production and consumption systems.

Follows a non exhaustive step guide of Multi Regional analysis:

1. Define the System Boundaries and Scope - specify the regions to be included as well as the temporal resolution and purpose of analysis. Besides, sectors are to be specified as well since databases aggregate them and therefore simplify their trade structure.
2. Collect and harmonise data sources - in accordance to the scope different databases are available all with specific limitations. For instance, Exiobase is already compiled for all the years from to but it could be necessary to disaggregate sectors or adjust currency.
3. Compute technical coefficient (A) - it represents the recipe of the sector, also defined as the input requirements per unit of output. It is obtained by dividing each element of the inter-industry matrix by the total output of the consuming sector.
4. Calculate the Leontieff inverse (L) - it is derived from the A matrix and captures both the direct and indirect production requirements throughout the economy.
5. Extend the MRIO with satellite accounts - depending on the scope, the analysis could require the transformation of monetary flows in environmental or social impacts
6. Scenario analysis - by introducing modifications, such as circular economy scenarios, trade disruptions or technology shifts, it is possible to assess supply systemic responses.
7. Interpret results and identify key interdependencies.

In summary, MRIO analysis captures the economic interconnections between sectors and regions, linking production, trade, and value creation across the economy. By tracing both direct and indirect effects of final demand, it enables the assessment of interindustry dependencies and the systemic impacts of policy or market changes. However, despite advances in waste and physical input-output, MRIO lacks the granularity and flexibility

of MFA for analysing specific materials or sectors, as it does not explicitly account for stocks, only gross capital formation can approximate them, and remains a static representation of the economy.

Appendix IV – MFA model implementation

The foundation of a stock driven MFA is clearly the fleet information. The more accurate and detailed the more the precise results the model will be able to generate. Unluckily the only official data about aircraft in the EU are supplied by Eurostat under the definition “Commercial aircraft fleet by aircraft category and country of registration” (Table 10. Commercial aircraft fleet by aircraft category and country of registration (Eurostat)). The registration status is a legal definition that can be easily circumvent by deregistering temporarily an airplane and therefore pay less taxes by not occupying capacity of airports. During Covid this became a normal procedure by airlines and therefore there is an artificial drop in the fleet that just after surged back to pre-pandemic levels. Assuming it to be real would be that in four years around 1500 new aircraft, with new titanium inflows, would be added to the stock, which is not a realistic assumption.

Table 10. Commercial aircraft fleet by aircraft category and country of registration (Eurostat)

Year	Observed fleet	Modified fleet
2000	4274	
2001	4200	
2002	4336	
2003	4420	
2004	4561	
2005	4776	
2006	5069	
2007	5398	
2008	5474	
2009	5460	
2010	5465	
2011	5505	
2012	5377	
2013	5241	
2014	5270	
2015	5219	
2016	5389	
2017	5566	
2018	5865	
2019	5958	5958
2020	4638	6017
2021	5473	6076
2022	5723	6135
2023	6196	6196

Appendix V – MRIO model implementation

Step 1. Identifying the parent sector

The static titanium metal flow analysis in the EU provides the foundation for identifying relevant materials, sectors, and regions involved in supplying to or demanding from the new industry. Four countries, namely United States, China, Japan, and the Russian Federation, represent the EU’s principal trading partners for titanium, while all others were aggregated into a “Rest of the World” (RoW) region.

By comparing sectoral classifications from Eurostat PRODCOM Nace code, UN Comtrade HS Code, and EXIOBASE, it was determined that the existing sector “Other Non-Ferrous Metal Production” encompasses the melting, fabrication, and manufacturing stages of titanium (Appendix II - Table 11). This sector was therefore selected as the parent from which the new one would be derived.

Step 1.1. Aggregation of sectors and regions

For ease of computation and interpretation, the original EXIOBASE tables were reduced to 31 sectors through the aggregation of industries only loosely connected to titanium production and use. Regional data were similarly aggregated according to the system boundaries defined above. The factors of production were consolidated under a single *Value Added* category, while the seven components of final demand were retained in their original form to preserve the detail needed for scenario analysis.

Step 2. Estimating titanium’s market share in the parent sector

To split the parent sector, the market share of titanium within “Other Non-Ferrous Metal Production” had to be estimated. Based on various sources, wrought titanium typically sells for between €20 and €60 per kilogram (EUROSTAT, 2025; ISE, 2019; Pakshal Steel, 2025). Adopting the conservative estimate of €20/kg and multiplying it by the global titanium metal consumption of 188 kt (Buesa et al., 2025), the total market value of titanium was derived. When divided by the total output value of the parent sector, titanium represents approximately 3% of its total market share. This proportion was used to scale the new industry relative to its parent.

Step 3. Constructing the new sector

As explained in section 3.1.2, in an IO framework, each sector can be interpreted both as a consumer of inputs (column) and as a supplier of outputs (row). Using the MARIO package for Python, the matrix was augmented by adding the new sector to both dimensions. As an initial approximation, 3% of the parent sector’s column and row values were used to define the total input and output of the new industry. These values served as a baseline for refinement based on empirical trade and process data.

A key challenge in filling the monetary flows arises from differences in price conventions between databases. While IO tables use *basic prices*, the amount received by producers, excluding taxes and margins, trade databases such as PRODCOM or Comtrade report values in *purchaser prices*, which include transport, trade margins, and taxes. Therefore, direct transfer of values between the two systems would distort the economic relationships. To align them, trade data were converted to basic prices using national accounts and assumptions derived from supply–use tables. Where direct data were unavailable, proxy adjustments were introduced to approximate these conversions.

It should also be noted that an exhaustive representation of the titanium supply chain would require additional augmentations. Appendix II - Table 12 shows the classification of the industries that demand titanium metal. For instance, “Other Transport Equipment” sector includes both civil aviation and defence applications. However, given the marginal improvement relative to the data and computational effort required, this sector was left aggregated and used as a proxy for titanium demand in aviation.

Step 3.1. Supplying industries

Each sector’s inputs can be interpreted as a “recipe” defining its production structure. Based on the Ecoinvent 3.1.1 under the item “titanium production - GLO – titanium”, one kilogram of titanium metal is produced from one kilogram of titanium sponge and one kilowatt-hour of electricity. Accordingly, the new industry was assumed to receive inputs from only two suppliers: “Electricity Production” and “Other Non-Ferrous Metal Production.”

The construction process followed a structured sequence. First, total production of the new sector was fixed at 3% of the parent sector’s total output. Value added was held constant. Trade data from UN Comtrade provided the physical volumes of wrought titanium traded between regions and produced within the EU, as determined by the MFA. These were converted into electricity requirements using the Ecoinvent recipe and then valued using average industrial electricity prices (World Bank, 2019). The remaining share of inputs was allocated among supplying regions proportionally to their trade shares. The resulting flows were normalised into input coefficients.

Step 3.2. Demanding industries

On the output side, only four industries were identified as significant users of manufactured titanium, primarily civil aviation, industrial machinery, defence, and medical equipment. The construction of demand flows followed the same logic. Total production of the new sector was fixed at 3% of its parent, with final demand initially set

to zero as only interindustry demand was recorded. Regional trade ratios from UN Comtrade and MFA results were used to allocate output among the relevant industries. These distributions were then converted into output coefficients.

Step 3.3. Satellite accounts

Given the objectives of this research, employment was the only satellite account included. In the absence of disaggregated data, employment coefficients for the new titanium industry were assumed equal to those of “Other Non-Ferrous Metal Production.”

Step 4. Matrix calculations?

- Define **Leontief inverse** ($L = (I - A)^{-1}$), **value added**, and **employment multipliers**.
- Include treatment of titanium sector using data derived from MFA (technical coefficients, final demand).

Table 11. Unified nomenclature for inflows to Manufacturing of titanium metal

Inflows	Nace code	HS code	Exiobase	Augmented Exiobase
Ti ores	07.29.19.30 Titanium ores and concentrates	-2614 - Titanium ores and concentrates	<i>Mining of other non-ferrous metal ores and concentrates</i>	<i>Mining of other non-ferrous metal ores and concentrates</i>
TiO2	20.12.11.10 Titanium oxides	-2823 - Titanium oxides	<i>Chemicals</i>	<i>Chemicals</i>
Ti sponge	24.45.30.43	810820 - Titanium unwrought	<i>Other non-ferrous metal production</i>	<i>Other non-ferrous metal production</i>
Ti ingot	Titanium and articles thereof (excluding waste and scrap)	810890 - Titanium other than unwrought		
Ti metal				<i>Manufacturing of titanium metal</i>
Ti scrap	38.32.20.00 -Metal secondary raw materials	810830 - Titanium waste and scrap	<i>Re-processing of secondary other non-ferrous metals</i>	<i>Re-processing of secondary other non-ferrous metals</i>

Table 12. Unified nomenclature for outflows from Manufacturing of titanium metal

Outflows	Nace code	HS code	Exiobase	Augmented Exiobase
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Civil aerospace	30.03 - Manufacture of air and spacecraft and related machinery	8802 - Aircraft, spacecraft, and parts thereof	<i>Manufacture of other transport equipment</i>	<i>Manufacture of other transport equipment</i>
Industrial applications	28.99 - Manufacture of other special purpose machinery	8479 - Industrial robots, not elsewhere specified or included	<i>Manufacture of machinery and equipment</i>	<i>Manufacture of machinery and equipment</i>
Military applications	30.04 - Military fighting vehicles	8710 - Tanks and other armoured fighting vehicles, motorised,	<i>Manufacture of other transport equipment</i>	<i>Manufacture of other transport equipment</i>
Consumer goods	32.50 - Manufacture of medical and dental instruments and supplies	9031 - Orthopaedic appliances.	<i>Manufacture of medical, precision and optical instruments</i>	<i>Manufacture of medical, precision and optical instruments</i>
Air transport operations	51.1 - Air transport services	8802 - Aircraft, spacecraft, and parts thereof	<i>Manufacture of other transport equipment</i>	<i>Air transport</i>
Maintenance, Repair and Overhaul	33.16.10 - Repair and maintenance of civil aircraft and aircraft engines	8802 - Aircraft, spacecraft, and parts thereof	<i>Supporting and auxiliary transport activities; activities of travel agencies</i>	<i>Supporting and auxiliary transport activities; activities of travel agencies</i>