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Multi-Criteria Assessment: A Case Study Integrating Eco-design Principles in Sustainable Manufacturing

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Abstract

This study integrates Eco-design principles and the Life Cycle approach in an MCA to evaluate the sustainability performance of manufacturing routes. The assessment is applied to conventional production across five use cases involving complex geometry parts. The aim is to evaluate areas of material criticality, environmental impacts, chemical risks, as well as social aspects, including gender dimensions (C-MET-ESG). Outcomes are synthesised into colour-coded hotspot tables and Eco-design recommendations. Key findings highlight opportunities such as substituting high-criticality alloys, increasing material efficiency, and promoting gender inclusive workplace practices. Technological transitions from CNC machining and hazardous post-processing to laser and additive manufacturing further enhance safety, resource efficiency, and resilience. The novelty of this study lies in the integration of LCA principles, the C-MET-ESG matrix, and CRA-SSbD guidelines within an MCA, establishing a hazard-aware, socially inclusive, and technically robust framework. This approach provides life cycle linked evidence that connects early design choices to sustainability outcomes. Furthermore, the study offers a transferable methodology for sustainable manufacturing in both established and emerging technologies.

Keywords: sustainability; life cycle; eco-design; multi-criteria assessment

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1. Introduction

Globally, there is growing concern for sustainable manufacturing and consumption due to the escalating environmental and social burdens associated with it. While manufacturing accounts for approximately 40% of total energy use and contributes more than 10% of global greenhouse gas emissions [1,2], these figures do not fully capture the upstream impacts embedded in the materials themselves.

From extraction to processing, raw materials have significant environmental and social consequences, responsible for over 60% of global greenhouse gas emissions and more than 90% of biodiversity loss and water stress [3]. These early life cycle stages affect local communities, particularly, low wages, hazardous labour conditions, land-use conflicts, and the displacement of Indigenous communities, with disproportionate gender risks, particularly in informal sectors [4–6].

Global and regional policy frameworks reinforce the need for material sustainability. The United Nations (UN 2030 Agenda) sets global goals that encompass social, environmental, and economic sector targets to "Leave No One Behind". Similarly, in Europe, sustainability imperatives are driving major transformations through the European Green

Deal [7], which targets climate neutrality and industrial circularity. Integral to these are the Critical Raw Materials Act [8] and comprehensive strategic assessments [9], which aim to secure sustainable and resilient raw material supply chains. Safety aspects are increasingly integrated into the EU's regulatory framework [7], via the Safe and Sustainable by Design (SSbD), which advances cleaner production and safer supply chains.

In manufacturing, complex-shaped parts, such as those with internal channels, lattice structures, or organic forms are challenging. Processes like CNC (Computer Numerical Control) machining offer precision but are inefficient for internal geometries. This generates significant material waste. Various studies have identified challenges associated with CNC and casting methods, such as low energy efficiency [10], spatial limitations [11], high material requirements, as well as resource and performance inefficiencies [12]. Additive manufacturing, as an emerging technology, particularly Powder Bed Fusion (LPBF) applications, is suited for high-performance metal components with fine detail, design freedom, and material use efficiency [13,14]. These processes are increasingly used in aerospace, medical, and tooling applications. However, constraints of extensive post-processing exist [11]. These can be tailored to improve performance [15], by integrating such functional treatments directly into the manufacturing process. These characteristics motivate an early-stage assessment of the process and supply chain of products, as well as choices in tandem with material use, safety, and usability criteria across the life cycle.

Multi-criteria techniques are widely used to interpret life cycle evidence in sustainability studies. These techniques encompass a set of methods for performing sustainability evaluations and informed outcomes. This is a result of its flexibility and the ability to facilitate dialogue among multiple stakeholders, including analysts, policymakers, and scientists [16]. A multi-criteria approach should be designed primarily to provide recommendations necessary for informed decision making that align with the highest standards of sustainability. On the other hand, specific MCDA approaches, such as MAVT/MAUT, AHP, TOPSIS, are preference-based, combining indicators with explicit inputs from stakeholders (for example, weights, value functions, or outranking rules) to produce a ranking or choice. For instance, the study [16] reported an increase in hybrid MCDA–LCA, preference-aware models; however, social (including gender) and chemical risk indicators are often limited. Many conventional approaches tend to prioritise technical and environmental metrics, while treating social aspects, especially gender-sensitive vulnerabilities, and chemical safety only superficially. While frameworks like ISO 14006:2020 [17] and the EU Eco-design Directive (2009/125/EC) offer guidance, they often focus on energy-related products and provide less universal standards for complex industrial systems. Thus, applying eco-design in high-tech manufacturing contexts is still challenging. Life cycle thinking remains essential in addressing such challenges.

MCA within life cycle thinking is a layer for evidence synthesis. There is a need for Multi-Criteria Assessment (MCA) in classic applications of sustainability indices [5], aiming to improve performance early in the development process. This evaluates the safety and sustainability of a product across its entire life cycle. Again, in support of a pre-decision MCA step to surface hazards and social vulnerabilities while keeping the data ready for preference-aware rankings. Guidance on Life Cycle Sustainability Assessment (LCSA) also encourages broadening indicators and maintaining a clear link between assessment evidence and decision stages.

Guided by the above perspective, the present study employs a multi-criteria assessment (MCA) approach to provide an evidence-based comparison across several criteria, thereby supporting early sustainability and product design. An eco-design perspective is applied to develop actionable recommendations. As an MCA for early screening, the present study emphasises resource supply and use, emissions potential, hazard visibility,

social/gender vulnerabilities, and traceability to the product life cycle. The analysis focuses on conventional production methods, specifically, CNC machining and casting, across the five use cases. This methodology is structured in accordance with the principles of life cycle assessment (LCA), focusing on goal and scope development, as well as inventory creation. Impacts are evaluated under the C-MET-ESG framework (Criticality, Material use, Energy consumption, Toxicity in the form of possible emissions, Environmental-land use impact, Social and Gender considerations) and chemical risk assessment. The results are visualised in colour-coded C-MET-ESG hotspot tables to highlight stages, materials, and practices that warrant design attention. The results are interpreted through the application of an eco-design checklist, which translates the hotspot into practical levers for action. The present contribution remains MCA to preserve transparency and avoid compensatory trade-offs. The matrix can be used as a preference-aware ranking for a decision gate requirement in MCDA applications. Compared with other MCA-LCSA studies, the present adds improvement and insights by (i) process-traceability life cycle inventory; (ii) anchored scoring with evidence-based within-category scaling (material, energy, hazard, etc.) rather than stakeholder preference; (iii) explicit coverage of chemical-risk and gender-responsive social dimensions, areas of limitations in prior studies, and (iv) an output hotspot matrix for recommendations.

This multi-criteria assessment provides decision support aligned with sustainability, enabling the systematic identification of opportunities for improvement. Consequently, this ensures that technological advancements are guided by safety, reduced negative environmental and social impacts along the supply chain, enhanced raw material resilience, and social responsibility. This study contributes to multi-criteria assessment (MCA) practices and frameworks applied in sustainable manufacturing. Thus, it integrates environmental, economic, and social dimensions to balance complex sustainability goals.

2. Materials and Methods

This section outlines the study's design, data, and approach. Section 2.1 provides a brief overview of the five use cases. Section 2.2.1 presents the positioned approach, which involves a multi-criteria assessment that incorporates the step-by-step LCA ISO framework, detailing goals and scope. Section 2.2.2 describes the compilation of life-cycle inventory data from secondary sources and expert inputs. The impact assessment step (Section 2.2.3) comprises the C-MET-ESG hotspot analysis, the chemical risk assessment, and the MCA synthesis in relation to the eco-design checklist.

2.1. Use Cases Description

The study is applied to five representative use cases, encompassing applications in aerospace and aviation (Use Cases 1–3) and biomedicine (Use Cases 4–5). These cases are selected to capture a broad range of functional and material requirements, as well as differing sustainability challenges across sectors. Each use case represents a distinct component with complex geometries and critical performance demands, including antibacterial functionality, corrosion resistance, and reduced friction. All components are produced through conventional CNC-based manufacturing routes to provide a consistent baseline for sustainability assessment. Detailed descriptions of the use cases, including their design characteristics and operational contexts, are provided in the Appendix A. The material compositions employed during CNC production are presented in Tables A2–A4.

2.2. Life Cycle Approach

The Life Cycle Assessment (LCA) methodology (ISO 14040) [18], adapted and incorporated in the MCA study, involves key steps illustrated in Figure 1. Each stage and its application in the study is further described.

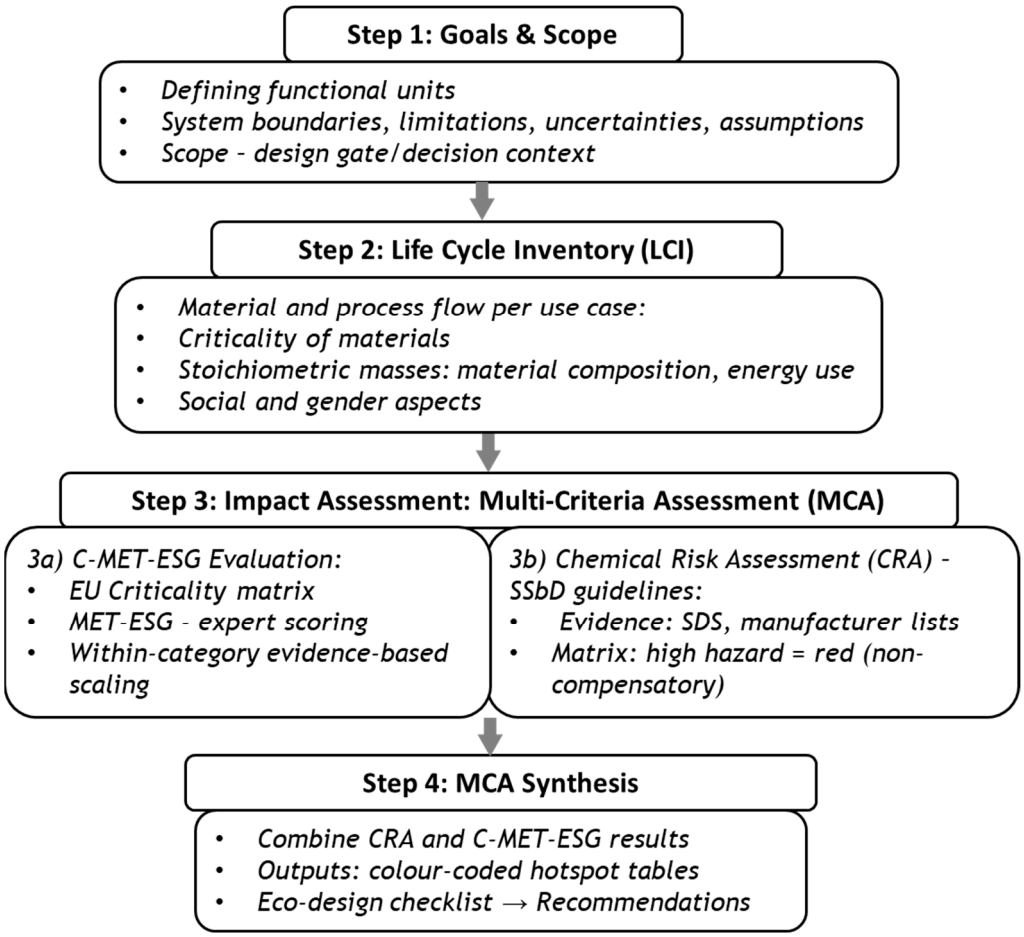


Figure 1. Overview of the LCA methodology adapted for the multi-criteria assessment.

2.2.1. Goals and Scope

The goal of the assessment is to evaluate impacts through a multi-criteria assessment: material criticality, energy demand, material use, toxicity, environmental impacts, and social and gender dimensions across the use cases. The functional unit of the assessment is defined as the quantity of annual production (or part thereof) for each use case: 230 parts for use case 1, 60 parts for use cases 2 and 3, and 10,000 parts for use cases 4 and 5. The scope of the assessment focuses on the conventional production process, including post-production steps and the use phase.

The system boundary applied to all relevant life cycle stages (LCSs) considered for each use case, using the life cycle perspective in Figure 2. Here, the material and product flow across the LCS is identified and presented in the form of process diagrams, referred to as process trees. Figure 3 illustrates a simplified process tree focused on the CNC-machined production stage, common among the use cases. Different process trees can be developed depending on the system boundaries defined for a given analysis, as these boundaries significantly influence the focus and depth of sustainability assessments. The process trees may vary in complexity, as demonstrated in Figures 2, 4, and 5. In contrast, Figure 4 provides a detailed Cradle-to-Grave process tree. Figure 5, on the other hand,

depicts a process tree specific to Use Case 4 (Knee Implant), offering a more targeted representation tailored to the particularities of that product system.

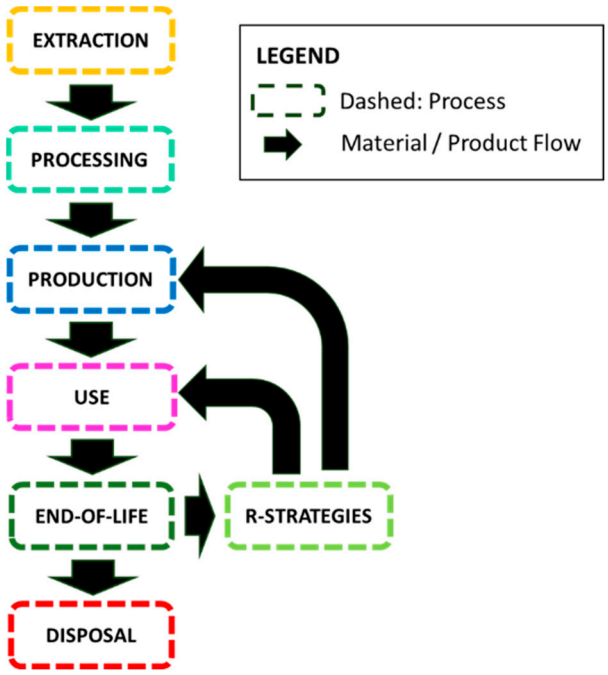


Figure 2. The system boundary for the use cases.

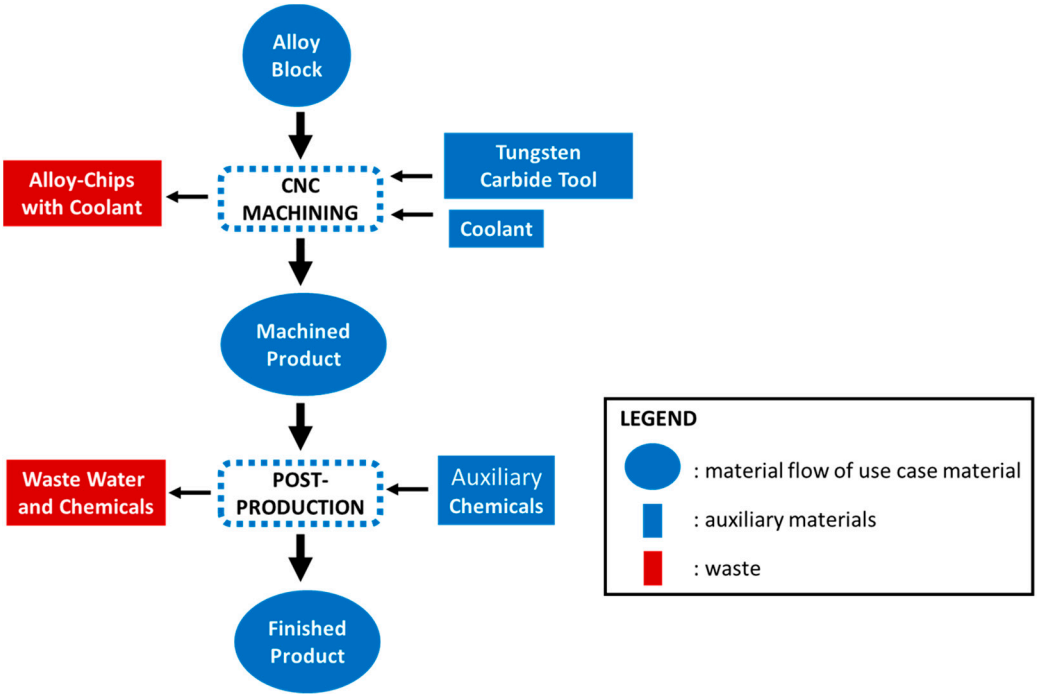


Figure 3. Material and product flow for conventional production (CNC), applicable to all use cases. It outlines the main steps of this production route, including all input and output materials.

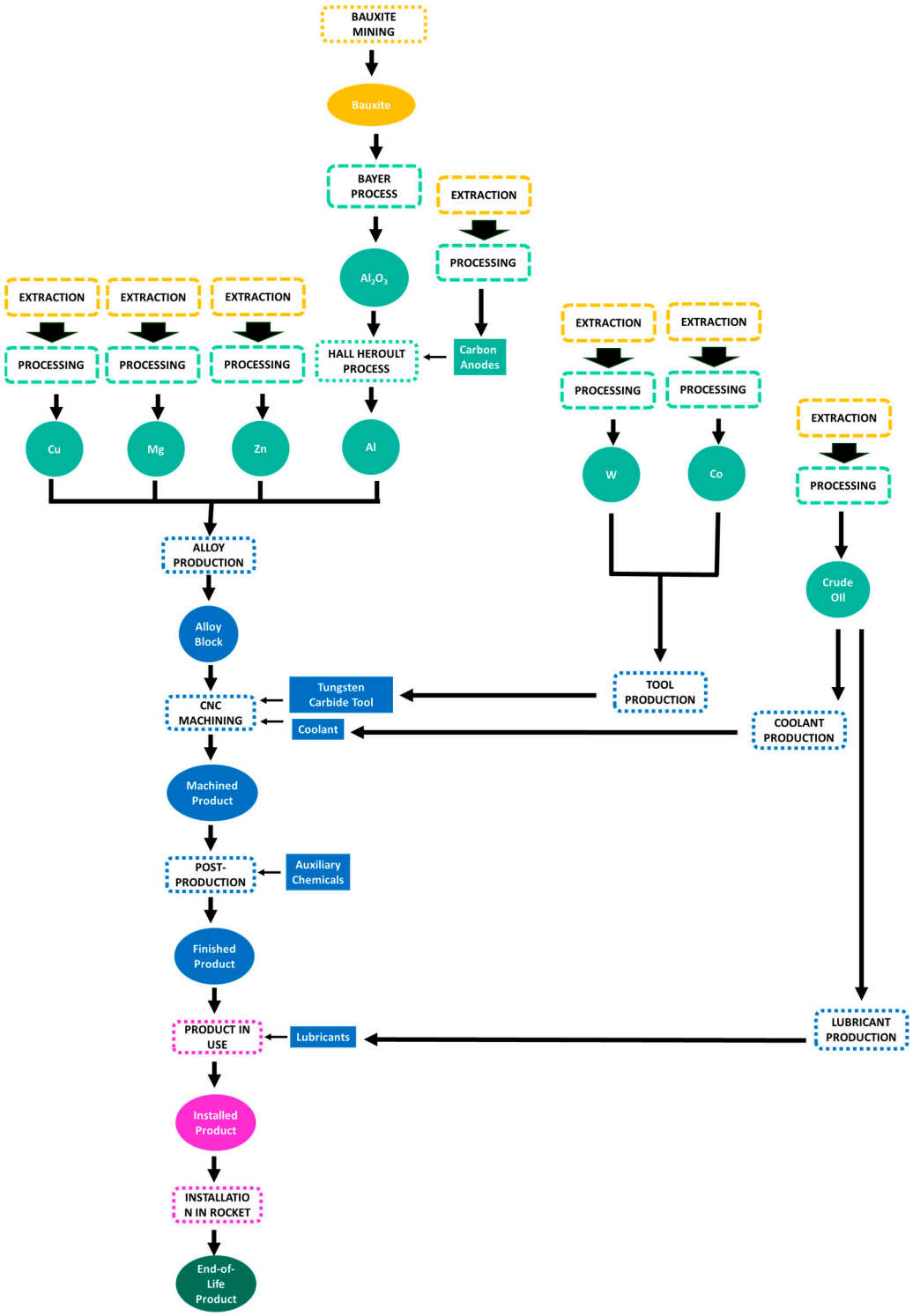


Figure 4. Detailed process tree for CNC-machined use cases, including upstream processes and relevant auxiliary materials, as well as downstream steps.

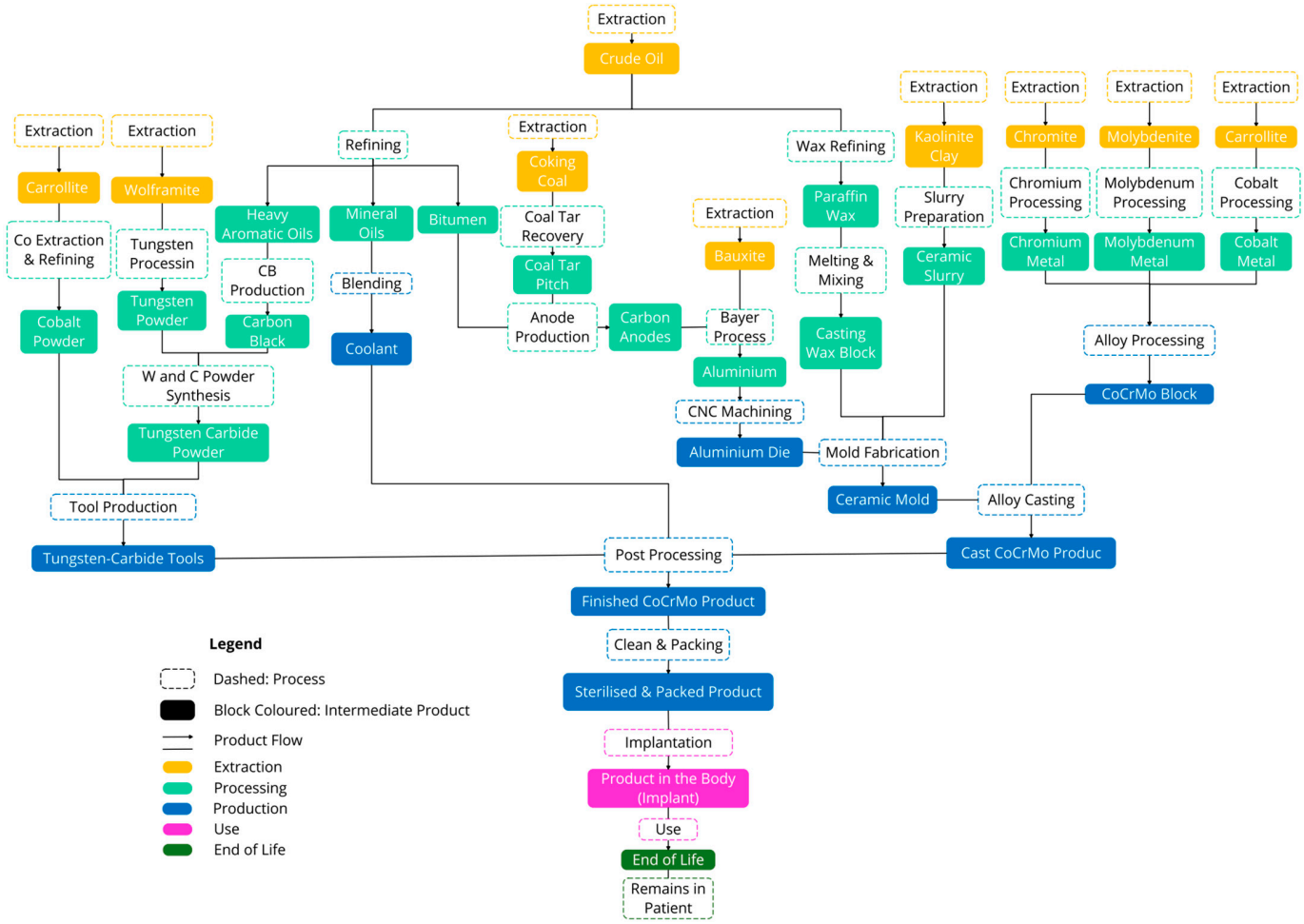


Figure 5. Process tree for use case 4 knee implant.

The materials considered include not only the primary material flows within the production process, but also auxiliary materials such as chemicals, water, and gases required during manufacturing. The upstream supply chain covering the extraction and processing of all relevant materials is analysed from a life cycle perspective in Figure 2. A cutoff criterion of 0.5% by mass is applied for materials used.

2.2.2. Life Cycle Inventory

The Life Cycle Inventory (LCI) collects input-output data on the Criticality, Material, Energy, Toxins (C-MET) analysis, extended with Environmental, Social, and Gender (ESG) aspects of each use case, referred to as C-MET-ESG.

This framework captures both quantitative and qualitative information across the product life cycle, including material use, energy consumption, waste, and emissions, as well as environmental and social impacts, with a specific focus on gender-related risks. Industry process information is collected via a Request for Information (RFI) sent to industry partners for each use case. Eleven domain experts from four companies completed RFI sheets, providing process flow details and stage-level inputs/outputs. The resulting information is used to build process trees and the life-cycle inventory (LCI). Secondary data supplied the stoichiometric masses of materials (Tables A2–A4) and all quantitative parameters needed to support the LCI. Moreover, it considers the primary extraction and processing for each material, with exceptions such as artisanal and small-scale mining, which are addressed only when particularly relevant (e.g., for cobalt). The goal is to generate a comprehensive overview of the technical processes, geographical context, and potential

environmental and social hotspots within each use. The definitions of each C-MET-ESG criterion are provided in Table 1.

Table 1. C-MET-ESG criteria definitions.

Criterion	Definition	Reference
Material Criticality	It is represented using the Supply Risk (SR) and Economic Importance (EI) scores from the EU 2023 Critical Raw Materials Report.	[9]
Energy	Refer to the total energy required to operate a given process. This includes fuels, particularly for extraction processes; heat energy, often needed during material processing; and electricity required for operations such as electrolysis or the use of machinery (e.g., CNC machines in production).	[2,7]
Toxins (Wastes/Emissions)	Include all solid waste and gaseous emissions released during a process: hazardous or non-hazardous. This category also includes thermal pollution, such as heat discharged via cooling water.	[3]
Environmental impacts	Focus primarily on land-related effects, including changes in land use and their consequences for vegetation, wildlife, and ecosystems.	[6]
Social	Cover both the risks and impacts on workers and local communities where specific life cycle activities occur. It captures aspects such as the likelihood and severity of unsafe working conditions and the broader social impacts on nearby populations, particularly vulnerable groups such as children, women, and the aged.	[4,5]
Gender	Specifically evaluates gender-differentiated risks and impacts, focusing on how each gender may be uniquely affected by conditions at each life cycle stage.	[19,20]

2.2.3. Impact Assessment-MCA

The Impact Assessment stage employs a multi-criteria assessment (MCA) approach, structured via C-MET-ESG analysis, chemical risk assessment, followed by an eco-design checklist. In this study, the multi-criteria assessment (MCA) denotes the overall assessment layer composed of (a) C-MET-ESG (EU Criticality matrix + MET-ESG scoring with within-category evidence scaling) and (b) Chemical Risk Assessment, guided by the SSbD principles. A brief overview of each approach is provided below.

C-MET-ESG Weighting and Scoring Criteria

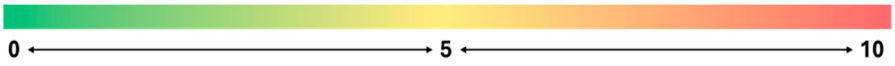
The scoring criteria for raw material criticality (CM) is based on the economic importance (EI) and supply risk (SR) matrix adopted from the EU critical raw materials list [9]. The scores (out of 10) are assigned by normalising the SR and EI scores with the highest raw material SR and EI score, within each use case life cycle. A material is considered critical if the SR $\geq$ 1.0 and EI $\geq$ 2.8 thresholds.

Economic importance is defined as "providing insight into the importance of a material for the EU economy in end-use application and value added of the corresponding designation". Supply risk is defined as "the risk of a disruption in the EU supply of the material with the corresponding designation". It is based on the concentration of primary supply from raw materials, considering the producing countries, their governance performance, and trade aspects. SR is measured as the 'bottleneck' stage of the material (extraction or processing), which presents the highest supply risk for the EU. Substitution and recycling are considered risk-reducing measures. Critical raw materials are both of high economic importance to the EU and carry a significant risk of supply disruption.

Scoring of the MET-ESG criteria (1 to 10, as defined in Table 2) is assigned across material, energy, toxins, environmental, social, and gender categories. The social assess-

ment along the LCS considers the working situation in the specific geographic location at each life-cycle stage [5]. This includes both formal industrial operations and informal or artisanal activities, recognising that working conditions, labour standards, and social vulnerabilities can vary substantially by context and production phase.

Table 2. Scoring criteria for categories (MET-ESG).

Category	Score 1	Score 10
		
Material	Consumption of materials with low environmental and/or human health toxicity.	Use of materials with significant environmental and/or human health toxicity.
Energy	Low relative energy consumption, defined as kJ/kg processed.	High relative energy consumption, defined as kJ/kg processed.
Toxins (Waste/Emissions)	Low risk of releasing non-hazardous waste or emissions.	Risk of releasing highly hazardous waste or emissions.
Environmental	Minimal impact on surrounding land, small facility footprint, and negligible effects on vegetation and animal populations.	Significant land impact, large facility footprint, and major damage to vegetation and animal populations.
Social/Gender	Standard procedures with low occupational health and safety risks and minimal impact on local populations, especially vulnerable groups such as women, children, and indigenous peoples.	Poor and unsafe working conditions violate regulations or have significant negative impacts on local vulnerable populations.

Gender dimension acknowledges that each stage, from raw material extraction to processing, production, use, and end-of-life, can interact with gender in ways that may reinforce inequalities or help promote more equitable outcomes. The gender sensitive dimension analysis review documented gender-related differences, followed by a targeted evaluation of risks faced across the life cycle stages [5]. The assessment evaluates these risks according to their likelihood and significance [21], systematically integrating them into a multi-criteria assessment. This approach supports more sustainable and equitable material use and technology policy [20].

Scoring is assigned by three field sustainability experts independently through a survey workshop, supported with the application of thematic knowledge from the quantitative LCI data and the functional unit (annual parts) to guide judgments. A score of 1 indicates low risk and low impact, and a score of 10 represents significant risk and high impact. For aggregation and subjectivity management, the median of the three expert scores is taken as the reported value (a robust small-sample estimator). The background LCI data (e.g., RFI from industry partners, stoichiometric composition, and supply chain information) accompanied each item to reduce ambiguity. These weightings are evidence-based scaling categories and are not stakeholder preference weights. No cross-category weights are applied, and no single overall ranking is produced. Given the screening focus and small panel size, the study relies on anchored scales, median aggregation, and a non-compensatory rule for high hazards to mitigate subjectivity.

These steps are conducted in both non-weighted and weighted forms. The non-weighted analysis represents the impacts along the life cycle stages according to the MET-ESG categories, expressed in absolute terms. In contrast, the weighted analysis accounts for the relative mass-based contributions (wt%) of individual materials to the final man-

ufactured product and its associated overall impact. Both materials and processes are weighted according to their proportional presence in the final product. This results in weighted impact tables that reflect the empirical magnitude, enabling the prioritisation of critical impact areas.

Chemical Risk Assessment

Chemical Risk Assessment (CRA) is performed for post-processing stages, aligning with the European Commission's Safe and Sustainable by Design (SSbD) framework [7,22]. The assessment of chemicals and materials is structured around three interconnected concepts, detailed in Table 3.

Table 3. CRA—Hazard risk assessment matrix.

Aspect	Term	Description	Meaning/Implication	Priority/Action
Assessment parameter	Criteria	Specific hazard or sustainability endpoints evaluated (e.g., carcinogenicity, toxicity, persistence).	Defines what is assessed.	Basis for assessment.
Classification	Levels	Categories rank severity or concern within each criterion (e.g., 0, 1, 2).	Degree of hazard or concern.	Level 0 = highest concern. Level 1 = chronic effects needing. Level 2 = other hazards needing review.
Hazard Score	H Numbers	Semi-quantitative hazard scores are primarily used in production/processing risk assessments.	Represents the magnitude of hazard/exposure.	H1 = High risk, prioritise substitution/modification. H2 = medium risk, flagged for review/reduction. H3 = Low risk

- Criteria define the specific endpoints or parameters under evaluation, such as carcinogenicity, persistence, bioaccumulation, or acute toxicity.
- Within each criterion, levels classify the degree of concern based on intrinsic hazard, ranging from *Level 0* (highest concern and priority for substitution) to *Level 2* (lower concern but requiring review or risk reduction).
- Complementing these, H numbers (hazard numbers) are semi-quantitative scores primarily applied in production and processing risk assessments to indicate the magnitude of safety hazards under specific exposure scenarios: H1 represents high risk that requires immediate mitigation or substitution, whereas H2 denotes medium risk requiring monitoring and risk reduction, and H3 as low risk.

Together, these elements enable structured screening, prioritisation, and decision-making to align chemical innovation with SSbD principles.

2.2.4. Interpretation-MCA Synthesis

Eco-design Checklist

The MCA synthesis compiles these module results into hotspot tables. The Eco-design checklist is applied to convert these hotspots into concrete design recommendations. The eco-design checklist, developed to support sustainable design practices, is a series of questions and considerations used to understand the current environmental, social, and economic footprint of the use cases. It is developed following UNEP Design for Sustainability: A Step-by-Step Approach [23] and aligned with the EU Directive 2009/125/EC [24]. The checklist corresponds to the eco-design approach detailed in Article 1 of EU Document 52022PC0142, addressing topics such as product durability and reliability; product

reusability; product upgradability, reparability, maintenance, and refurbishment; the presence of substances of concern in products; product energy and resource efficiency; recycled content in products; product remanufacturing and recycling; products' carbon and environmental footprints; and products' expected generation of waste materials.

The checklist questions outlined in the Appendix A (Table A5) are structured around five main eco-design strategies—Use of Low-Impact Materials, Resource Efficiency, Design for Functionality, Contribution to Health and Social Well-being, and Design for Recyclability—and are systematically applied. This approach enables identification of improvement opportunities for the use case production compared to conventional production, thereby advancing the sustainability and eco-efficiency of the products.

Recommendations

Following the data collection and subsequent analysis, a summary of key recommendations is developed to guide the production routes. These recommendations are intended to support and enhance the sustainability of products associated with emerging technologies. By integrating sustainability considerations into the early stages of use case design and development, the proposed framework aims to encourage resource efficiency, reduce environmental impact, and promote long-term viability. This strategic approach ensures that sustainability is embedded not as an afterthought, but as a core component of innovation within the evolving technological landscape.

3. Results

This section presents the overall MCA and synthesis results from the life-cycle inventory, providing process-traceable hotspot evidence. Section 3.1 summarises the LCI into process trees. Section 3.2 presents C-MET-ESG hotspot tables and CRA outcomes by life cycle stages, with targeted eco-design implications in Section 3.2.3. Cross-case observations highlighting social and gender dimensions are presented. Detailed tables and figures are provided in the Appendix A.

3.1. Life Cycle of Use Cases

Life Cycle Description of the Use Cases

The life cycle of the use cases is graphically presented in process and material flow diagrams, referred to as "process trees", based on information about the life cycle stages. Also, the material, energy use, chemicals, and process details are classified. An example of the Knee Implant use case is presented in Figure 5, where all steps from raw material extraction to end-of-life are briefly summarised. An overview of the process trees for all five use cases is shown in the Appendix A (Figure A1). This highlights the complexity of the upstream activities involved in the production processes across the various use cases. Each use case is described in detail below.

3.1.1. Use Case 1: Clamp Band

The clamp band is manufactured via CNC machining using a lathe machine (TORNO BOST Smart 36 C, BOST, Zona Industrial, Spain). The life cycle begins with the extraction of raw minerals for the aluminium 7075 alloy block—namely chalcopyrite, calamine, dolomite, and bauxite, shown in Figure 4. Additionally, raw materials are extracted for tungsten carbide cutting tools (e.g., wolframite and carrollite). Coking coal is used for producing carbon anodes required in the Hall–Héroult process, and crude oil is used to produce the cooling fluid and carbon black for the tungsten carbide powder.

These materials are processed to produce the Al alloy block, which is then machined using tungsten–carbide tools to create the final clamp band components. The compo-

nent undergoes an extensive inspection process, which includes dimensional verification, hardness testing, crack detection (using penetrant liquids), conductivity testing, visual inspection, and roughness measurement. Following these inspections, the part is subjected to sulfuric acid anodising according to ISO 8079 [25]. This electrochemical treatment of aluminium parts ensures that alloys have improved resistance to corrosion and produce coloured surfaces. The purpose of anodic oxidation is to form a dense and thick oxide coating on the surface of alloy-based parts for aerospace applications.

During the use phase, the finished clamp bands are installed on the Ariane 5 launcher. A synthetic lubricant is applied to ensure proper separation functionality during deployment. The clamp band plays a critical role in facilitating the separation of the satellite from the launcher. Based on the current application, the clamp band is dissipated after use, as the launcher does not return to Earth.

3.1.2. Use Cases 2 and 3: Pivot Bracket and Lever

The product life cycle begins with the extraction of raw minerals required for the main Ti-alloy block, including rutile, ilmenite, magnetite, and bauxite, as well as minerals for the tungsten carbide cutting tools (e.g., wolframite and carrollite). Additional resources include coking coal for producing carbon anodes (used in the Hall-Héroult process for aluminium production), and refined coke for ilmenite smelting and the carbo-chlorination process to produce titanium sponge. Other extraction activities involve crude oil to produce mineral oil coolants and carbon black, the latter of which is used in tungsten carbide powder for cutting tools. The extracted and processed materials are then used to produce the Ti-6Al-4V alloy block, which is machined using CNC equipment with tungsten carbide tools to form the lever and pivot bracket. The Pivot Bracket and Lever are currently manufactured using 3-, 4-, and 5-axis CNC machining with sharp, rigid carbide tools. Quality control primarily involves visual inspection. After machining, the parts undergo solvent cleaning. The primary cleaning agent applied to the lever and pivot bracket is Ecoclean GT-12, an alkaline detergent containing disodium metasilicate, potassium hydroxide, caustic potash, and sodium alkane (C13–17) sulfonate. The parts must withstand exposure to air, moisture, oil, fuel, methyl ethyl ketone, hydraulic fluid, and severe thermal fluctuations.

The completed lever and pivot bracket are then installed in the belly fairing of the A350, where they must withstand highly corrosive environments (exposure to air, water, oil, fuel, methyl ethyl ketone, and hydraulic fluids), as well as extreme temperature variations. No additional lubricants or surface treatments are applied during their use phase. The expected service life is approximately 25 years. At the end of their life, the parts are valorised through specialised channels and repurposed for non-aeronautical applications. The pivot bracket and lever can be disassembled from the A350 belly fairing and are treated through R-strategies (such as reuse, remanufacturing, or recycling) [26].

3.1.3. Use Case 4: Femoral Component of Knee Implant

The Knee implant is produced from a Cobalt–Chromium–Molybdenum (CoCrMo) alloy using lost-wax investment casting, followed by CNC machining and mechanical-drag polishing in Figure 5.

The product life cycle begins with the extraction of raw minerals for the primary CoCrMo alloy block, namely chromite, molybdenite, and carrollite, along with kaolin clay for the ceramic slurry and crude oil to produce investment casting wax. Additional mining is required for wolframite and carrollite to produce tungsten–carbide cutting tools. Crude oil is also needed for mineral oils (coolant) and for carbon black used in tungsten-carbide powder. Manufacturing of the knee implant begins with the creation of wax patterns, traditionally made using metal dies of aluminium, steel, duralumin, or brass. For this study,

aluminium dies are assumed. The dies form the wax models, which are assembled and encased in a ceramic slurry to produce the mould. The wax is subsequently melted out, potentially recovered for reuse, and replaced with molten CoCrMo alloy during the investment casting stage. After solidification, the ceramic mould is broken away and discarded, revealing the femoral component. It exhibits antimicrobial properties, promotes cell adhesion, features low friction, and has a roughened surface to adhere to polymethylmethacrylate (PMMA) medical cement, facilitating osseointegration.

Post-processing involves CNC machining to achieve final tolerances, followed by mechanical drag polishing with abrasive and polishing media, such as ceramic slurry, plastic beads, and walnut shells. Ultrasonic cleaning in an alkaline solution containing 5–10% potassium hydroxide and sodium hydroxide removes any surface impurities. Afterwards, the parts are rinsed in deionised water, marked with a nanosecond laser for black surface oxidation and identification, and then packed and sterilised. Once implanted, the femoral component remains in the patient for the duration of their life, with no additional treatments required.

3.1.4. Use Case 5: Trauma Plate

The trauma plate follows a material extraction and processing similar to that for the lever and pivot bracket use cases. The trauma plate is manufactured via CNC machining. After machining, the trauma plate undergoes a sequence of post-processing steps similar to those used for the knee implant: mechanical-drag polishing using abrasive and polishing media, such as ceramic slurry, plastic beads, and walnut shells, ultrasonic cleaning in an alkaline solution, rinsing in deionised water, and laser marking with a nanosecond laser to create black oxide markings. Post-processing includes mechanical polishing, followed by ultrasonic cleaning, rinsing, laser marking, packing, and sterilisation. The components are then packed and sterilised using gamma rays. They provide antimicrobial properties, controlled surface finishes to prevent soft tissue irritation and promote healing, low friction, and sufficient strength for load bearing.

Once implanted during surgery, the trauma plate typically remains in place for the remainder of the patient's life without the need for further maintenance or post-operative treatments. However, it can be removed if necessary.

3.2. Impact Assessment—MCA and Synthesis

3.2.1. C-MET-ESG Hotspot and CRA

The outcomes of the C-MET-ESG analysis for each use case are shown in Figures 6 and A2–A5. Each colour-coded hotspot table lists the life cycle stages, along with the relevant materials at each stage and their corresponding downstream materials. The primary geographic location where each specific life cycle step mainly occurs is also indicated. The subsequent rows present the non-weighted and weighted hotspot results. The colour gradient ranges from dark red (representing life cycle stages with the highest potential impact) to dark green (indicating stages of least concern). Non-coloured cells indicate criteria that are not relevant or not applicable at the respective life cycle stage. For example, material criticality is assessed only for EU-based stages, and not for countries involved in the mining or processing of the corresponding raw materials. This colour coding is applied independently within each category (e.g., energy demand is only compared to other energy demands), enabling meaningful comparisons within the same impact type. Weighting during the extraction stage is based on stoichiometric mass calculations derived from chemical equations that link metal ores to their intermediate products. For all other stages, weighting reflects the relative alloy composition of the materials. Accordingly, impacts can only be directly compared within the same life cycle stage because, for the functional unit

(parts production per year), several tonnes of ore must be mined and processed to yield just a few kilograms of material for CNC machining. Therefore, comparing energy and other impacts across different stages is not appropriate given the vastly different material quantities involved.

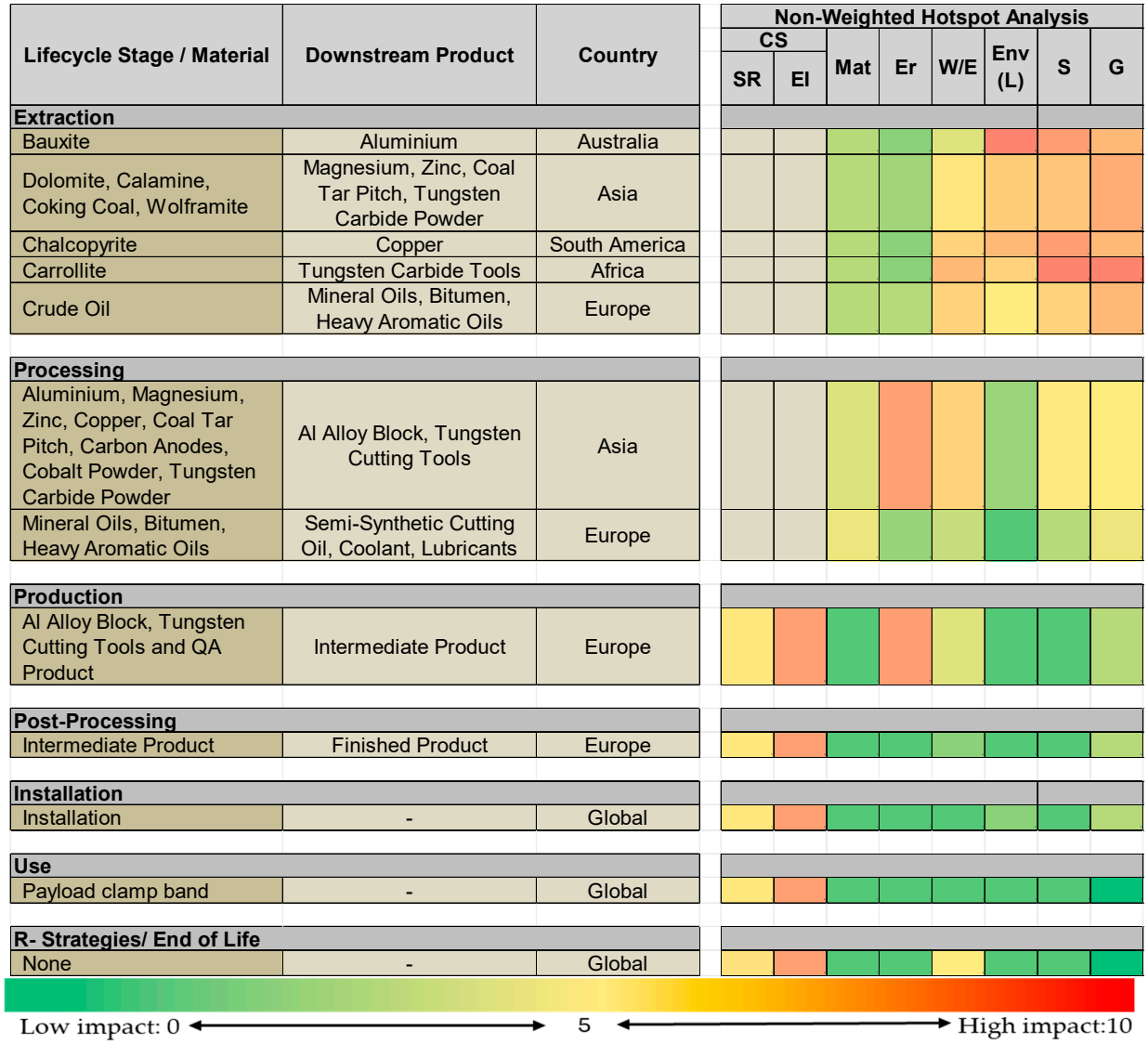


Figure 6. C-MET-ESG colour-coded hotspot table results for use case 1: clamp band. [CS, Criticality Score; SR, Supply Risk; EI, Economic Importance; Mat, Material; Er, Energy; W/E, Wastes/Emissions; Env (l), Environment (land); S, Social; G, Gender; 0 = low impact, 10 = high impact].

Use Case 1: Clamp Band

Figure 6 shows the simplified results of the C-MET-ESG analysis for the clamp band. The assessment covers Cradle-to-Grave. This excludes end-of-life (EoL) treatment processes, as clamp bands are non-recoverable due to launcher dissipation after missions. The non-weighted hotspot analysis identifies geographic regions for the processing stage of cobalt and copper as having the highest material use impacts. In these regions, chemicals, such as sulfuric acid, hydrogen sulfide, ammonia, and hydrochloric acid, are extensively used [27]. Copper processing additionally requires acids such as sulfuric acid. At the extraction stage, primary materials used include water and flotation additives. CNC machining of components during the production stage is also highly energy intensive, requiring a reported 144 kW for 85 h, 10 times per year, a total of 3326 MJ/kg [27].

The post-processing stage is assessed using a Chemical Risk Assessment, focusing on the anodic treatment of aluminium alloys in Table A6. The highest chemical hazards are associated with two sealer steps during sulfuric acid anodisation. Nickel(II) acetate tetrahydrate, cobalt (II) acetate, sodium dichromate dihydrate, and potassium dichromate are ranked H1 for human hazard. This indicates the harmful substances, which are classified as Level 0, prioritising them for substitution and redesign. Sulfuric acid, acetic acid, and sodium hydroxide are assessed as Level 1 chemicals, posing high risks to human health and the environment. Beyond toxicity, this stage exhibited moderate environmental impacts due to the ecotoxicity and persistence of chemicals in wastewater.

For the weighted hotspot, the most significant concern shifts to the extraction stage due to the large masses of ore required to produce elemental metal. Hotspots include coking coal and the environmental and social impacts of bauxite mining. Coking coal is primarily used to produce coal tar pitch, which is then utilised in the manufacture of carbon anodes. Large amounts of coking coal need to be extracted because of the low yield of coal tar pitch from coke. Interestingly, areas that are of greater concern, for example, processing metals for the tungsten-carbide tool bits (cobalt, tungsten) in the non-weighted assessment, are of lesser concern in the weighted assessment due to their minor relative contribution to the overall product.

Use Cases 2 and 3: Lever and Pivot Bracket

The results of the C-MET-ESG analysis for the pivot bracket and lever use cases are shown in Figure A3. The non-weighted hotspot analysis identifies the most significant concern for material use in the processing of Ti sponge, cobalt powder, and tungsten powder. When processing cobalt powder, sulfuric acid, hydrogen sulfide, ammonia, and hydrochloric acid are used. Chlorine gas is required in the processing of Ti sponge [28]. In comparison, the material footprint at the extraction stage is moderate, with water and flotation additives being the predominant materials used.

For energy, most consumption occurs during material processing, especially for aluminium and titanium sponge (381 MJ/kg metal produced) [28,29]. The post-processing step of component cleaning for the pivot bracket and lever use case is identified as the process stage with the highest occurrence of chemical use, as presented in Table A7. However, the used chemical (Ecoclean GT-12) is classified as H3 for human, environmental, and physical hazards—meaning "other hazard classes"—and assigned Level 3, indicating that it passes all intrinsic hazard safety criteria and is considered of no concern based on its inherent hazardous properties. Nevertheless, such chemicals may still pose risks in specific applications, depending on exposure scenarios and operational settings. In this assessment, the environmental and social risks associated with this cleaning step is scored as low, reflecting the limited intrinsic hazard but acknowledging the need for safe handling and effective waste management during use.

Use Case 4: Femoral Component Knee Implant

Figure A4 presents the results of the C-MET-ESG analysis for the femoral component of the knee implant. In the non-weighted hotspot analysis, the most significant material-use impacts occur at the processing stages of cobalt powder and chromium metal. Hazardous chemicals, such as sulfuric acid, hydrogen sulfide, ammonia, and hydrochloric acid, are used during cobalt powder processing, while sulfuric acid is required for chromium processing [30]. Molybdenum processing, which involves hydrogen, is associated with a lower material risk compared to cobalt and chromium [31]. Aluminium processing, used for die production in wax moulding, contributes significantly to energy consumption.

Regarding post-processing, the chemical risk assessment for the cleaning step indicates that potassium hydroxide and sodium hydroxide are classified as H3 for human, environmental, and physical hazards and assigned Level 3 (in Table A8), signifying no intrinsic hazard concerns. However, safe handling practices remain essential due to the potential risks under specific exposure conditions, and substitution with non-hazardous alternatives is recommended where feasible. The environmental and social risk score for this cleaning step is low in the C-MET-ESG assessment, reflecting a limited intrinsic hazard that is balanced by necessary safety measures.

The weighted hotspot analysis highlights that the primary impacts stem from the extraction of cobalt and molybdenum across all evaluated indicators, due to their greater proportional significance in the final product. Aluminium, although evident in the non-weighted analysis, is of moderate concern in the weighted analysis due to its smaller contribution to the final product mass. This concern is further mitigated by the reuse of aluminium dies in the casting process.

Use Case 5: Trauma Plate

Figure A5 shows the C-MET-ESG analysis results for the trauma plate. Since this component uses the same titanium alloy as in the pivot bracket and femoral component use cases, the results are broadly similar. The weighted hotspot analysis identifies titanium mining as the main driver of environmental impacts. This is primarily due to the large volume of trauma plates produced annually and the relatively low-grade ilmenite and rutile ores, which require extensive mining operations. Consequently, titanium extraction dominates impacts across all life cycle stages, including processing [29].

Ilmenite mining, the source of titanium feedstock, is associated with severe environmental challenges such as habitat destruction, water pollution caused by chemical and heavy metal contaminants, and substantial carbon emissions from the energy-intensive mining and extraction process. These impacts are intensified by open-pit mining techniques that disturb ecosystems and generate large volumes of tailings waste. Sustainable practices like water management, adoption of green energy sources, and land rehabilitation, are critical efforts within the sector to mitigate these effects [29]. The titanium extraction stage thus plays a more significant role in environmental impact than subsequent processing steps [32]. In line with the findings for use case 4, the post-processing cleaning step for the trauma plate, which involves using potassium hydroxide and sodium hydroxide in ultrasonic cleaning, is also scored as low risk for environmental and social impacts.

3.2.2. Cross-Case Synthesis and Social and Gender Outcomes

Environmental impacts related to land use are concentrated mainly around the extraction stage, due to the extensive land areas needed for mining and raw material acquisition [33]. In the processing phase, for all use cases, Aluminium use is applicable. The most significant energy consumption occurs during material processing, notably for magnesium (electrolytic) at 313 MJ/kg [27] and for aluminium, where the process totals 212 MJ/kg (21 MJ/kg for the Bayer process and 191 MJ/kg for the Hall–Héroult process) [34]. Both processes contribute to wastes such as red mud. Although red mud is classified as "non-hazardous" by the EU, it can result in long-term harm due to toxic heavy metals and hydroxides, and poses risks of physical collapse [34]. The working situation is analysed, with particular attention given to the following:

1. Labour standards and enforcement;
2. Occupational safety risks, such as exposure to hazardous chemicals and physical injury;
3. Worker rights, including conditions for migrant labour and collective bargaining;
4. Gender-specific vulnerabilities in factory and laboratory settings [19].

Processing facilities are often technologically advanced, risks remain especially for lower-wage, temporary, or migrant workers due to uneven enforcement of labour protections. While the literature on gender dimensions in material science and emerging technologies remains limited [5,19], it is increasingly recognised as essential. A gender-informed life cycle assessment revealed gender-specific risks at every stage. The social and health considerations across life cycle stages are presented in Tables 4 and A9. Some consistent patterns are also identified across the use cases, such as the following:

- Upstream alloy choice drives social risk. The use cases involving Co/Cr-bearing alloys show higher upstream social risk (Figure A4) due to extraction and processing and associated chemical processes Table A6. Where Ti-based routes are feasible, upstream vulnerability is comparatively lessened while maintaining performance requirements.
- Post-processing concentrates on gender-differentiated exposure. Surface finishing/cleaning stages exhibit higher gender-differentiated risks (e.g., sensitising agents, dermatitis), and risks intensify when manual handling is involved.
- Steps occurring in regions with weaker OSH enforcement and labour protections present elevated social-risk scores.

Table 4. Social and gender dominant drivers and levers among use cases.

Use Case	Dominant Social-Risk Driver	Gender-Specific Concern	Primary Mitigation Lever
1: Clamp band	Finishing/cleaning with wet chemistries	Women in finishing; dermatitis/sensitisation	Safer chemistries; laser finishing; PPE fit and training
2 and 3: Pivot bracket and Lever	Powder/acid processing context. Regional processing with weak OSH	Exposure during cleaning, Informal task allocation	Closed handling, automation, and OSH supplier audit. Supplier compliance, ventilation, and job rotation
4: Knee implant	Upstream Co/Cr processing	Nickel/Co allergy prevalence	Ti6Al4V substitution, avoid allergenic finishes
5: Trauma plate	High extraction footprint; community impacts	Indirect community burdens	Water/land management criteria; supplier code of conduct

In Table 4, these patterns may differentiate impacts. The biomedical use cases show higher upstream vulnerability when CoCrMo is present but benefit from Ti6Al4V substitution and from avoiding allergenic finishes. Aerospace use cases demonstrate a processing stage prominence, where finishing/cleaning practices, as well as supplier context, dominate risk. The gender lens adds specificity to mitigation in role assignment, PPE fit, targeted training, and substitution of sensitising chemistries.

3.2.3. Eco-design Checklist

The eco-design checklist questions, developed specifically for these use cases, are answered individually to support the assessment process and subsequently create recommendations for decision support. The process trees from the life cycle stages and C-MET-ESG hotspot tables are reviewed to determine for which life cycle stage(s) each question is relevant. This may apply to all stages, several stages, or only one specific stage. In the second step, each question is answered using the results and insights from the preceding C-MET-ESG table assessments. A short example of applying the eco-design checklist to Use Case 1 is presented in Table 5, using the question "Are the materials being used toxic to humans"? This question is relevant across all stages of the existing product's life cy-

cle with detailed questions in the Appendix A (Table A5). The assessment findings across these stages are summarised below.

Table 5. Example—Use Case 1: Eco-design Question.

Eco-design Question:	**Are the Materials Being Used Toxic to Humans?**
Processing Stage:	Material toxicity is highest during the processing stage. Harmful and toxic chemicals are used in multiple processing steps, e.g., H_2SO_4 (cobalt, vanadium), H_2S (vanadium), HF (Hall–Héroult process for aluminium). Hydrogen fluoride (HF) is highly toxic. $TiCl_4$, generated during carbo-chlorination and used in the Kroll process for titanium, is a toxic, corrosive, water-reactive chemical that, upon contact with water, rapidly forms toxic hydrochloric acid (HCl).
Manufacturing Stage:	Material toxicity during manufacturing (CNC machining) is limited, mainly arising from coolant use. Coolant typically consists of water with mineral oil, but it still requires proper handling and the use of personal protective equipment (PPE).
Recommendations for improvement based on the eco-design checklist:	
Reduce the use of materials requiring harmful chemicals (e.g., cobalt, vanadium) or highly toxic chemicals (e.g., aluminium, titanium) via improved resource efficiency—for example, by adopting additive manufacturing in place of CNC machining.	
Minimise material wastage in downstream processes, thereby reducing the quantity of toxic and harmful chemicals consumed in upstream processing.	
Eliminate the generation of toxic, corrosive, water-reactive $TiCl_4$ during titanium processing through material substitution and implementation.	

Chemical hazards: The highest chemical risks are associated with the anodisation of the clamp band (use case 1), which utilises substances classified as H1 for human hazards (most harmful) and Level 0 (chemicals that fail to meet H1 criteria). These substances are prioritised for substitution and process redesign. Accordingly, there is an opportunity to replace sulfuric acid anodisation with laser polishing (LP) and laser functionalisation via direct laser interference patterning (DLIP). Despite substitution, the required corrosion resistance should be achieved. Elemental fluorine, used in lubricant manufacture for the current use phase (use case 1), is highly toxic and the most chemically reactive element. It presents a significant human health risk. The target is to achieve the required surface friction coefficient of 0.1, as recommended by standards, through surface functionalisation techniques, thereby reducing lubricant use and elemental fluorine consumption in earlier life cycle stages. The chemicals used for cleaning the use Cases 2 and 3 -pivot bracket and lever (Ecoclean GT-12) exhibit low intrinsic hazards. They meet all safety criteria and pose no concerns regarding intrinsic toxicity. The low toxicity means these cleaning agents may continue to be used without a significant priority for substitution. For use cases 4 and 5, Potassium and sodium hydroxide, used in ultrasonic bath cleaning (classified as H3, Level 3—no intrinsic hazard), require safe handling throughout their life cycle. The findings suggest that, wherever possible, non-hazardous alternatives should be selected.

Reducing harmful material: While production stages cannot directly influence the use of toxic/harmful chemicals during upstream stages and material processing, their demand can be reduced through material efficiencies. In use case 4, Chromite ore is a key hotspot in the existing product's life cycle. Its processing residues contain Cr^{6+} (0.1–0.2 wt%), which is highly toxic to both the environment and human health. Therefore, a material change from CoCrMo to Ti6Al4V is recommended. This potentially reduces material toxicity in earlier life-cycle stages, alongside delivering improved energy and resource efficiency in manufacturing. A material substitution eliminates the need for cobalt, an EU-listed critical raw material [9], with a high supply-risk rating due to its concentration in the DRC, depen-

dence on unregulated ASM (artisanal and small-scale mining), and associated social and human rights concerns.

Addressing manufacturing inefficiencies: Wax injection casting is highly material-intensive, consuming numerous auxiliary materials (e.g., wax, ceramics, and aluminium dies) and generating waste streams, such as used ceramic moulds and surplus gating metal. Each of these materials has upstream energy, water, and resource demands. CNC machining of titanium involves significant health and safety challenges. Titanium is highly flammable and prone to tool wear and heat buildup due to its low thermal conductivity and chemical reactivity with cutting tools. Fire and explosion risks exist during machining operations if not properly controlled. Toxic gases, such as chlorine, are also used in titanium processing. Therefore, strict operational safety measures, proper ventilation, and fire prevention systems are essential. Looking further, the additive manufacturing (AM) route greatly reduces raw material use and waste. By preventing oxidation and contamination of unused powder, unutilised feedstock can be reused in subsequent builds, further improving resource efficiency.

Choice of Certified Suppliers: Although raw material extraction remains necessary, both material selection and manufacturing methods are designed to reduce reliance on socially sensitive materials, such as tungsten and cobalt, which are typically used in cutting tools. Nevertheless, the primary product materials, titanium and aluminium, continue to present supply-chain challenges, including intensive land use, displacement of indigenous communities for mining, high energy demand during production, generation of waste (notably red mud), and significant greenhouse gas (GHG) emissions. These impacts can be mitigated and made more transparent by sourcing from certified sustainable suppliers, such as those complying with Aluminium Stewardship Initiative standards.

4. Discussion

The analysis across multiple product use cases yielded a set of findings based on a holistic, multi-criteria assessment encompassing environmental, social, and technical dimensions. Incorporating criticality as a core criterion addresses material supply vulnerabilities and strengthens manufacturing resilience and cost stability. This complements environmental concerns (energy use, emissions, material and chemical toxicity, and land use) and social considerations (general social risks and gender-responsive vulnerabilities) embedded throughout the product life cycle—from raw material extraction to processing, production, use, and end-of-life. These patterns are consistent with the broader MCA practice of using pre-decision, evidence screening to surface material and process hotspots before preference elicitation, when a ranking is required [17,18]. The study outcomes are discussed in the following thematic areas.

4.1. Processes and Material Efficiency

Process and material efficiency are identified as areas for improvement from the use case scenario. Considering the LCS investigated (in Section 3.1), the material extraction stages are characterised by compromised methods. For example, open-cast mining and blasting are applied for the extraction of aluminium, tungsten, cobalt, and titanium, such as in the DRC, China, Australia, and offshore drilling for petroleum products. These methods are reported to be associated with several environmental issues [35] and concerns regarding mining waste disposal [36]. On the other hand, the conventional production approach of CNC machining is identified as highly energy intensive [10]. Alternative to CNC machining or lost wax casting, additive manufacturing (AM) with laser-based post-processing significantly reduces raw material consumption and scrap compared. This technique reduces the amount of raw material extraction. As reported in other studies [13], reuse of

protected, uncontaminated metallic powders further enhances efficiency. Replacing high-loss processes, such as wax injection casting, eliminates auxiliary materials like wax, ceramics, and dies. Laser polishing and Direct Laser Interference Patterning (DLIP) substitute chemical-intensive steps, cutting chemical use, processing time, and hazardous exposure. The dominance of material use and finishing hotspots mirrors findings in multi-criteria sustainability studies, which identify design-stage material choices and post-processing modality as primary levers for early improvement [37,38]. Reducing energy use, toxic chemical demand, and waste through additive manufacturing and laser techniques, within the use cases scenario, contributes to SDG 13 (Climate Action) and SDG 15 (Life on Land) by minimising environmental impacts and protecting ecosystems. LB-AM also enhances and extends the product life in applications with complex geometry [39] and anticorrosion for biomedical applications [40]. Evidence that AM and laser finishing reduce raw material loss, auxiliary materials, and chemical demand is consistent with prior assessments on complex-geometry parts and biomedical surfaces [12]. Material criticality assessments enhance supply chain resiliency by prioritising alternatives to high-risk raw materials, ensuring reliable sourcing. Material changes replace hazardous chemicals (e.g., hexavalent chromium) and materials with sustainability concerns (e.g., cobalt), strengthening workplace safety and supporting sustainable production. Improved material efficiency also promotes social and environmental responsibility by lowering material demand and minimising upstream supply chain impacts. In context, similar studies demonstrate the need for early stage assessment of product life, including SSbD context for material and process improvements in the nanomaterial applications [41] and industrial applications [42].

4.2. Supply-Chain Resilience

Reliance on raw material associated with high impacts is identified as promoting and enhancing social concerns along the supply chain. In the use case, switching from CoCrMo alloys to titanium reduces dependency on cobalt, a critical raw material with high supply risk due to concentrated production in the Democratic Republic of Congo [29]. Although titanium and aluminium have higher energy and land use demands, diversified sourcing improves resilience. Certified sustainable sourcing initiatives, such as the Aluminium Stewardship Initiative (ASI), add transparency and enforce embedded social and gender criteria. It also enhances supply chain transparency and mitigates environmental and social impacts. The result that substituting Co/Cr routes with Ti-based options reduces upstream vulnerability aligns with EU critical raw materials guidance. Thereby, emphasising design-stage substitution to lower exposure to concentrated supply risks [8,9]. These findings are consistent with earlier studies [43], where it is reported that sustainable supply chain practices are key to environmental performance. Thus, stakeholders of any group and downstream activities can affect an organisation s or a product's supply chain performance. A linkage is established between certified sourcing and reduced social and environmental risk. In agreement, the other sustainability supply-chain literature reports that governance and supplier compliance have a material influence on performance and resilience [44]. Furthermore, ref. [45] established that sustainable sourcing, when implemented with compliance, enhances supply chain resilience, especially in emerging economies.

4.3. Worker and Operational Safety

Occupational Health and Safety (OHS) is a major aspect of a product's life cycle. In the assessed use case, operational factors may influence the risk or any hazards associated with occurrences. Replacing hazardous processes such as anodisation and ultrasonic cleaning with laser finishing and functionalisation lowers occupational chemical exposure across all use cases. Substituting allergenic metals (such as nickel, cobalt, and chromium) with tita-

nium alloys reduces metal allergy risks during manufacturing, handling, and product use, which is important for overall workforce health. Hazard and criticality-based exclusions, such as substituting risky raw materials like cobalt, enhance supply chain resiliency, and material efficiency, contributing to SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production). In a supply chain study [45], the findings affirm that improving health and safety contributes to overall cost savings, enhanced reputation, and sustainability performance of the organisation or product under study. The outcome from this study also supports SDG 8 (Decent Work and Economic Growth) by improving labour conditions and promoting inclusive policies. Furthermore, by eliminating hazardous chemicals and reducing occupational risks through inclusive work practices, the findings support SDG 3 (Good Health and Well-being) by promoting safer workplaces and reducing health risks. Rating high chemical hazard as non-compensatory (i.e., not offset by favourable scores elsewhere). This addresses a well-noted limitation of compensatory aggregation in MCDA, reported in the study [46]. This choice maintains visibility of critical safety hotspots in line with assessment practice.

4.4. Social and Environmental Responsibility

The analysis identified chemical hazards along the LCS of the use cases studied. The framework accounts for both general social risks (unsafe working conditions, child labour, wage disparities, precarious employment, impacts on Indigenous communities) and gender-responsive vulnerabilities. Among the major hotspots are the displacement of settlements, as well as OHS issues, child and forced labour at the extraction stage. Supplier selection criteria, with embedded social responsibility requirements, including equitable labour practices, certified safety standards, and inclusiveness across supply chains, are key to curbing these impacts. Comparative evidence in social-LCA and MCA applications indicates that finishing/cleaning roles and regional OSH enforcement are recurring contributors to social risk [37], reinforcing the targeted supplier and workplace measures identified here. Again, emphasising social responsibility and gender-responsive criteria throughout the material life cycle, addresses inequalities, advancing SDG 5 (Gender Equality) and SDG 10 (Reduced Inequalities), and fosters equitable, inclusive production systems alongside environmental sustainability. As part of the findings, it affirms the results of other studies [44,47] that replacing hazardous chemicals with alternatives yields equal or superior surface properties. Toxicity risks, such as hexavalent chromium from chromite ore are reduced by substituting CoCrMo alloys with titanium (Ti6Al4V) [31].

4.5. Gender Specific Risk Mitigation

Gender and diversity mainstreaming are important aspects of supply chain and risk assessment. The concept has been analysed in various aspects of applications, such as in nanotechnology [22], material science [21] and industrial food processing [44]. In this study, targeted actions address risks disproportionately affecting women in manufacturing. Women often have a higher prevalence of nickel and cobalt allergies (17–22% vs. 3–5% in men). The cross-case synthesis reveals that the choice of upstream alloy and post-processing steps significantly contributes to social and gender outcomes. Mitigation is, therefore, concentrated on alloy substitution where feasible, safer finishing practices, and gender-responsive workplace policies at all levels. Outcomes from the use case assessment indicate that mitigation of these vulnerabilities can be achieved by ensuring supplier compliance with gender-responsive labour standards. Reducing hazardous chemical use, such as replacing anodisation with laser finishing, is thus critical to protect vulnerable workers. In line with MCA applications that prioritise non-compensatory treatment of chemical hazards at early gates [16]. This is to minimise differential exposure risks and promote equi-

table, safe workplaces throughout the supply chain. In this respect, the cross-case patterns, upstream alloy choice and finishing modality as the main drivers, align with multi-criteria studies that link gender-differentiated risk to specific stages and tasks rather than to sector alone [5,21]. Gender sensitive LCA raises awareness of gender-specific risk mitigation, fostering greater equity and inclusion in manufacturing. The results, therefore, extend prior descriptive coverage by providing stage-linked, design, and workplace levers that can be operationalised in supplier requirements. These combined measures enhance workplace safety, promote inclusion, and contribute to gender equity, alongside technical and environmental benefits. Overall, the findings accord with MCA evidence on early-stage hotspot identification.

5. Conclusions

This study and the applied methodology build upon existing multi-criteria assessment practice widely applied in sustainable manufacturing. Thus, it integrates environmental, economic, and social dimensions to balance complex sustainability goals. It establishes the integration of material efficiency, reducing raw material consumption, the use of toxic chemicals, and production waste, while improving work and occupational safety. Outcomes from this study contribute to advances in the state of the art in complex geometry product production and supply.

First, it applies up-front hazard identification and chemical risk assessment to eliminate extreme chemical hazards in the early stages of a design process (H1/Level 0 substances). This proactive approach is consistent with emerging hazard-prioritisation models, reduces occupational exposures, improves workplace safety, and mitigates downstream environmental risks. Second, through its C-MET-ESG framework, it is recognised to integrate gender-responsive social criteria, quantifying and weighting disparities in occupational risk, wage inequality, allergy prevalence, water-collection burdens, and broader social vulnerabilities, alongside environmental and economic factors. Third, it incorporates economic criticality as a formal criterion, identifying and excluding high-risk raw materials. For example, cobalt from artisanal mining in the DRC to enhance supply-chain resilience and reduce vulnerability to geopolitical and market disruptions.

By embedding rigorous chemical risk assessment, gender equality and social justice, material efficiency, environmental responsibility, safety, and economic resilience, the study establishes a holistic, hazard-aware, and socially inclusive decision support layer. This comprehensive scope aligns closely with best-practice recommendations for sustainable and equitable manufacturing. The outcomes align with the objectives of multiple UN SDGs towards production and consumption cycles, most notably advancing SDGs 3, 5, 8, 9, 10, 12, 13, and 15. Furthermore, it delivers a comprehensive, hazard-aware, and socially inclusive eco-design framework, positioning itself as a next-generation model for safe, equitable, and sustainable manufacturing. The multi-criteria approach supports advances in sustainable manufacturing. Holistic multi-criteria sustainability assessments enable informed decision-support layer, balancing environmental, social, economic, and technical factors.

The study is also policy relevant, especially within the EU. The outcomes support European Green Deal priorities on climate neutrality, safer chemicals, and circular production by making early, traceable improvement levers explicit. Another aspect is seen in the area of the Critical Raw Materials Act by identifying opportunities for substitution, material efficiency gains, and supply risk mitigation along the supply chain, presented in process trees in this study. These features enable direct uptake in eco-design requirements, supplier codes, and certified sourcing schemes.

However, the study is not void of limitations and uncertainties, arising from several factors. Firstly, assessing social impacts is inherently subjective, as it is based on ratings of social conditions affecting different stakeholders (e.g., workers, local communities, Indigenous peoples). Secondly, significant data gaps also exist, especially concerning conditions in China, for example, supplier-specific operating conditions where data is not fully public. The RFI from the industry partners 'use case owners' data was useful to meet these limitations. Nonetheless, all assumptions and data sources are transparently documented, thereby supporting the overall reliability of the evaluation.

Future studies are recommended in areas of quantifying environmental impacts across the scope of sustainability under different scenarios. Additionally, a comparative assessment considering alternatives, possible impacts, and trade-offs. A detailed, gender-sensitive social study is required to establish further perspective on weighted parameters that may differ across geographic locations, policies, and economies of scale. Inter-rater summaries and probabilistic sensitivity analysis for a broader scope are recommended for future studies.

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Appendix A

Presented here are tables and figures as supplementary data from the study.

Table A1. Terminology used in assessment.

Terminology	Description Applied in the Study
Extraction	Obtaining raw materials from the environment—through mining, drilling, or agriculture—and may include beneficiation at the extraction site.
Material processing	Converting these primary products into usable materials via processes such as smelting, purification, or leaching.
Production	The conventional manufacturing process defined for each use case, such as CNC machining or lost-wax injection moulding.

Table A1. *Cont.*

Terminology	Description Applied in the Study
Post-processing	Operations after production, such as surface treatments, cleaning, testing, and inspection. In biomedical use cases, this also includes packing and gamma-ray sterilisation.
Installation	The assembly and integration of the final product to ensure its operability.
Use	The operational phase, including any maintenance required to retain functionality.
End-of-life	All processes following the product's use phase, including disposal, recycling, or remanufacturing into new products.
R-strategies	Approaches include recycling, remanufacturing, reuse, refurbishing, and similar methods.

Use Case Description.

Use Case 1: Generic component payload "Clamp Band" for launchers in the aerospace industry.

- Product function: The clamp band serves as a separation system for medium and large-sized commercial telecommunication satellites on the Ariane rocket. It enables satellites to attach to the rocket and separate precisely during the flight.
- The main materials used in the clamp band are aluminium (Al), magnesium (Mg), copper (Cu), and zinc (Zn). The base material is Aluminium 7075, in compliance with ISO 209 [48] in Table A2.

Table A2. Elemental composition for Use Case 1.

Material (Aluminium 7075)	Mass (%)
Al	89.0–91.6
Cu	1.2–2.0
Mg	2.1–2.9
Zn	5.1–6.1
Others < 1%	Fe (max 0.5), Mn (max 0.3), Si (max 0.4), Ti (max 0.2), Cr (0.18–0.28)

Use Case 2: "Pivot Bracket" and Use Case 3: "Lever" in the aviation industry.

- Product functions: The pivot bracket provides a fixed point, and the lever acts as the moving component in an actuator within the A350 belly fairing. This actuator controls the angle of attack of the NACA profile inside the engine nozzle, which modulates thrust, exhaust expulsion, and mass flow rate.
- The main material composition of the pivot bracket and lever consists of titanium (Ti), aluminium (Al), and vanadium (V), with trace elements, such as iron (Fe) and carbon (C), illustrated in Table A3.

Table A3. Elemental composition for Use Cases 2, 3, and 5.

Material (Ti6Al4V)	Mass (%)
Ti	91.0
Al	5.5
V	3.5
Others < 1%	Fe (< 0.3), O (<0.2), H (<0.0015), C (<0.08), N (<0.05)

Use Case 4: Femoral component of a "Knee Implant" in biomedical applications

- Product function: This unicompartmental knee implant component restores knee joint movement.
- The main component of the knee implant is made from a cobalt–chromium–molybdenum (CoCrMo) alloy, as shown in Table A4.

Table A4. Elemental composition for Use Case 4.

Material (CoCrMo)	Mass (%)
Co	63.0–68.0
Cr	27.0–30.0
Mo	5.0–7.0
Others < 1%	Ni (<0.5%), Fe (<0.75%), C (<0.35%), Si (<1%), Mn (<1%), W (<0.2%), P (<0.02%), S (<0.01%), N (<0.25%), Al (<0.1%), Ti (<0.1%), B (<0.01%)

Use Case 5: "Trauma Plate" in biomedical applications

- Product function: Trauma plates serve as reconstruction devices that support bone fracture healing.
- The trauma plate, composed of titanium, aluminium, and vanadium, as the main materials, as listed in Table A3.

Table A5. Eco-design checklist questions.

Use of Low Impact Material	**Resource Efficiency**
1. Are materials sourced from environmentally sensitive geographic location? 2. Do the materials have high embodied energy? (How much energy is required, what is the energy source, and what pollution is generated? 3. Are materials used toxic to humans? 4. Are materials used toxic to the environment? 5. Can materials be recycled during production and re-used in the product? 6. Does the product contain materials that are biodegradable?	1. Can the use of energy, water, and materials be reduced during production? 2. What additional outputs are generated during production, and can they be captured and utilised? 3. Can the weight of the product be reduced? 4. Is the manufacturing method reliable and consistent? 5. Can transport distances be reduced or made more efficient? 6. Can the weight and material intensity of packaging be reduced?
Design for Functionality	**Design for Recyclability**
1. Is energy required during the product's use, and can it be reduced? 2. Are additional resources (e.g., water, chemicals) required during the product's use, and can their consumption be reduced? 3. Can the product be refurbished? 4. Is the product's performance stable over time?	1. What is the average lifespan of the product, and what factor determines it? Can the product's lifespan be extended? 2. Can the product be upgraded? 3. Does the product contain both long-life and short-life components? 4. Can the product be disassembled at the end of life? 5. Can the product be reused or recycled?
Contribution to Health and Social well-being	
1. Are the materials sourced from socially sensitive origins (e.g., conflict materials or regions with human rights concerns)? 2. Are there specific occupational health and safety risks associated with the manufacturing process?	

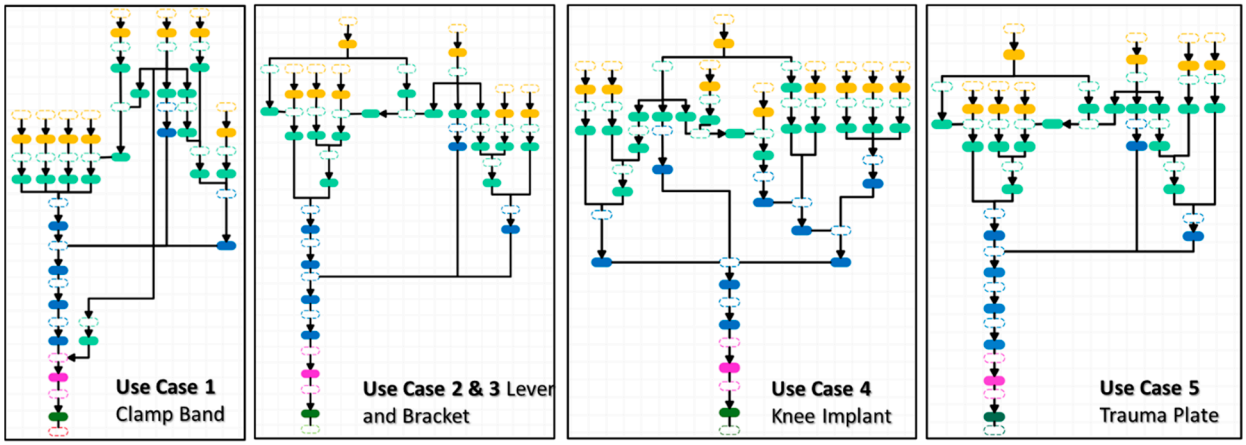


Figure A1. Process trees for all five use cases.

Lifecycle Stage / Material	Downstream Materials	Country	Non-Weighted Hotspot Analysis								Weighted Hotspot Analysis							
			CS								CS							
			SR	EI	Mat	Er	W/E	Env (L)	S	G	SR	EI	Mat	Er	W/E	Env (L)	S	G
Extraction																		
Bauxite	Al Alloy	Australia																
Dolomite	Al Alloy	Unk - China																
Calamine	Al Alloy	China																
Chalcopyrite	Al Alloy	Chile																
Coking Coal	Al Processing	China																
Carrollite	Tungsten Carbide Tools	DRC																
Wolframite	Tungsten Carbide Tools	China																
Crude Oil	Coolant, Lubricants	Europe																
Processing																		
Aluminium	Al Alloy	China																
Magnesium	Al Alloy	China																
Zinc	Al Alloy	China																
Copper	Al Alloy	China																
Bitumen	Al Processing	Russia																
Coal Tar Pitch	Al Processing	China																
Carbon Anodes	Al Processing	China																
Cobalt Powder	Tungsten Carbide Tools	China																
Carbon Black	Cutting Tools	China																
Tungsten powder	Cutting Tools	China																
Tungsten-Carbide Powder	Cutting Tools	China																
Tungsten carbide tools	Cutting Tools	China																
Cutting Fluid	Coolant	Spain																
Lubricants	Lubricants	France																
Production																		
Machined Product	-	Spain																
QA Product	-	Spain																
Post-Processing																		
Finshed Product	-	Spain																
Installation																		
Installation	-	French Guyane, Japan, USA																
Use																		
Payload clamp band	-	Global																
R- Strategies/ End of Life																		
None	-	Global																

Low impact: 0 ← → 5 ← → High impact:10

Figure A2. Detailed C-MET-ESG colour-coded hotspot table results for use case 1: clamp band.

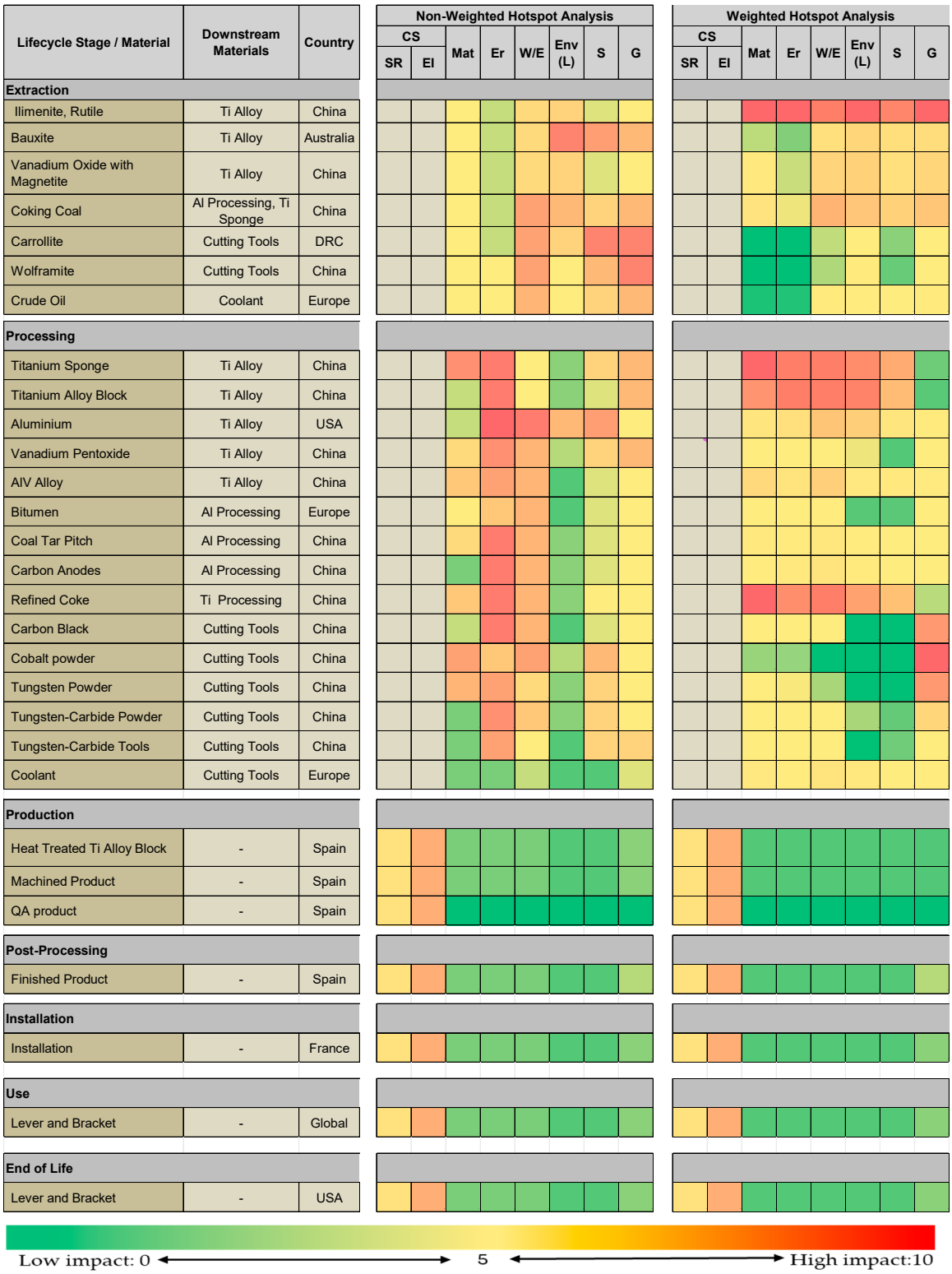


Figure A3. Detailed C-MET-ESG colour-coded hotspot table results for use case 2 and 3: lever and pivot bracket.

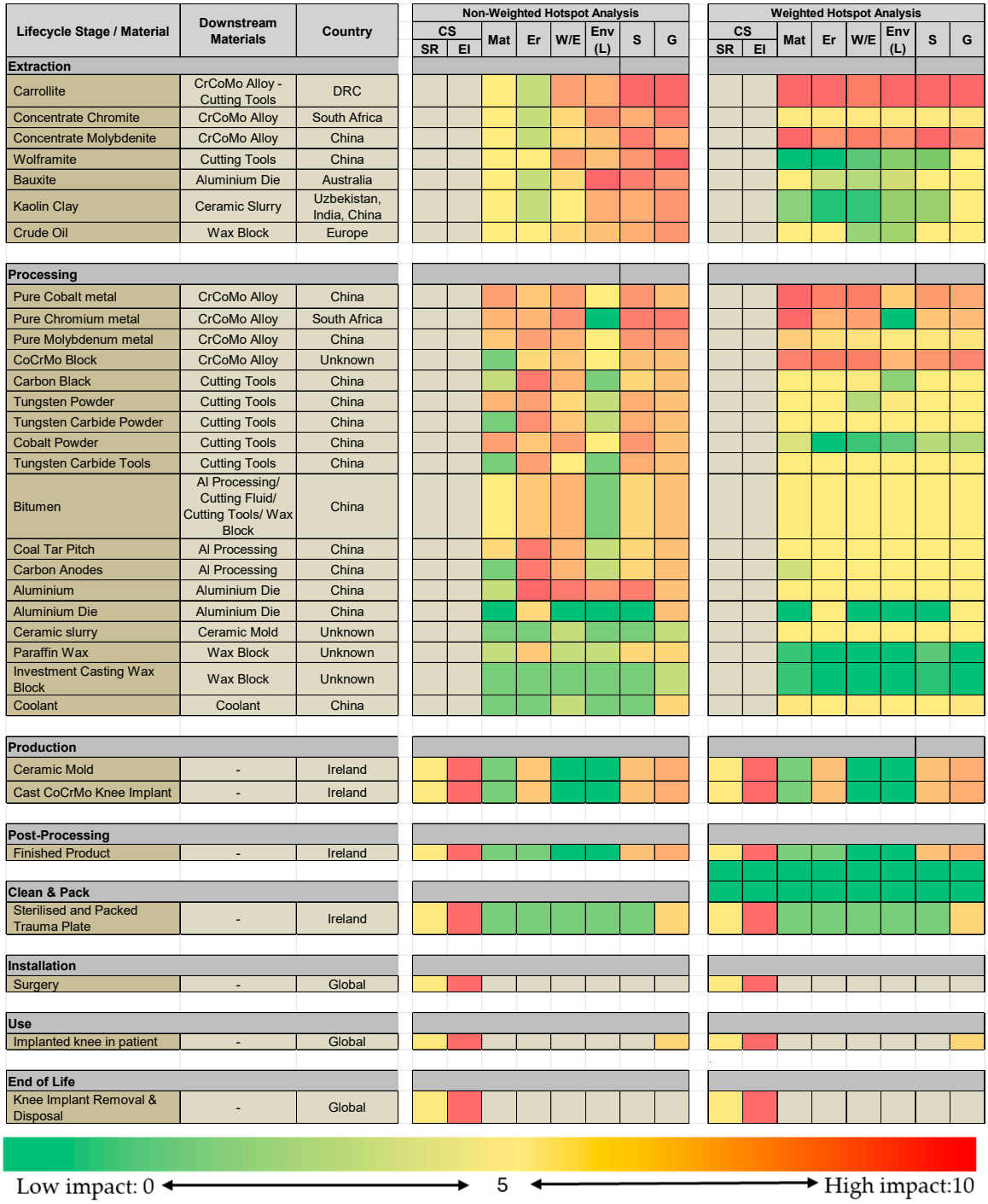
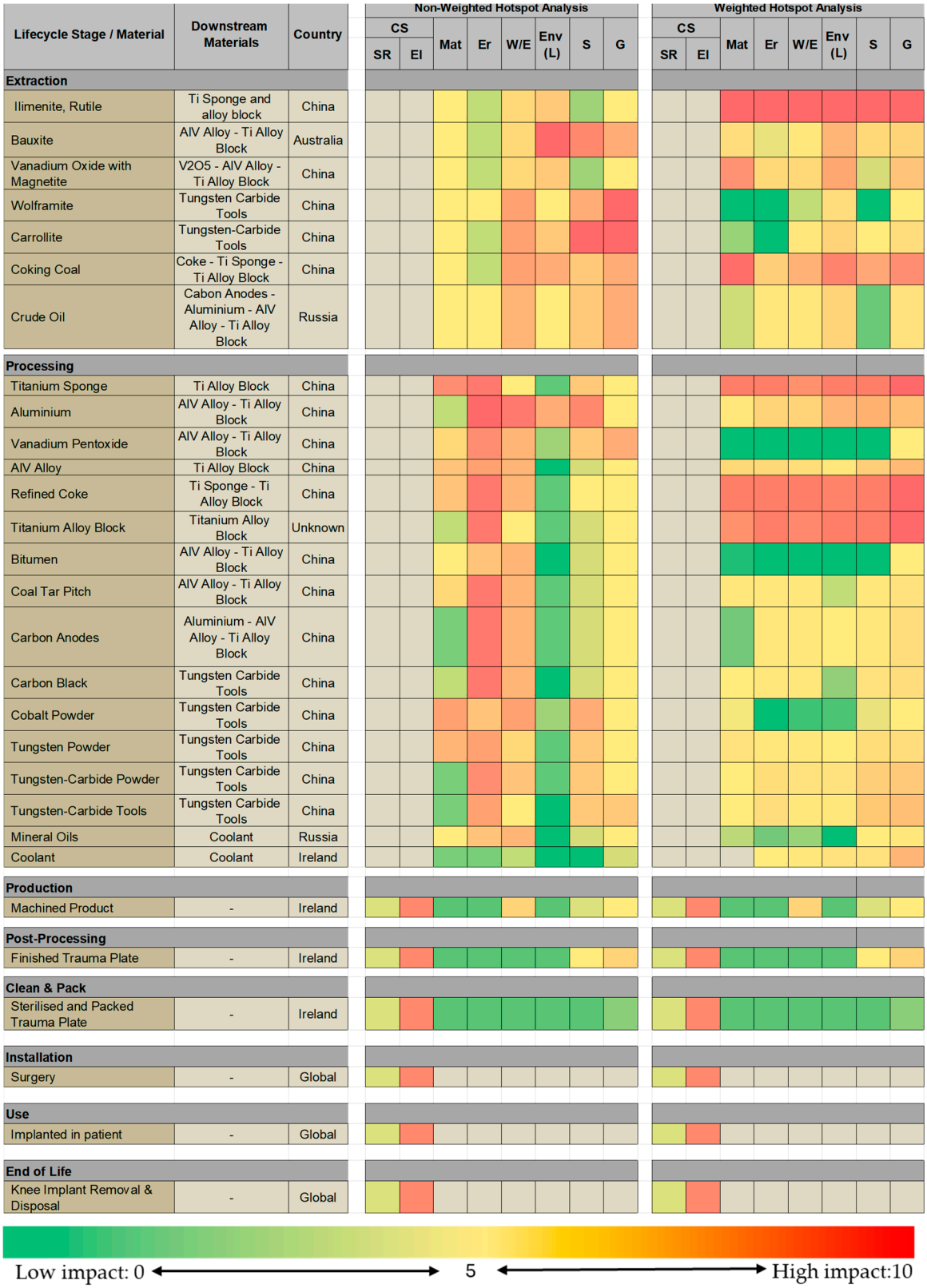


Figure A4. Detailed C-MET-ESG colour-coded hotspot table results for use case 4: femoral component knee implant.



Lifecycle Stage / Material	Downstream Materials	Country	CS		Mat	Er	W/E	Env (L)	S	G
			SR	EI						
Extraction										
Ilimenite, Rutile	Ti Sponge and alloy block	China								
Bauxite	AlV Alloy - Ti Alloy Block	Australia								
Vanadium Oxide with Magnetite	V2O5 - AlV Alloy - Ti Alloy Block	China								
Wolframite	Tungsten Carbide Tools	China								
Carrollite	Tungsten-Carbide Tools	China								
Coking Coal	Coke - Ti Sponge - Ti Alloy Block	China								
Crude Oil	Cabon Anodes - Aluminium - AlV Alloy - Ti Alloy Block	Russia								
Processing										
Titanium Sponge	Ti Alloy Block	China								
Aluminium	AlV Alloy - Ti Alloy Block	China								
Vanadium Pentoxide	AlV Alloy - Ti Alloy Block	China								
AlV Alloy	Ti Alloy Block	China								
Refined Coke	Ti Sponge - Ti Alloy Block	China								
Titanium Alloy Block	Titanium Alloy Block	Unknown								
Bitumen	AlV Alloy - Ti Alloy Block	China								
Coal Tar Pitch	AlV Alloy - Ti Alloy Block	China								
Carbon Anodes	Aluminium - AlV Alloy - Ti Alloy Block	China								
Carbon Black	Tungsten Carbide Tools	China								
Cobalt Powder	Tungsten Carbide Tools	China								
Tungsten Powder	Tungsten Carbide Tools	China								
Tungsten-Carbide Powder	Tungsten Carbide Tools	China								
Tungsten-Carbide Tools	Tungsten Carbide Tools	China								
Mineral Oils	Coolant	Russia								
Coolant	Coolant	Ireland								
Production										
Machined Product	-	Ireland								
Post-Processing										
Finished Trauma Plate	-	Ireland								
Clean & Pack										
Sterilised and Packed Trauma Plate	-	Ireland								
Installation										
Surgery	-	Global								
Use										
Implanted in patient	-	Global								
End of Life										
Knee Implant Removal & Disposal	-	Global								

Figure A5. Detailed C-MET-ESG colour-coded hotspot table results for use case 5: trauma plate.

- Chemical Risk Assessment Results Tables

Table A6. Process steps and hazards identified for Use Case 1.

	M.	Chemical	CAS No.	Human Hazards	Environmental Hazards	Physical Hazards	Level
1	Anodising	Sulfuric acid	7664-93-9	H3	H2	H3	Level 1
2	Rinsing solution (H_2O with ph 5.5–6.9)	Acetic acid	64-19-7	H3	H2	H3	Level 1
		Ammonia	7664-41-7	H3	H3	H3	Level 3
3	1. Sealer	Nickel(II) acetate tetrahydrate	6018-89-9	H1	H2	H3	Level 0
		Cobalt(II) acetate	71-48-7	H1	H2	H3	Level 0
4	2. Sealer	Sodium dichromate dihydrate	7789-12-0	H1	H2	H3	Level 0
		Potassium dichromate	7778-50-9	H1	H2	H3	Level 0
5	Additive to adjust sealer 1. and 2. ph (5.0–6.0)	Acetic acid	64-19-7	H3	H2	H3	Level 1
		Sodium hydroxide	1310-73-2	H3	H3	H3	Level 3

(Data source: ECHA Reg., CLP annex VI entry available). Chemicals that pass all safety criteria (level 3) are shown in green, intermediate in orange (level 1) and chemicals that do not pass safety criteria (level 0) in red. The least harmful (H3) are shown in yellow, intermediate shown in orange and the most harmful (H1) are shown in red.

Table A7. Process steps and hazards identified for Use Cases 2 and 3.

Method	Chemical	CAS No.	Human Hazards	Environmental Hazards	Physical Hazards	Level
Alkaline detergent	Ecoclean GT-12	29057	H3	H3	H3	Level 3

(Data source: ECHA Reg., CLP annex VI entry available). Chemicals that pass all safety criteria (level 3) are shown in green. The least harmful (H3) are shown in yellow.

Table A8. Process steps and hazards identified for Use Cases 4 and 5.

Method	Chemical	CAS No.	Human Hazards	Environmental Hazards	Physical Hazards	Level
Ultrasonic bath cleaning	Potassium hydroxide	1310-58-3	H3	H3	H3	Level 3
	Sodium hydroxide	1310-73-2	H3	H3	H3	Level 3

(Data source: ECHA Reg., CLP annex VI entry available). Chemicals that pass all safety criteria (level 3) are shown in green. The least harmful (H3) are shown in yellow.

- Social and Gender Dimensions Output Tables

Table A9. Gender-sensitive outcomes across the five use cases.

Upstream and Extraction Stages	Processing and Manufacturing
Women involved in artisanal and small-scale mining (ASM), often working alongside children in hazardous tasks, like bagging and sorting minerals, face unsafe environments, wage disparities, and perpetuated poverty than the men [4,49]. Broader social impacts affect women disproportionately, including resource scarcity, land dispossession, and insecure, low-wage employment with poor legal protections, especially for indigenous communities affected by forced resettlement due to mining [5,50]. Women and girls often bear the burden of water collection, especially where industrial activities deplete or pollute sources, increasing time demands and exposure to harassment risks, which reduce opportunities for education and personal development [6].	A significant share of materials in use cases are processed in China, where both genders experience high exposure to hazardous chemicals with limited access to personal protective equipment (PPE) [5,19] In most cases, the women constitute a large part of the factory workforce. Women workers, particularly migrants, often face longer hours, precarious job security and limited access to well-fitting women's PPEs than men. Social vulnerabilities, such as wage gaps, limited training and promotion opportunities, childcare deficiencies, and sexual harassment are further compounded risks for women in these settings [5,19].
Metal-allergy risks (use phase)	**Chemical exposure risks (Production and post-production)**
Women show a notably higher prevalence of contact allergies to metals—especially nickel, cobalt, and chromium—with prevalence estimates between 17–22% for nickel allergy in women versus 3–5% in men. [51,52]. Allergic reactions can arise during material handling and manufacturing stages due to repeated occupational exposure, causing dermatitis and other allergic responses [52]. For medical devices, like knee implants using cobalt-chromium alloys, women's higher hypersensitivity rates contribute to clinically relevant local or systemic reactions, potentially impacting implant success [52].	Occupational exposure to process chemicals (e.g., solvents, acids, and anodising baths) in manufacturing and finishing stages poses health risks. Both men and women may have increased sensitivity due to biological factors and higher cumulative exposure from both workplace and daily life activities (e.g., household chemical use) [5,19].

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