UNIVERSITY OF TWENTE

Bachelor Thesis

# Assessing Sustainable Metal Alternatives: A Feasibility Study for NTS Hengelo

L. M. Osorio Loyola

Department of Industrial Engineering and Management

First Supervisor: Patricia Rogetzer

Second Supervisor: Marcos Machado

Company Supervisor: Bram Verhaagen

# COLOPHON

## Assessing Sustainable Metal Alternatives: A Feasibility Study for NTS Hengelo

**University of Twente**

BSc Industrial Engineering & Management
P.O. Box 217 7500 AE Enschede Tel. 0534
89 91 11

Department of Industrial Engineering and Management
Faculty of Behavioural, Management and Social Sciences

**NTS Hengelo**

Opaalstraat 31
7554 TS Hengelo
Nederland
+31 (0)88 66 76 500



| | |
|---|---|
| Author: | Lia M.O. Loyola |
| First supervisor: | Patricia Rogetzer |
| Second supervisor: | Marcos Machado |
| Company supervisor: | Bram Verhaagen |
| Publication date: | 27/06/2025 |
| Number of pages (only chapters): | 41 |
| Total number of pages: | 61 |
| Number of appendices: | 4 |

# PREFACE

Dear Reader,

This thesis, titled "Sustainable Metal Substitution at NTS Hengelo," completes my Bachelor of Industrial Engineering & Management at the University of Twente. The project explores how NTS Hengelo, a precision manufacturing company, can transition to more sustainable metals by substituting at least 4% of its present usage through a structured decision-making approach. The project applies analytical tools to real-world industrial difficulties and reflects my interest in data, sustainability, and strategy.

Throughout this thesis, I have received both technical knowledge and professional insight into the complex nature of industrial decision-making. The project helped me improve my data analysis skills, grasp sustainable principles, and communicate effectively in academic and corporate settings.

I would want to express my deepest gratitude to my first supervisor, Patricia Rogetzer , for her guidance, critical feedback, and valuable academic viewpoint. Your assistance helped to transform this thesis from an analytical exercise to a significant contribution to the subject of sustainable procurement. I would also like to recognize my second supervisor, Marcos Machado, whose feedback helped reinforce the methodology and enhance the model and dashboard validation processes.

I am grateful to NTS Hengelo for the opportunity to collaborate on a relevant and significant industrial topic. Special thanks to Bram Verhaagen, who contributed important data and practical context, as well as to the entire team for their openness and time throughout this project.

Finally, I would like to thank my family and friends for their encouragement and support during this academic adventure. Their faith in me helped me keep focused even in times of uncertainty or exhaustion. With their assistance, I am proud to close this chapter and move to the next one.

Lia
June 2025

## MANAGEMENT SUMMARY

NTS Hengelo is a high-precision manufacturing company that works in the semiconductor and analytical sectors, it is under increased pressure from clients and regulators to improve its sustainability performance. A significant part of the company's environmental impact is due to its use of traditional metals such as aluminium and stainless steel, which are one of the main inputs for unsustainable behaviour in the company’s process.

A strategy for NTS to address this problem is replacing at least 4% of its total metal use with a more sustainable alternative while keeping technical compatibility, cost-effectiveness, and supplier reliability. However, they currently lack an approach for evaluating these materials. To assess the problem, this thesis has created a tailored Analytic Hierarchy Process (AHP) model that helps the company with better decision making, specially multi-criteria material substitution decision-making.

The methodology looks at six sustainable metal alternatives, three recycled aluminium grades, green steel, and two secondary stainless steels, using 12 sub-criteria arranged into three main dimensions: environmental, financial, and supplier. Each sub-criterion was measured using quantitative indicators such as carbon footprint, embodied energy, recycled content, material cost, scrap value, lead time, and certification traceability. These were normalized and weighted with data from Granta EduPack, supplier reports, and EU sustainability guidelines before being integrated into the AHP model.

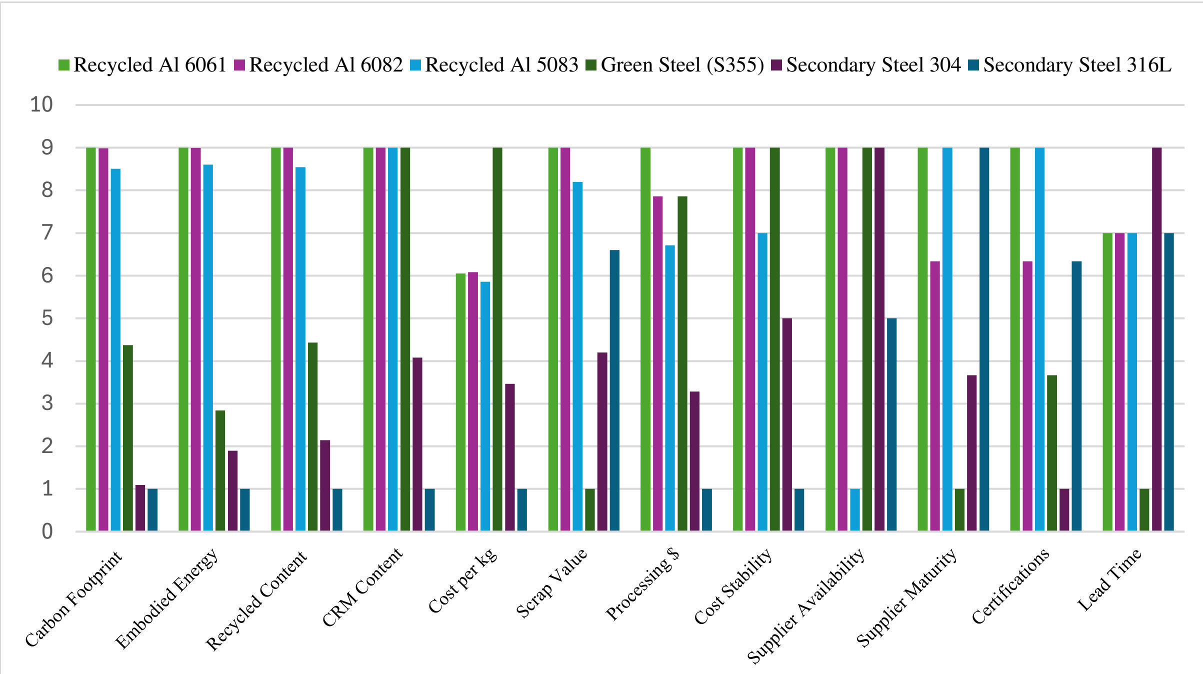



*Figure 1: Rankings per sub-criterion*

The findings, as seen in Figure 1, showed that recycled aluminium grades performed the best in most categories, particularly carbon footprint, embodied energy, and supplier maturity. On one hand, while recycled aluminium 6061 received the best overall score, from Figure 2 we can see that it accounts only 2% of NTS' total metal usage, restricting its strategic relevance. On the other hand, recycled aluminium 6082, which performs almost as well and accounts for 40% of current volume, was chosen as the most viable

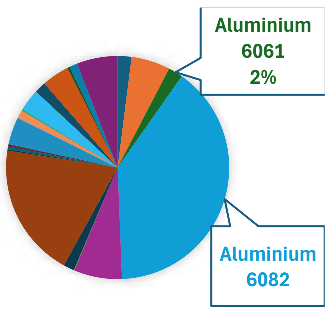



*Figure 2: Metal volume*

choice to achieve the 4% sustainable substitute requirement. Green steel has significant environmental potential, but is now limited by lead time and supply maturity, making it a viable choice for future phased implementation. Secondary stainless steel, while it is strong in supplier criteria, presented a lower environmental impact because of their high CRM content and embodied energy.

To improve future use, a dynamic and interactive Excel dashboard was created. The model enables NTS to visualize scores across multiple scenarios and tailor the decision-making process by modifying weight situations in real time. This ability allows for rapid sensitivity testing and transparent, flexible evaluation in response to changing procurement needs.

Based on these data, the thesis suggests that recycled aluminium 6082 be prioritized in the short term, while supplier engagement and green steel adoption potential are reviewed. In parallel, the company is recommended to strengthen connections with suppliers that provide certified recycled content and credible documentation (EPDs, ISO 14001), as well as to continue collecting internal cost and performance data to enhance future evaluations. Overall, this AHP-based framework provides a realistic, transparent, and adaptive instrument to help NTS Hengelo make sustainable procurement decisions.

## CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

## TABLE OF ABBREVIATIONS

*Table 1: List of Abbreviations*

| Abbreviation | Definition |
|---|---|
| AHP | Analytic Hierarchy Process |
| CRM | Critical Raw Materials |
| $CO_2$ | Carbon Dioxide |
| EU | European Union |
| EAF | Electric Arc Furnace |
| EPD | Environmental Product Declaration |
| ESG | Environmental, Social, and Governance |
| GHG | Greenhouse Gas |
| GRI | Global Reporting Initiative |
| $H_2$-DR | Hydrogen-based Direct Reduction |
| ISO | International Organization for Standardization |

| | |
|---|---|
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| MJ | Megajoule |
| MCDA | Multi-Criteria Decision Analysis |
| MADM | Multi-Attribute Decision Making |
| MODM | Multi-Objective Decision Making |
| RI | Random Index (in AHP) |
| CI | Consistency Index (in AHP) |
| CR | Consistency Ratio (in AHP) |
| CSRD | Corporate Sustainability Reporting Directive (EU) |
| CBAM | Carbon Border Adjustment Mechanism |
| CBA | Cost Benefit Analysis |
| ETS | Emissions Trading System |
| TRL | Technology Readiness Level |
| UNEP | United Nations Environment Programme |
| kg $CO_2e$/kg | Kilograms of carbon dioxide equivalent per kilogram of material |
| €/kg | Euros per kilogram |
| LME | London Metal Exchange |
| TCO | Total Cost of Ownership |
| HYBRIT | Hydrogen Breakthrough Ironmaking Technology |
| EP | EduPack (Granta EduPack material database) |
| S355 | Structural Steel Grade 52 / S355 equivalent |
| Al | Aluminium |
| AISI | American Iron and Steel Institute |

# Chapter 1: Introduction

## 1.1 COMPANY BACKGROUND AND MOTIVATION

NTS Hengelo specializes in ultra precise manufacturing and complicated mechatronic assemblies with accuracies of up to 1µm (micrometre). The company serves the semiconductor and analytical sectors with extensive in house capabilities such as design support, precision machining, heat treatment, and clean assembly. The company uses a wide range of metals for production and assembly. Among these metals we can find iron, aluminium, stainless steel, invar, titanium, among others (for details see Appendix 1) (NTS Hengelo: Ultra-Precision, 2022). Although this metals are applicable in terms of strength, corrosion resistance, electrical conductivity and other technical properties, their processing tends to be very energy intensive creating high Carbon Dioxide $CO_2$ emissions (von Gleich, 2006). As sustainability is becoming a critical component, and companies are now expected to decrease their carbon footprint, increase resource efficiency, and adopt circular economy principles, NTS is now looking at a sustainable focus future, with clear goals and objectives to be met. One of this goals is to make the production process more environmentally friendly by looking at sustainable metal alternatives to the ones mentioned before, to reach a supply chain stability and competitiveness in today's high tech manufacturing sector.

Adopted by the European Commission, the European Green Deal lays out ambitious goals such as achieving climate neutrality by 2050 and reducing net greenhouse gas emissions (GHG) by at least 55% by 2030 (European Commission, 2025). This regulatory framework emphasizes the adoption of sustainable materials and processes across European industries. As a provider of high precision metal components, NTS Hengelo is coming under increasing pressure from customers, authorities, and sustainability groups, to use sustainable production techniques and materials to not fall behind in the sustainable market.

## 1.2 PROBLEM IDENTIFICATION

NTS Hengelo focuses in ultra precise manufacturing for the semiconductor and analytical industries, applying high performance metals including stainless steels, titanium alloys, aluminium alloys, and nickel-based superalloys. These metals are used due to their mechanical, thermal, and electrical properties, they ensure precision and reliability in production. Although good for production, major issues arise from these. Most, if not all of the metals used at NTS are unsustainable and their extraction is energy intensive, leading to high $CO_2$ emissions (Herman *et al.*, 2017).

NTS biggest customer, Costumer X, is pushing sustainability into the company, forcing them to attain certain goals for 2030 within scopes 1, 2 and 3, **scope 1:** direct emissions from company owned operations, **scope 2:** indirect emissions from purchased energy, and **scope 3:** all other indirect emissions along the value chain, including raw material sourcing (See Appendix 1, Figure 19). Among these goals is to attain sustainability in the entire production system. The company knows that a big part of the $CO_2$ emissions, and unsustainable practices come from the metals supplied. Most manufacturing companies use conventional metals, resulting in a high global demand (European Commission, 2025). The European Commission (2025) forecasts tighter supply chains and market volatility for these metals within 3 to 5 years, particularly due to geopolitical dependencies. In addition to vital metals such as nickel and cobalt, popular metals like aluminium and steel also provide sustainability concerns for NTS. Although not geographically scarce the usual production processes for both materials are extremely carbon-intensive, adding to global emissions (Jacquemin et al., 2012; Allwood et al., 2011; von Gleich, 2006). The implementation of European Union (EU) legislation such as the Carbon Border Adjustment Mechanism (CBAM) and the Emissions Trading System (ETS) is increasing, and high dependence on these materials create a danger of increased costs and trade limitations (European Commission, 2025).

Looking at this, the biggest problems for NTS are, initially, unstable access and increased metal costs may make difficult the purchasing and manufacturing planning, risking operational efficiency. Secondly, continuous utilization of such materials compromises client relationships, particularly with sustainability focused partners such as Client X, and may lead to violations with future European sustainability regulations. The anticipated policy tightening by 2025–2030, along with market indicators suggesting potential price rises and shortages if global demand remains at present levels, makes this transition necessary (Allwood et al., 2011; European Commission, 2025).

Lack of implementation on these measures could limit NTS to out of date, risk supply chains, raising financial and reputational vulnerability, and compromising its sustainability objectives for the future.
Considering these problems and demands from customers and policymakers, NTS must identify sustainable metal alternatives that keep technical criteria while improving the overall sustainability of the process.

**CORE PROBLEM STATEMENT**

The production process of NTS Hengelo mostly depends on virgin metals that are not only resource intensive but also greatly contribute to $CO_2$ (carbon dioxide) emissions because of their energy intensive extraction and processing techniques. Many of these elements also include critical raw materials such Nickel (Ni), Cobalt (Co), Niobium (Nb), Molybdenum (Mo), and Vanadium (V), which are linked with supply threats, environmental degradation, and market instability (European Commission, 2025). The company does not use a structured approach to assess or set up sustainable metal alternatives, which leads to high carbon intensity and insufficient alignment with circular and low carbon economy goals. This distinction creates a quantifiable gap between the existing virgin metal dependence (reality) and the intended increase in the usage of more 'sustainable metals' into production (norm).

- Current Situation (reality): The company's dependence on virgin metals leads to significant reliance on suppliers and materials that are energy intensive and produce high $CO_2$ emissions.

- Sustainability Goal (norm): A minimum of 4% of the entire metal volume utilized in NTS Hengelo's production is substituted with more sustainable metal alternatives. These alternatives must be comparable or satisfactory regarding mechanical, environmental, and cost-related requirements.

This percentage is obtained by conforming to long-term EU climate objectives and standards established by major industry leaders such as Customer X. The EU Green Deal targets complete $CO_2$ neutrality and circularity by 2050, implying a 4% annual growth over the next 25 years, given that the current baseline is around 0% (100% ÷ 25 years = 4%). This gradual strategy helps NTS to shift slowly while preserving technical performance and operational viability, by assessing different material or alloy modifications that satisfy current production standards.

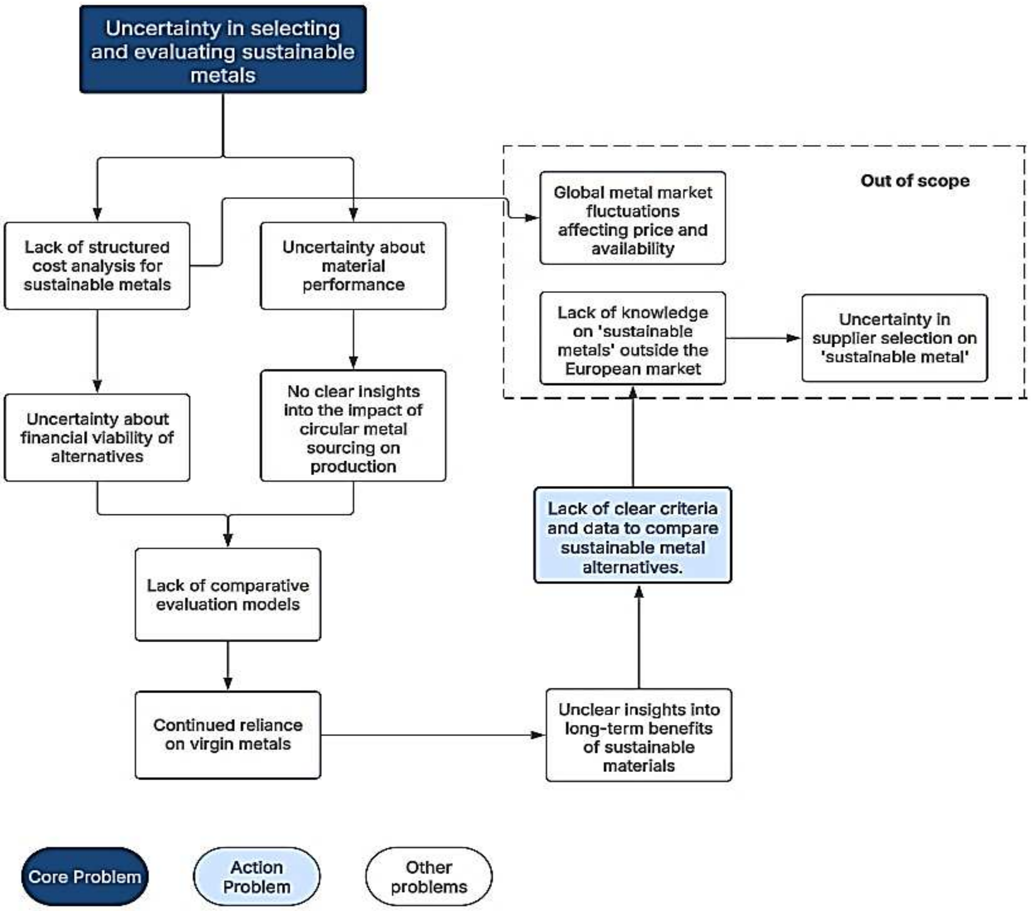



*Figure 3: Problem Cluster*

The pressure from Client X, the market and policy makers into NTS Hengelo is critical to transition towards more sustainable metals in production. This transition is made harder by insufficient clarity about the evaluation and effective adoption of these alternatives, ass seen in Figure 3. The uncertainty on this evaluation is related to multiple factors that together connect, leading to a core problem. This central problem is mainly caused by an interaction of financial, technical, and data uncertainty. From Figure 3 we can view these interactions. Starting from the top left, the company lacks a systematic cost study for sustainable metals, raising concerns regarding the economic feasibility of metal alternatives. Looking at the top right, there is little knowledge of the performance of these metals in high precision manufacturing environments and the potential effects of circular sourcing on production quality. These uncertainties prevent the company's ability to create and evaluate effective comparison models for comparing metal alternatives, thus still keeping a reliance on traditional virgin metals. The issue becomes bigger by an overall deficiency, leading to the man action problem characterized by the absence of clear requirements and solid data for evaluating alternatives in terms of sustainability, performance, and cost. The lack of a standard evaluation system complicates the justification for adopting new materials, particularly when the long-term benefits are uncertain. While external issues like market fluctuations and supplier dynamics are recognized, they are beyond the immediate scope of the investigation. Together, these internal challenges generate a decision-making environment in which sustainable solutions can be difficult to evaluate. In view of these obstacles, the core problem can be articulated as follows: **NTS Hengelo faces uncertainty in selecting and evaluating sustainable metals.**

## 1.2 RESEARCH APPROACH

Before going into the methodological structure employed in this study, it is essential to describe the strategy chosen to solve the topic at hand. Given the multidimensional nature of sustainable metal selection, this work combines conceptual and empirical approaches to achieve reliable and context-sensitive results. The next section describes the methodological framework that guided the research design and implementation.

### 1.3.1 METHODOLOGICAL FRAMEWORK OVERVIEW

This thesis follows a structured problem solving approach to systematically evaluate and select sustainable metal alternatives for NTS Hengelo. Due to the complexities of the research on material selection, and the combination of applied and fundamental research, the study combines the Research Process (Heerkens, van Winden, & Tjooitink, 2017) with Multi-Criteria Decision Analysis (MCDA) focusing on the Analytical Hierarchy Process (AHP) (Saaty, 1987). The decision to chose this type of MCDA is further explained in Section 1.5. The Research Process offers an organized research phase, as mentioned by Heerkens, van Winden, & Tjooitink 2017,facilitating an extensive literature evaluation, problem identification, and data collection regarding alternative metals. Subsequently, AHP as stated by Saaty (1987), is employed in the operationalisation, facilitating a quantitative assessment of metal options based on technical feasibility, financial viability, supplier evaluation and environmental sustainability.

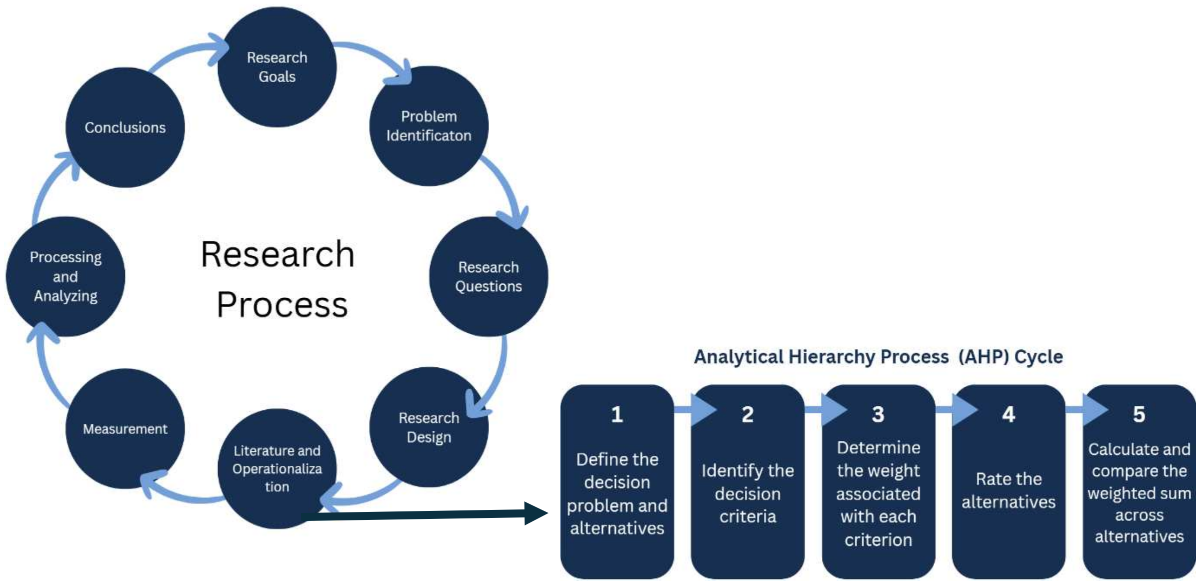



*Figure 4: Methodology Cycle*

The diagram above (Figure 4) shows the mixed application of the Research Process (Heerkens, van Winden, & Tjooitink, 2017) and the AHP (Saaty, 1987), which simultaneously form the methodological framework of this thesis. The research method starts with the formulation of the **research objective**, which discusses the reason for the study and defines the knowledge gap that needs to be addressed to tackle the practical problem of selecting sustainable metal alternatives. This is followed by **problem identification**, when the fundamental and operational problems are converted into a structured knowledge problem. Upon defining the problem, it is broken into distinct **research questions** that direct the research. The questions are used to develop the **research design**, specifying the data sources, methodological approach, and strategy for addressing each topic. The **operationalization** process guarantees that abstract variables like "sustainability" or "performance" are converted into quantifiable measures. These indicators are then employed in **measurement**, where data is gathered and evaluated for reliability and validity. This is followed by the **processing and analysis of data** to derive significant insights, that eventually contribute to the **conclusions** that address the initial research questions and help with decision-making (Heerkens, van Winden, & Tjooitink, 2017).

The AHP cycle functions as a decision support instrument that assesses the available options. The initial step involves **defining the decision problem** and listing options, so establishing the objective, specifically, the identification of viable sustainable metals. The subsequent stage involves **identifying key decision criteria**, including mechanical performance, carbon footprint, cost, and recyclability. Then **weights are defined** so criteria are then prioritized based on their significance through pairwise comparisons. After weighting, the **alternatives are rated**, so the various metal options are assessed according to each criterion, and the results are brought together in the last stage, where **weighted scores are computed and compared** to establish a ranked list of alternatives (Saaty, 1987).

The combination of both cycles guarantees that the problem is tackled with precise analysis and systematic decision-making, providing a transparent, evidence based methodology for material selection at NTS Hengelo.

### 1.3.2 PROBLEM SOLVING APPROACH

This thesis uses a methodical, step-by-step problem-solving strategy shown in the Research Process and Analytical Hierarchy Process (AHP), asnmentioned in the previous section, to guarantee a logical and ordered path toward solving the primary challenge at NTS Hengelo. Every chapter of this thesis corresponds to particular phases of these frameworks, therefore taking the reader from problem definition through to the formulation of practical recommendations.

Developing precise and structured research questions is crucial for directing the research towards a methodical and data driven problem solving methodology (Heerkens, van Winden, & Tjooitink, 2017). The following summary describes how every chapter helps to fulfill the research goal align with the primary knowledge question, and each chapter containing sub-questions that help in the answering of this.

The primary research question motivating this study is:

***How can NTS Hengelo identify and select the most suitable sustainable metal alternative to replace at least 4% of its current metal usage to a more sustainable version ?***

To methodically address this question, numerous sub questions are developed, each aligned with a phase/phases of the methodology cycle (Figure 4):

**Chapter 1**
***KQ1) What is the main problem with the integration of sustainability at NTS's production system?***
This question follows the first four steps of the Research Process, outlining the goal, problem setting, research objectives, and research questions.

Intended deliverables: A defined research goal, core problem and action problem, a series of organized research questions, research design and a clear scope and limitation of the study.

**Chapter2**

***KQ2) Which sustainable metal alternatives, currently available and commercially used, are applicable to high-precision manufacturing?***

***KQ2.2) How can supplier, financial, and environmental criteria for evaluating sustainable metal alternatives be defined for application in high-precision manufacturing?***

This questions are addressed with in depth literature review, concentrating on the investigation of sustainable metal alternatives. This chapter focuses on steps 5 of the Research Process (Literature Review and Operationalization) , and steps 1 and 2 of the AHP analysis (Define Alternatives and Define the Criteria). The literature review and operationalize step integrates the results of the research on sustainable metals and defines and reviews this alternatives in Step 1 of the AHP. Step 2 of the AHP is then performed where criteria for the evaluation are assessed.

Intended deliverables: A list of applicable sustainable metal alternatives accessible in the market, along with a systematic framework of quantifiable evaluation criteria (supplier, economical, and environmental), prepared for incorporation into the AHP model.

**Chapter 3**

***Q3) How can the AHP hierarchy be structured to compare the evaluation criteria to support the selection of the most suitable sustainable metal alternatives?***

This question examines the methodology for establishing AHP weightings, utilizing the criteria from the results of the previous chapter to translate AHP into a research output. Chapter 3 follows Step 6 of the Research Process (Measurements) and Steps 3, 4 and 5 of the AHP (Defining the weights, Rate the alternatives and Compare the weighted sum of alternatives).

Intended deliverables: A comprehensive AHP hierarchy framework, steps to perform the AHP with formulas and guidelines to do so. The operationalization and measurement of the criteria for the integration to the framework.

**Chapter 4**

***Q4) What is the most effective way to present the AHP results to facilitate interpretation and implementation?***

***Q4.2) How strong are the AHP based rankings of sustainable metal alternatives under different decision-making scenarios and company priorities?***

This questions concentrate on the evaluation of the results and the presentation of these, making it easy for the company to evaluate and implement them. This chapter discusses Step 7 of the Research Process (Processing and Analysing), it assesses the results based on the steps of the previous chapter.

Intended deliverables: A visual and textual presentation format (weighted score tables, graphs, dashboards) of the results designed for managers at NTS Hengelo. And a sensitivity analysis or scenario testing of the AHP rankings.

**Chapter 5**

***Q5) What are the key trade-offs between the top-ranked sustainable metal alternatives and the currently used metals at the company in terms of performance, cost, and sustainability?***

This section focusses on the last step of the Research Process (Conclusions) where recommendations and conclusions from the research are presented in a trade-off based on the results from the AHP analysis.

Intended deliverables: A comparative trade-off analysis of new versus current materials, and strategic recommendations for the integration of sustainable metals into NTS Hengelo's production, ensuring minimal impact on performance and cost.

## 1.4 RESEARCH DESIGN

This study employs both applied and fundamental research methodologies. This research is applied in the way that it aims to address a specific, real world issue at NTS Hengelo: identifying sustainable metal alternatives to integrate into production ensuring sustainable and economical viability. Simultaneously, it is fundamental, as it formulates and implements a comprehensive multi criteria decision making framework (AHP), based on theoretical constructs like Sustainability, Engineering Design, and Cost-Benefit Analysis. This research enhances academic understanding by a literature review, the operationalization of essential criteria, and the organization of choice criteria, thus having knowledge in sustainable material selection and industrial decision-making frameworks.

This research uses both qualitative and quantitative methods, but the quantitative component is more prominent in the research. Early in the project, the literature review, formulation and operationalization of evaluation criteria, and contextual analysis of sustainability integration problems at NTS Hengelo highlight the qualitative component. Qualitative research uses flexible, context-dependent analysis to comprehend complex, real-world events (Mehrad & Zangeneh, 2019). This thesis relies on the AHP, which uses systematic, quantitative comparisons and statistical weighting of many criteria. Quantitative research emphasizes objectivity, numerical data, and logical reasoning using frameworks (Mehrad & Zangeneh, 2019). Thus, while qualitative insights back the research, quantitative AHP analysis of sustainable metal alternatives leads the approach.

### 1.4.1 DATA GATHERING AND PROCESSING

This research utilizes a mixed methods strategy for data collection and process, integrating both qualitative and quantitative methods to facilitate an organized and evidence based decision-making process. Data was gathered from several and different sources in order to make sure the information is relevant and academically appropriate. Qualitative data were obtained via company interviews, internal documents, and academic papers, which made easy the identification of the research problem, integration of the sustainability problems at NTS Hengelo, and formulation of the evaluation methods. The quantitative component used technical and environmental data on sustainable metal alternatives obtained from Granta EduPack, LCA databases, and supplier datasheets, producing standardized and consistent information. The AHP model was constructed and evaluated using Excel with expert input from NTS stakeholders through systematic pairwise comparisons to figure out the relative weights of each criterion. The data processing covered qualitative content analysis for theme aggregation, comparison and indicator-based scoring for quantitative evaluations, and scenario modelling to assess the reliability of the AHP outcomes. Also, data visualization techniques were utilized to transform findings into coherent and practical conclusions, customized for management understanding. The combination of tools and methodologies facilitated an organized development from exploratory research to practical suggestions.

For a summarized overview of the research design and data gathering see Appendix 2, Table 18.

Principal subjects impacting or contributing to the research encompass:

- NTS Hengelo Engineering and Procurement Teams: in charge for material selection and sourcing.

- Sustainability and Quality Manager: responsible for evaluating commitment and alignment to EU directives and environmental goals.
- External stakeholders, Client X, the primary customer: advocating for sustainability implementations throughout the whole supply chain.
- Industry databases and literature sources: utilized to assess technical, environmental, and cost performance metrics for metals.

### 1.4.2 OPERATIONALIZATION OF KEY VARIABLES

The study evaluates and contrasts the performance of sustainable metals by identifying essential characteristics in three areas: environmental, supplier availability and economical. These are integrated into the AHP architecture.

Main group of variables:

- Lifecycle Carbon Footprint (kg $CO_2$/kg): Assesses the environmental impact derived from emissions during extraction, production, and recycling processes. Data is obtained from Life Cycle Assessment (LCA) databases and Granta EduPack (Jacquemin et al., 2012; EU CRM reports; Granta EduPack, 2023).
- Costs and market prices: Raw material market costs (EUR/kg) obtained from market analysis and reports.
- Supplier Availability: Available suppliers for 'sustainable metal alternatives' obtained from market research.

Each variable is operationalized ( recycling efficiency %, market €/kg) and is aligned with requirements in the AHP model. Refer **Error! Reference source not found.**, for a comprehensive enumeration of variables and their operational definitions.

*Table 2: Operationalization of Key Variables*

| Variable | Definition | Operationalization | Source |
|---|---|---|---|
| Carbon Footprint | Total $CO_2$-equivalent emissions during material production | kg $CO_2$-eq per kg of material | Granta EduPack (2023) |
| Embodied Energy | Total energy required to produce 1 kg of material | MJ/kg | Granta EduPack (2023) |
| Recycled Content | Proportion of material derived from recycled sources | % of recycled input material | Outokumpu, 2025; European Aluminium, 2025; Hybrit, 2025; Responsiblesteel, 2025 |
| Critical Raw Materials | Share of material composed of EU-designated critical raw materials | Binary or weighted scale (CRM presence/absence) | European Commission CRM list, Granta EduPack (2025) |
| Material Cost | Price of raw material per unit weight | Euro per kg | Muslemani et al., 2021; Lopez et al., 2023 and industrial studies McKinsey, 2025; HYBRIT, 2025, |
| Scrap Value | Value recovered per kg after end-of-life processing | Euro per kg | ScrapPrices, 2025; ScrapMonster, 2025; Scrap Metal Price Index: Netherlands - Metaloop, 2025 |
| Processing Cost | Additional cost of manufacturing or machining per unit | Euro per kg | Granta EduPack, 2023, Raabe 2023 |
| Cost Stability | Volatility or fluctuation of material cost over time | Indexed score based on historical price variability | HKEX Company, 2025, Bloomberg, 2025, Matmatch, 2025, EU CRM supply risk indexes |
| Supplier Availability | Availability and abundance of the material from suppliers | Technology Readiness Level (TRL) or qualitative 1–5 scale | Supplier interviews, industry sources |

| | | | |
|---|---|---|---|
| Supplier Maturity | Technological maturity of suppliers working with the material | Technology Readiness Level (TRL) or qualitative 1–5 scale | Supplier documentation |
| Certifications | Degree to which the material and supplier meet quality or sustainability standards | Number or presence of certifications (e.g., ISO, Cradle2Cradle) | Supplier documentation |
| Lead Time | Time required to receive material from order to delivery | Days or qualitative scale (Low, Medium, High) | Supplier data, logistics estimates |
| Total Environmental Score | Aggregate performance across environmental criteria | Weighted AHP score based on normalized environmental indicators | Model (based on AHP) |
| Total Financial Score | Aggregate performance across cost-related criteria | Weighted AHP score from cost-based sub criteria | Model (based on AHP) |
| Total Supplier Score | Aggregate supplier-related performance | Weighted AHP score from supplier-related sub criteria | Model (based on AHP) |
| Final AHP Score | Overall ranking score of material alternative | Sum of weighted Environmental, Financial, and Supplier scores based on chosen scenario | AHP model and sensitivity analysis |

## 1.5 THEORETICAL FRAMEWORK

This section establishes the methodologies behind this research, explaining the theoretical foundations of multi criteria decision making, focusing on the Analytical Hierarchy Process (AHP), employed to prioritize material alternatives, focusing on criteria like sustainability, costs and supplier feasibilities.

### 1.5.1 MULTI CRITERIA DECISION MAKING (MCDM) & AHP

More trade-offs exist around material selection for production, which need to be taken into account specially when sustainability is being considered. This thesis utilizes a systematic decision making framework grounded in Multi Criteria Decision Making (MCDM). This approach, as articulated by Taherdoost and Madanchian (2023), provides a systematic framework for evaluating alternatives when decisions require a consideration of technical effectiveness, environmental impact, and financial assessment. This frameworks enable a combination of quantitative and qualitative inputs and are widely used in industrial and sustainability related decision making contexts.

This research concentrates on one of the MCDM methods, the Analytic Hierarchy Process (AHP), a systematic methodology developed by Saaty (1987). AHP enhances decision making by breaking down complex scenarios into a structured hierarchy of goals, criteria, and alternatives. It enables the integration of expert assessment and empirical data through paired comparisons, while providing a consistency verification to ensure logical coherence. The method is particularly suitable for this study since it enables the integration of technical, environmental, othet factors within a clear and adaptable decision making framework (Saaty, 1987; Taherdoost and Madanchian, 2023).

### 1.5.2 SUSTAINABILITY AND CIRCULARITY

Sustainability mentions the need to balance present actions with the future generation needs which provides the theoretical basis for environmental frameworks (Velenturf and Purnell, 2021).

The circular economy ensures the promotion to reduced material extraction, increased reuse and recyclability, and a systemic approach to waste reduction and resource efficiency (Velenturf & Purnell, 2021). However, circularity alone does not guarantee sustainability, environmental impacts must be equally assessed. Consequently, this research uses Life Cycle Assessment (LCA) methodologies to evaluate the environmental performance of metals. This thesis does not conduct new LCA but rather compares materials based on carbon footprint, recyclability, and critical raw material (CRM) content utilizing data from previous LCA studies (Jacquemin et al., 2012). These environmental indicators are incorporated into the AHP model under the "Environmental Feasibility" criteria.

### 1.5.3 MATERIAL DESIGN

For the part of technical feasibility, engineering theory is used to assess the viability of metal substitutes, particularly with relation to material choice techniques established by Holloway (1998). By means of material criteria such as strength to weight ratio, these models link material properties to performance objectives so facilitating optimal selection under design constraints. This study applies these ideas by assessing materials depending on mechanical strength, corrosion resistance, machinability, and availability. These criteria form the filtering stage of the material selection, therefore facilitating the further comparison of material performance.

### 1.5.4 COST BENEFIT ANALYSIS (CBA)

The financial viability of metal alternatives is assessed using concepts derived from the CBA. As Mishan and Quah (2021) mention, CBA is an economic tool used to evaluate if the advantages of a decision exceed their negative consequences. Particularly in terms of market price, processing expenses, supply issues, and waste effects, cost analysis ensures that, technically and environmentally suitable materials are also financially feasible in material choice.

This thesis combines parameters like material price per kilogram, production cost, price stability, and scrap value, to add cost analysis into the AHP model. These criteria then ensure that the selected metal replacements balance operational efficiency with financial sustainability.

## 1.6 VALIDITY AND RELIABILITY

According to Thanasegaran, (2009), a methodology's reliability is its capacity to produce consistent outcomes across different contexts. In other words, a method is reliable if it consistently generates the same results under equal situations. This research takes into account reliability by using methodologies that are reproducible in various contexts. The Analytic Hierarchy Process (AHP) offers a consistent decision-making paradigm including an integrated consistency ratio, Chapter 3, section 3.2.3, to support the rationale of expert judgments (Saaty, 1987). In this research, all estimated CR values were less than the recommended 0.1 limit, indicating internal consistency (Appendix 3 Table 32). Moreover, used to ensure traceability and input integrity, are normalized secondary data obtained from current Life Cycle Assessments and market cost databases (Section 3.3).

Validity determines the degree to which a technique correctly finds the underlying cause of an issue (Thanasegaran, 2009). To account for validity, the research focuses on known concepts like it is sustainability, engineering design, circular economy, and cost benefit analysis. The AHP criteria follows company demands in the real world, therefore improving construct and content validity. Also, a sensitivity analysis was performed to assess the robustness of the results under different stakeholder priorities. Different weighting situations demonstrated how different rankings varied, putting the model's reliability and validity to the test. The company provided final weightings for real-world validation, confirming consistency between model recommendations and internal decision logic

(Section 4.4). Overall, the combination of consistency checks, traceable data, scenario testing, and stakeholder involvement adds to high internal and external validity, making the results usable both within and outside of NTS Hengelo.

# 1.7 OUTLINE

The remainder of this thesis is organized as follows:
Chapter 2 establishes the basis for the thesis by exploring the environmental and industrial contexts that drive the need for sustainable metal substitution. It covers fundamental ideas like the circular economy, EU sustainability policies (e.g., CSRD), and environmental indicators. It also explains how key metals were chosen based on supplier information and manufacturing compatibility. The chapter then focuses on six possible alternatives, three recycled aluminium grades, green steel, and two stainless steels, and explains why they were chosen.

Chapter 3 presents the study's methodological framework. It discusses the use of Multi-Criteria Decision Analysis (MCDA), with a focus on the Analytic Hierarchy Process (AHP) as the primary approach for evaluating metal choices. The chapter outlines the step-by-step method of creating the AHP hierarchy, implementing sustainability, cost, and supplier criteria, and scoring using literature and data. It also describes how pairwise comparisons and consistency checks were used to ensure reliable decision-making.

Chapter 4 analyses the AHP evaluation results under several weighting situations (e.g., cost-driven, environment-driven). Final scores and rankings are supplied for each alternative, along with visualizations and trade-off analysis. The chapter also describes the Excel-based decision-support dashboard created throughout the research. It explains how the dashboard automatically alters rankings based on user-defined priorities, allowing for practical implementation in NTS Hengelo's procurement process. Validation findings based on stakeholder feedback are also provided.

Chapter 5 closes the thesis by summarizing the findings and directly answers the research question. It analyses the strategic implications of using specific material alternatives and provides implementation advise that is suited to NTS Hengelo's operating setting. The chapter finishes by outlining the study's limitations and making recommendations for future research, such as incorporating dynamic supplier assessments or live environmental data.

# Chapter 2: Literature Review

This chapter aims to evaluate a selection of sustainable metal alternatives that meet the performance of high precision manufacturing companies, as well as to create a systematic framework of assessment criteria for comparing these materials. This stage of the research aligns with Step 5 of the Research Process (Literature Review and Operationalization) as delineated by Heerkens, van Winden, and Tjooitink (2017), and encompasses Steps 1 and 2 of the Analytical Hierarchy Process (AHP), specifically outlining the selection alternatives as well as the decision criteria (Saaty, 1987; Saaty, 2012). It primarily discusses the second sub-questions: ***Which sustainable metal alternatives, currently available and commercially used within the market, are applicable to high-precision manufacturing? How can supplier, financial, and environmental criteria for evaluating sustainable metal alternatives be defined for application in high-precision manufacturing?***

The chapter provides two essential deliverables through a literature evaluation. 1) a compilation of commercially accessible sustainable metals appropriate for high-precision engineering applications, and 2) a collection of validated, measurable evaluation criteria classified into financial, supplier and environmental categories. The results outlined here provide the basis for the AHP framework described in Chapter 3.

## 2.1 UNDERSTANDING SUSTAINABLE METALS IN HIGH-PRECISION MANUFACTURING

Sustainable metals, are defined as metallic materials that are manufactured, utilized, and reclaimed in ways that mitigate environmental impact, save limited resources, so has a reduction on Critical Raw Materials (CRM) and guarantee accessibility for future generations (Raabe, 2023). Their sustainability is evaluated not only on availability or recyclability but through a perspective covering environmental, economic, and technical aspects, especially their life cycle impact, recyclability, and incorporation into circular flows (Raabe, 2023; von Gleich, Ayres, and Gobling-Reisemann, 2006). The production of metal covers almost 40% of industrial greenhouse gas emissions and around 10% of global energy consumption, with primary extraction generating large waste, emissions, and deposits (Raabe, 2023). Metals are almost in all cases non-degradable and several types are highly recyclable, still, their increasing demand, highlighted by industries, passes the supply of high quality post consumer scrap. As a result, the metal industry still relies significantly on primary production, which has a high environmental impact due to its fossil fuel based methods (Raabe, 2023).

There are four principal techniques to best address the sustainability of metals: reducing carbon emissions in primary production, increasing recycling and circularity, designing contaminant-tolerant alloys, and improving material efficiency through minimizing weight and avoiding or reducing CRM (Raabe et al., 2019). Sustainable metals are defined not only by their reduced harm during extraction and processing but also by their support of resource efficiency, lower Carbon Dioxide ($CO_2$), and enhanced flexibility against quality degradation through reuse and recycling. In high-precision manufacturing environments, a sustainable metal must have consistent mechanical and thermal performance, minimal quality fluctuation, and compatibility with strict tolerances and functionality (Raabe, 2023). Recycled aluminium, low-carbon stainless steels, 'green' steel, secondary steel 'green' titanium and recycled titanium are increasingly recognized as acceptable alternatives when performance compromises can be minimized (von Gleich et al., 2006).

An important factor is the degradation of material quality during recycling, mostly caused by impurity accumulation and alloy contamination. These factors make the reusability of high-value scrap materials in high-tech applications sometimes challenging. Consequently, sustainable alloy design, which incorporates recyclability and contamination tolerance from the beginning should have certifications of quality an reliability, this is essential for metals to be viewed as really sustainable across many life cycles (Raabe et al., 2019).

## 2.2 IDENTIFICATION OF SUSTAINABLE METAL ALTERNATIVES

This section lists feasible and market available metal substitutes to help on the integration of sustainable metal alternatives into high-precision manufacturing. The alternatives are chosen based on their availability in the market (based on supplier spend data), compatibility to sustainability principles (as established in the literature, see Section 2.4), and linked with the functional requirements of industrial manufacturing environment (evaluated in consultation with NTS engineers and technical specifications). The materials must satisfy specific criteria in three areas: environmental sustainability, costs, and supplier performance.

This study initially assessed internal supplier spending data to find material alternatives that enable NTS Hengelo's high-precision manufacturing with sustainable metals (see Appendix 1). This investigation found that NTS uses mostly aluminium grades 6082, 6061, and 5083, stainless steels 304 and 316L, and structural steel (S355). High consumption volumes motivated further investigation of these materials.

### 2.2.1 RECYCLED ALUMINIUM

Recycled aluminium is a significant sustainable metal alternative, principally because of its recyclability and much less harmful to the environment compared to primary aluminium. The fabrication of secondary aluminium needs approximately 5% of the energy consumed in primary production, which could reduce carbon emissions from 14.4 kg $CO_2$/kg to as low as 0.6 kilogram $CO_2$/kg of metal (Yakubov et al., 2024; Al-Alimi et al., 2024). The energy efficiency and sustainability advantages of recycled aluminium positions it as a fundamental component of sustainable metal operations in high-performance manufacturing industries.

European markets have well established infrastructures for closed-loop aluminium recycling, together with an extensive range of EN standards governing chemical composition and mechanical qualities. Standards like EN 573 and EN 515 facilitate uniformity in material performance, even with the utilization of scrap inputs (Krupka, 2016). Machining studies indicate that specific recycled aluminium alloys, despite variation, achieve surface finishes and cutting forces similar to primary alloys under controlled settings (Bruschi et al., 2024). This highlights their relevance in high-precision manufacturing, relying upon a guarantee of quality control.

### 2.2.2 ‘GREEN’ STEEL

By eliminating fossil fuels in iron reduction and steel production, green steel is produced with significantly lower greenhouse gas emissions. This is usually done via Hydrogen-based Direct Reduction (H-DR) with Electric Arc Furnaces (EAF) using renewable electricity. Green steel can produce almost zero emissions, depending on the carbon footprint of electricity and hydrogen utilized, in contrast with the traditional blast furnace-basic oxygen furnace (BF-BOF) method, which relies on coal and produces 2.25 $tCO_2$ per tonne of crude steel (tCS) (Lopez et al., 2023)

Steel manufacturing makes up for 4% of the EU's total $CO_2$ emissions, making green steel essential for obtaining the climate goals. Green steelmaking using H-DR tries to substitute coal with green hydrogen, hence "defossilizing" the production process (Muslemani et al., 2021). The Swedish HYBRIT initiative and ArcelorMittal and Thyssenkrupp investments imply a major industry shift toward low-emission technology (Lopez et al., 2023).

Green steel is impacted by the fast decline in renewable electricity and green hydrogen costs. For example, the Levelised Costs of Crude Steel (LCOCS) developed utilizing green technologies in Spain and Morocco may drop to €351–€352/tCS by 2050, making them competitive or cheaper than traditional steel even without carbon price (Lopez et al., 2023). Some policy considerations include green public procurement, carbon adjustments, and demand side incentives. Demand from environmentally conscious industries may motivate the market adoption (Muslemani et al., 2021).

### 2.2.3 SECONDARY STEEL

Secondary steel, mainly manufactured via the EAF with scrap as the main input, establish a fundamental approach to sustainable steel production. This established and widely utilized process constitutes roughly 26–32% of global steel production and is characterized by significantly reduced environmental impacts relative to primary steel production through the BF–BOF method (Suer, Traverso, & Jäger, 2022; Suer et al., 2022).

An important environmental benefit of secondary steelmaking is the high decrease in $CO_2$ emissions and energy use. For example, research on the Chilean steel industry revealed that transitioning from primary to secondary steel manufacturing resulted in a 66% decrease in global warming potential, including reductions of 60% in $CO_2$ emissions, 89% in particulate matter (PM), and 55% in sulphur dioxide ($SO_2$). In Europe and other developed areas, where recycling systems are well established, this reduction increases even more due to cleaner electrical sources and enhanced industrial efficiency (López et al., 2023).

Secondary steel production is aligned with the ideas of a circular economy. Its dependence on scrap facilitates the reutilization of steel without considerable degradation of characteristics, lowering the demand on natural resources like iron mine. Suer et al. (2022) indicate that the EAF method requires just 5.2 GJ/t of energy, in contrast to 23 GJ/t for the BF–BOF method, with $CO_2$ emissions potentially as low as 0.3 t $CO_2$/t of crude steel, dependent of the electricity supply.

## 2.3 TECHNICAL PREQUALIFICATION OF ALTERNATIVES

This study identified candidate materials for substitution using technical background checks based on engineering standards and after environmental, accessibility, and economic performance indicators. All shortlisted alternatives were compared to meet high-precision manufacturing technical performance criteria, using sources like Granta EduPack, 2023.

This screening process checked literature, standards, and supplier data to ensure that the proposed sustainable metals' mechanical properties (tensile strength, yield strength, thermal expansion, fatigue resistance, and elastic modulus) were within acceptable tolerance ranges of conventional metals. Machine experiments, for example, demonstrate that recycled aluminium 6061 can match primary

alloys in surface polish and cutting performance (Bruschi et al., 2024), while steels from chip recycling retain major grade mechanical integrity.
These materials should not need redesigns or major reconsideration. Their compliance with dimensional, structural, and functional requirements allowed them to be evaluated using sustainability, cost, and availability as the main criteria. Standard procedures in material selection stress mechanical requirements (Ashby, 2011) and strategic decisions prioritize life-cycle impact, sourcing risks, and sustainability (ISO 14040, 2006).

This research filters by technical equivalence to focus the AHP-based evaluation model on NTS Hengelo's sustainability transition's most important and differentiating variables.

## 2.4 DEFINING EVALUATION CRITERIA

This section outlines the evaluation criteria for a systematic comparison of sustainable metal alternatives, which are employed at subsequent decision-making stages. The criteria are classified into three fundamental dimensions: environmental, financial, and supplier.

### 2.4.1 ENVIRONMENTAL CRITERIA

The environmental impact is an increasing concern in the materials business, especially for climate objectives and circular economy activities. The criteria are derived from life cycle assessment (LCA) research and are frequently highlighted in eco-design literature (Pusateri et al., 2024), emphasizing the necessity of incorporating environmental factors into engineering design. The next environmental criteria are taken into account:

- **Carbon Footprint (kg $CO_2$e/kg material):** From raw material extraction to refining and manufacture, this index measures metal production greenhouse gas emissions. Metals including aluminium, nickel, and titanium have high $CO_2$ emissions during primary production due to their energy-intensive production (Nuss & Eckelman, 2014; Torrubia et al., 2023). Thus, carbon footprint is essential for evaluating alternative metals' environmental sustainability.
- **Recycled Content (%):** This shows how much secondary or post-consumer material a metal product contains. Recycling uses less energy than original extraction and processing, therefore higher recycled content is usually better for the environment. As an example, recycled aluminium is valuable for sustainability as it uses just ~5% of the energy consumed in primary production (UNEP, 2023; Graedel et al., 2011).
- **Embodied Energy:** This criterion measures the overall energy needed to create a unit of material in the supply chain, including direct and indirect energy. Embodied energy is consumed upstream in extraction, processing, transportation, and transformation. High-embodied energy materials, especially in metals and construction, cause environmental damage before usage. Low embodied energy values help meet energy efficiency and carbon reduction goals, making them crucial in sustainable material selection (Liu et al., 2012).
- **Critical Raw Material (CRM) (%):** This criterion shows how much important CRMs, like cobalt, niobium, vanadium, and rare earth elements, a metal or alloy contains. High CRM materials are limited in geological availability, posing supply problems. These elements cause geopolitical, price, and environmental stress during extraction (Graedel et al., 2015; Tercero, 2019).

### 2.4.2 FINANCIAL CRITERIA

Cost and market accessibility are also critical factors in the selecting process. An optimal manufactured material could be not feasible if its availability is unreliable or too expensive. These criteria are commonly employed in sustainability studies cantered on manufacturing (Aires & Ferreira, 2022) and assist NTS in balancing sustainability with competitiveness.
The subsequent financial criteria are incorporated:

- **Cost per Kilogram (€/kg)**: Life cycle costing (LCC) and cost-benefit analysis use this criterion to calculate raw material unit costs. Cost is often the deciding element in multi-criteria material selection frameworks, along with performance and environmental indices. Additionally, economic feasibility is vital in competitive businesses where material choices impact profitability (Ashby, 2011).
- **Scrap Value (€/kg or €/tonne):** This criterion considers the economic value recovered at the end of a product's life. Metals that can be reused or recycled, like titanium and aluminium, can be used to generate funds. Adding value to scrap is in line with the ideas behind the circular economy and is a good idea for sustainable design. (Shamsuddin, 1986).
- **Processing Cost Impact:** Even though some sustainable metals are better for the environment, they may cost more to machine, shape, or finish because of how the materials behave. This measure figures out how big of an effect these kinds of changes have. It is a useful thing for manufacturers to think about when they want to balance sustainability with running costs (Raabe, 2023).
- **Cost stability/future in the market:** Material price reliability is crucial to manufacturing and production financial stability. Manufacturers may better predict expenses and eliminate economic uncertainty with stable pricing. Thus, raw materials price stability affects industrial financial stability (Schwartz, 1998).

### 2.4.3 SUPPLIER CRITERIA

Adopting sustainable materials also depends on how easy it is to source them, how well they work with transportation, and how mature the suppliers are. Even if a material is technically viable and affordable, it can not be used if it fails to be sourced properly. The following factors about suppliers are used in this thesis:

- **Supply Chain Availability (EU Market Access)**: This indicator measures material reliability and geographic accessibility, especially for EU sourcing. Sustainable supply chain management studies emphasise local and diverse sourcing for material resilience and embedded risk reduction (Reuter et al., 2013).
- **Lead Time / Delivery Speed:** It measures how soon and reliably an item or component may be delivered following purchase. Shorter lead times allow organizations to adapt faster to demand shifts or disruptions, boosting resilience planning, responsiveness, and recovery (Chang & Lin, 2019). Thus, when assessing materials, manufacturers must consider delivery speed and supply lead time stability.
- **Supplier Maturity / Track Record:** High-maturity suppliers have defined, repeatable processes that improve delivery performance and reduce risk. However, mismatches in capability, such as a low-maturity customer working with a high-maturity supplier, can cause misunderstandings, underutilization, and project failure. Thus, harmonizing supply chain

partner maturity levels reduces financial risk and improves predictability (Kasse & Johansen, 2013).

- **Certifications and Traceability:** This refers to the supplier's ability to demonstrate compliance with standards (ISO 14001, EPDs, CE marking) and to trace recycled content or carbon footprint claims. These certifications ensure credibility and help companies align with sustainability reporting standards (UNEP, 2011).

### 2.4.4 OPERATIONALIZATION OF CRITERIA

To conduct a systematic assessment of sustainable metal alternatives, each chosen criterion must be converted into a measurable indicator. This operationalization guarantees consistency and independence in evaluation, facilitating cross-comparison among various material alternatives.

Indicators are established according to international standards, scientific literature, and engineering data sources, including Granta EduPack, ISO material standards, and life cycle assessment databases. Where relevant, values are standardized to a comparable scale to facilitate multi-criteria analysis. This operationalization of criteria is done in Section 3.3.

### 2.4.5 DATA NORMALIZATION & APPLICATION IN AHP

Due to the measurement of certain criteria on different scales ($CO_2$ emissions against €/kg or qualitative ranges), a normalizing technique is implemented before conducting the pairwise comparisons. Min-max scaling or z-score normalization are utilized for continuous variables such as cost or $CO_2$ footprint to standardize values into a consistent scoring range of 1–9. Qualitative criteria are evaluated using defined classification rubrics or industry ratings, this process is conducted in Chapter 3.

In the absence of precise values (for new green alloys), ranges derived from literature or supplier data are utilized, with relevant information. In cases of data disagreement, median values are utilized to eliminate bias.

## 2.5 SUMMARY OF CHAPTER 2

This chapter set the foundation for assessing sustainable metal alternatives in High-tech manufacturing. Through a literature research and material evaluation, Iron, Inconel, Invar, mu-metal, and nickel-based alloys utilized at NTS Hengelo were among the many viable candidates investigated and material screening process. Due to a lack of sustainable sourcing choices like certified recycled content or green production methods, these were left out from further research. Other popular materials including green aluminium, titanium alloys, and alternative steels were reviewed but left out for different reasons. While appealing, green aluminium lacks alloy-specific certification and traceability in the EU market, making it difficult to assess performance or availability. Titanium alloys were rejected due to their high cost, processing complexity, and minimal relevance to NTS's component range. Due to their lack of environmental value relative to structural steel baselines or technical accuracy and machinability criteria for NTS's operations, several alternative steels were removed.

Recycled aluminium (grades 6061, 6082, and 5083), green steel (S355 equivalent), and secondary steels (AISI 304 and 316L or Steel 52) were the six acceptable AHP alternatives after this structured screening process. These materials were chosen for their environmental potential, technical compatibility with traditional grades, and procurement ease.These results motivate Chapter 3, which builds the Analytical Hierarchy Process (AHP) model. The above information and criteria help construct the decision-making framework and evaluate sustainable alternatives.

# Chapter 3: Methodology

After identifying sustainable metal options and formulating evaluation criteria in Chapter 2, this chapter moves from exploratory research to decision model design. The purpose is to apply a structured, objective method to analyse the selected criteria, financial, supplier and environmental performance using operationalized, measurable variables.

The chapter analyses the different MSDM's to identify the best option for the study. After selecting the best option (Analytical Hierarchy Process (AHP)) it follows three key stages of the AHP methodology: 1) structuring the decision hierarchy, 2) performing pairwise comparisons to determine weights, and 3) outlining the weighted aggregation model to evaluate alternatives. These steps align with Step 6 of the Research Process and Steps 3 to 5 of the AHP.

## 3.1 JUSTIFICATION FOR AHP SELECTION WITHIN MCDM FRAMEWORKS

This study used the Analytic Hierarchy Process (AHP) from Multi-Criteria Decision Making (MCDM), a systematic method for ranking alternatives based on several criteria. MCDM approaches help sustainable material selection decisions balance qualitative and quantitative elements. MCDM is applied in supply chain management, energy, healthcare, infrastructure planning, and sustainability (Taherdoost & Madanchian, 2023).

MCDM methodologies are generally divided into two major categories: Multi-Attribute Decision Making (MADM), and Multi-Objective Decision Making (MODM). MADM is utilized when the alternatives are discrete and known, like in this study, whereas MODM is used for continuous problem spaces (Taherdoost & Madanchian, 2023). MADM contains popular methods including TOPSIS, PROMETHEE, ELECTRE, and AHP. AHP is known for its simplicity, capacity to incorporate expert opinions through pairwise comparisons, and hierarchical decomposition based logical structure (Bhole & Deshmukh, 2018).

AHP is ideal for this study because it incorporates quantitative indicators (e.g., cost per kg, carbon footprint) and qualitative assessments (e.g., supplier maturity, certifications) utilizing a hierarchical framework. The decision environment at NTS Hengelo requires continuous evaluation of sustainability, financial, and supplier concerns. AHP's consistency checking maintains expert input's reliability, which is crucial for traceable and transparent industrial judgments (Bhole & Deshmukh, 2018).

AHP was chosen above PROMETHEE or ELECTRE, which are preferred for outranking approaches or fuzzy-based models, for problems that require ranking and logic based on stakeholder opinion and company objectives. In supplier selection, energy planning, and sustainability strategy formulation, AHP has also been successful (Taherdoost & Madanchian, 2023).

This implementation is based on a case study at NTS Hengelo, but AHP's structure, reasoning, and application can be applied to similar high-precision manufacturing environments or any multi-criteria material selection problem with well-defined alternatives and decision criteria.

## 3.2 OVERVIEW OF THE ANALYTICAL HIERARCHY PROCESS (AHP)

Saaty, (1987), developed the Analytical Hierarchy Process (AHP) to organize and analyse complicated decisions. It works well when qualitative and quantitative factors must be examined and combined rationally. AHP breaks a decision problem into a hierarchy of simpler sub-problems that may be analysed separately. An objective at the top, one or more criteria and sub-criteria, and decision options at the bottom are the usual structure (Saaty, 1987).

AHP compares elements at each hierarchy level pairwise. Expert judgment is used to transform these comparisons into ratio scales using a fundamental scale of relative importance from 1 (equal importance) to 9 (extreme importance). Eigenvector computations are used to calculate local priority weights from these comparisons and synthesis them across the hierarchy to determine global alternative priorities (Saaty & Vargas, 2012). AHP excels in transparently and rationally integrating quantifiable measures (cost, strength) with intangible assessments (strategic alignment, sustainability perception). The technique also includes a consistency ratio to assess decision-maker judgments (Saaty, 1987). Although beneficial, AHP has drawbacks. Pairwise comparisons increase rapidly with element count, causing cognitive stress or response inconsistency. Rank reversal, when the corresponding ordering of alternatives changes if one option is added or removed, may also occur (Saaty & Vargas, 2012).

AHP's adaptability in multidisciplinary contexts has allowed it to prioritize alternative materials, select suppliers, and evaluate environmental trade-offs in materials engineering and sustainable design. AHP provides the analytical foundation for analysing and selecting sustainable metal alternatives in this thesis, balancing environmental, supplier, and financial concerns.

## 3.3 CONSTRUCTION OF THE AHP HIERARCHY

The selection process for sustainable metal alternatives is structured using the Analytical Hierarchy Process (AHP) model, which is arranged into a four-tier hierarchy, going from the primary goal to evaluation criteria, then sub-criteria and eventually to the collection of alternatives. This structured breakdown facilitates a methodical comparison of several material options by clearly stating the decision objective, the influencing criteria, and the alternatives to be evaluated (Saaty, 1987).

Figure 5 shows the AHP hierarchy established for identifying the best sustainable metal alternative for high-precision manufacturing. The hierarchy consists of four levels. The decision objective lies at the highest level (Level 1). This is followed by three principal evaluation criteria: supplier, environmental, and financial criteria (Level 2). Each of these is subdivided into quantifiable sub-criteria (Level 3), which incorporate specific material attributes. The last layer (Level 4) delineates the six alternative materials indicated in Chapter 2, which are assessed and prioritized via the AHP approach.

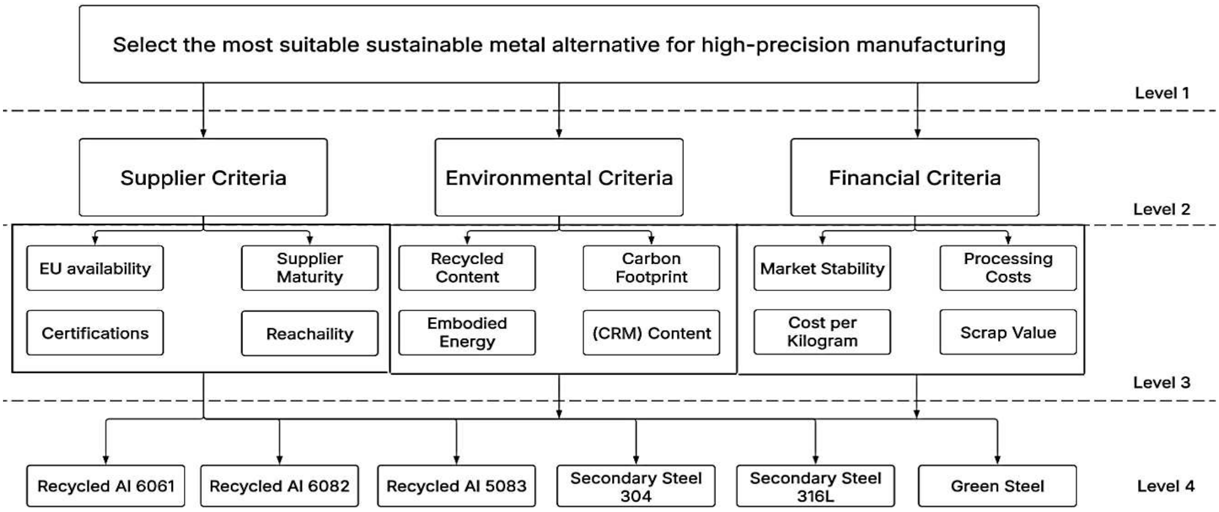



*Figure 5: AHP Framework for Sustainable Metals*

## 3.3.1 PAIRWISE COMPARISON OF CRITERIA

Once the hierarchy is constructed, the next step is to perform pairwise comparisons to determine the relative importance of the main criterion and sub-criteria. These comparisons employ Saaty's fundamental scale of relative importance, which goes from 1 to 9 (Table 3).

*Table 3: AHP Ranking System*

| Intensity | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two criteria contribute equally to the goal |
| 3 | Moderate importance | One criterion is slightly more important than the other |
| 5 | Strong importance | One criterion is strongly more important |
| 7 | Very strong importance | One criterion is very strongly more important |
| 9 | Extreme importance | One criterion is extremely more important |
| 2, 4, 6, 8 | Intermediate values | Used for compromises between the above judgments |
| 1/x | Reciprocal of above | When the second criterion is more important than the first |

Each pairwise comparison $a_{ij}$ expresses how much more important criterion *i* is over criterion *j*. The reciprocal is automatically assigned:

**(1)** $$a_{ji} = 1/a_{ij}$$

The diagonal elements of the matrix (comparisons of a criterion with itself) are always 1:

**(2)** $$a_{ii} = 1$$

Then the matrix is arranged in the following way:

**(3)** $$A = \begin{bmatrix} 1 & a_{12} & a_{13} \\ \frac{1}{a_{12}} & 1 & a_{23} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & 1 \end{bmatrix}$$

## 3.3.2 NORMALIZATION AND PRIORITY VECTOR CALCULATION

This step is important for turning the expert opinions, which were given using Saaty's 1–9 scale, into equivalent weights that show what the decision-makers want. As part of the standardization, each element in the matrix is divided by the sum of its column. This turns each column into a scale from 0 to 1, which lets the input of each criterion be compared to that of the others in a proportional way.

A= [$a_{ij}$] represents the original matrix where:

$a_{ij}$ represents the importance of criterion *i* over criterion *j,* and $a_{ji} = 1 / a_{ij}$ , the reciprocal property.

**Normalization**: the normalization formula for each element is formulated as:

**(4)** $$\widehat{a_{ij}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

$\widehat{a_{ij}}$ is the normalized value of $a_{ij}$ , and *n* is the number of criteria.

**Priority Vector**: When the values are normalized, then the weight $w_i$ for criterion *i* is calculated based on the mean of the values of the corresponding row of the normalized matrix:

**(5)** $$w_i = \frac{1}{n}\sum_{j=1}^{n} \widehat{a_{ij}}$$

These weights show how important each criterion is in relation to the goal. It makes sure that the results are in line with both the company's qualitative opinions and the AHP model's quantitative structure.

### 3.3.3 CONSISTENCY RATIO (CR) VALIDATION

Because pairwise comparison relies on subjective human input, logical inconsistency is always important. The CR measures how logically clear comparisons are and how reliable the weightings are. If criterion A is more important than B and B is more important than C, then A should be more important than C. Judgements are inconsistent if this logic is violated. Complex decision-making involves some inconsistency, but Saaty (1987) presented a three-step approach to measure it:

**Step 1: Calculate the Principal Eigenvalue**

To do this, multiply the original paired matrix *A* by the vector of weights, then divide each element by the weigh of *i*. The highest eigenvalue can be found by taking the sum of these numbers.

**(6)** $$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{(A.w)_i}{w_i}\right)$$

**Step 2: Compute the Consistency Index (CI)**

The CI is calculated by equation (7), where *n* is the number of criteria:

**(7)** $$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1}$$

**Step 3: Compute the Consistency Ratio (CR)**

The CI is compared to a Random Index (RI), which is a reference number made from matrices that were generated at random, to see if it is good enough. This gives us the following Consistency Ratio (CR):

**(8)** $$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}$$

Saaty, (1980) provided the following RI values for common matrix sizes:

| n (matrix size) | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| RI | 0.58 | 0.90 | 1.12 | 1.24 |

**Interpretation of CR**

If CR is less than 0.10, the matrix is said to be acceptably consistent. This means that the decisions make sense and the weights that come from them are correct. If the CR is greater than or equal to 0.10, it means that the comparisons might not be accurate enough, and changes should be made.

### 3.3.4 WEIGHT AGGREGATION AND OUTPUT

Once the weights for the criteria and sub-criteria are set, they are used to find the global priority score for each metal option.

**(9)** $$Global\ Score_j = \sum_{i=1}^{n} w_i \cdot s_{ij}$$

$Wi$ is the weight of the criterion *i,* and $Sij$ is the score of alternative $j$ on criterion *i.*
The decision-making tool, Appendix 4, Figure 21, that ranks all metal options is based on this weighted sum model.

## 3.4 MATERIAL SELECTION FRAMEWORK

In addition to using the AHP, this thesis creates a customized framework that operationalizes sustainability evaluation for metal selection in high-precision production. The framework was built in stages, beginning with a review of existing material selection literature (Chapter 2), followed by the identification of important sustainability indicators and their translation into measurable sub-criteria (Section 2.4). This was followed by technical metal screening and the systematic integration of financial, supplier, and environmental aspects (Section 2.3). Unlike generic AHP models, this framework takes into account supply chain maturity, certification traceability, and EU legal constraints, making it context sensitive and relevant to real-world industrial requirements. The framework design is part of this thesis's methodological section, since it provides a structured and flexible instrument for decision-making in sustainable procurement and engineering contexts.

This section describes how each sub-criterion was developed, quantified, and normalized to obtain consistent assessment ratings for the selected material choices for this framework. Each sub-criterion is based on both academic literature and industry insights, providing theoretical accuracy and practicality. Definitions were influenced by sustainability theory and EU policy standards (see Section 2.4), whereas performance values were derived from validated industry data, supplier documentation, and input from experts at NTS Hengelo. The company also decided the amount and type of criteria to asses. The normalization approaches adhered to known AHP protocols, assuring consistency across all values (Saaty, 1987).

Each sub-criterion is introduced with:

- A specific definition based on sustainability theory or policy (Section 2.4).
- The data source(s) used to estimate performance values.
- The method used to convert raw values into normalized AHP inputs (scaled from 1 to 9).

This operationalization provides reliability, reproducibility, and methodological logic, making the approach applicable not only to academic research but also to industrial sustainability assessments and procurement decisions.

Sections 3.3.1 to 3.3.3 outline the operationalization approach for each of the three key criteria groups.

### 3.4.1 OPERATIONALIZATION OF ENVIRONMENTAL CRITERIA

The environmental dimension measures the material's carbon emissions, recycled content, critical raw material utilization, and embodied energy. These parameters represent life cycle analysis and circular economy ideas and were chosen based on literature relevance (UNEP, 2023; UNEP, 2011; Raabe, 2023; Granta EduPack) and EU material availability (European Commission, 2025). All sub-criteria were normalized into AHP ratings (1–9), with higher scores indicating better sustainability.

## I. Carbon Footprint

As recommended by Granta EduPack (2023), this study employed a blended life cycle approach using virgin and recycled production methods to evaluate each metal alternative's carbon footprint. Recycled content percentages were based on supplier sustainability disclosures and market averages for recycled or secondary grades (HYBRIT, 2025; Outokumpu (2025), and academic literature (Raabe, 2023; Graedel et al., 2011). Equation for sustainable grades footprint:

**(10)** $$Sustainable\ Grade\ CO_2 = (\frac{100 - R_f}{100} * Virgin\ CO_2) + (\frac{R_f}{100} * Recycled\ CO_2)$$

$R_f$ is the recycled content of the sustainable metal (%).

*Virgin $CO_2$, and Recycled $CO_2$* is the carbon intensity of producing 1 kg of metal from raw ore, and from scrap respectively.

The sustainable $CO_2$ footprint for each metal was converted to normalized AHP ratings on a 1-9 scale using percentage reduction from virgin grade:

**(11)** $$Reduction\ \% = (\frac{Virgin\ Value - Sustainable\ Value}{Virgin\ Value}) * 100$$

**(12)** $$Normalized\ Score = 1 + ((\frac{Observed\ Value - Min\ Value}{Max\ Value - Min\ Value}) * (9 - 1))$$

As seen in Table 4, materials with the largest decrease in $CO_2$ emissions obtained the highest AHP scores, while those with minimal benefits were graded lower.

*Table 4: Carbon Footprint Normalized Score*

| Carbon Footprint | | | | | | |
|---|---|---|---|---|---|---|
| Metal | CO2 footprint, recycling | Virgin $CO_2$ (kg / kg) | Recycled Content (%) | Sustainable CO2 (kg / kg) | Reduction | score |
| Recycled Al 6061 | 2.39 | 12.7 | 90 | 3.421 | 73.06% | 9 |
| Recycled Al 6082 | 2.38 | 12.6 | 90 | 3.402 | 73.00% | 9 |
| Recycled Al 5083 | 2.475 | 13.05 | 88 | 3.744 | 71.31% | 9 |
| Green Steel (S355) | 0.569 | 2.985 | 70 | 1.2938 | 56.66% | 4 |
| Secondary Steel 304 | 1.235 | 4.95 | 60 | 2.721 | 45.03% | 1 |
| Secondary Steel 316L | 1.39 | 7.415 | 55 | 4.10125 | 44.69% | 1 |

## II. Recycled Content

This study used supplier sustainability statistics, industry publications, and databases including Granta EduPack (2023), Outokumpu (for stainless steel), European Aluminium Association, HYBRIT, and ResponsibleSteel to calculate recycled content levels for each material (Outokumpu, 2025; European Aluminium, 2025; Hybrit, 2025; Responsiblesteel, 2025).

Recycled content values were standardized to a 1–9 scale using the linear min–max approach in Equation (3) for AHP comparison, in Table 5 this values are displayed.

*Table 5: Recycled Content Normalized Score*

| Recycled Content | | |
|---|---|---|
| Metal | Recycled Content (%) | Score |
| Recycled Al 6061 | 90% | 9 |
| Recycled Al 6082 | 90% | 9 |
| Recycled Al 5083 | 88% | 9 |
| Green Steel (S355) | 70% | 4 |
| Secondary Steel 304 | 60% | 2 |
| Secondary Steel 316L | 55% | 1 |

### III. Critical Raw Materials

The European Commission (2025) lists nickel, molybdenum, cobalt, and rare elements as critical. Granta EduPack (2023), and supplier technical datasheets were used to estimate CRM content from alloy chemical compositions.

An inverted 1–9 AHP scale was used to standardize the estimated CRM content where lower CRM content equals higher score. So, normalization followed a modified min–max formula, giving the material with the lowest CRM % a 9 and the highest a 1.

**(13)** $$Normalized\ Score\ =\ 1\ +\ ((\frac{Max\ Value - Observed\ Value}{Max\ Value - Min\ Value})\ *\ (9-1))$$

In line with the EU's CRM strategy and circular economy aspirations, this sub-criterion lowers items that use sensitive or environmentally hazardous raw materials (European Commission 2025). Refer to Appendix 3 Table 19, for a normalized ranking table.

### IV. Embodied Energy

Embodied energy was computed using a mixed approach that considered material recycled content, like carbon footprint. Granta EduPack (2023), approach provided the following equation:

**(14)** $$Sustainable\ Grade\ Energy = (\frac{100 - R_f}{100}\ *\ Virgin\ Energy)\ +\ (\frac{R_f}{100} * Recycled\ Energy)$$

$Virgin\ Energy,\ and\ Recycled\ Energy$ is the embodied energy of producing 1 kg of metal from raw ore, and from recycled feedstock respectively.

To convert these values into AHP scores, the percentage reduction in embodied energy was determined with Equation (2) and normalized with Equation (3). Normalized scores can be seen in Table 6.

*Table 6: Embodied Energy Normalized Score*

| Embodied Energy | | | | | | |
|---|---|---|---|---|---|---|
| Metal | Recycled Content (%) | Virgin Energy (MJ / kg) | Recycled energy | Energy Sustainable (MJ / kg) | Reduction | Score |
| Recycled Al 6061 | 90 | 172.5 | 30.450 | 44.655 | 74.11% | 9 |
| Recycled Al 6082 | 90 | 171.5 | 30.350 | 44.465 | 74.07% | 9 |
| Recycled Al 5083 | 88 | 180 | 31.500 | 49.32 | 72.60% | 9 |
| Green Steel (S355) | 70 | 26 | 7.235 | 12.8645 | 50.52% | 3 |
| Secondary Steel 304 | 60 | 72 | 15.700 | 38.22 | 46.92% | 2 |
| Secondary Steel 316L | 55 | 84.3 | 17.650 | 47.6425 | 43.48% | 1 |

## 3.4.2 OPERATIONALIZATION OF FINANCIAL CRITERIA

The framework's financial dimension contains four sub-criteria these include direct purchasing costs, scrap value at the end of life, operational processing costs, and market price volatility. These criteria address both typical procurement problems and circular economy finance. Data was chosen based on literature relevance (UNEP, 2011; Raabe, 2023; Granta EduPack) and EU material availability (European Commission, 2025). All sub-criteria were normalized into AHP ratings (1–9), with higher scores indicating lower financial problems and higher benefits.

### I. Cost per Kilogram

Two steps were taken to assess sustainable material costs for this research. For each alloy's virgin (primary) version, Granta EduPack (2023) provided typical prices. Second, supplier sustainability disclosures (Hydro, 2025 Outokumpu, 2025), academic papers (Muslemani et al., 2021; Lopez et al.,

2023) and industrial studies (Hoffman *et al*, 2024; HYBRIT, 2025, reports) were used to alter traditional averages to calculate sustainable prices.
The following were assumed:

- Aluminium alloys (6061, 6082, 5083) with recycled content are expected to be 10% cheaper than virgin ones.
- HYBRIT (2025) reports that green steel ($H_2$-DRI and EAF-based) costs 25% more than conventional structural steel due to early industrial scaling and green hydrogen input costs. However, McKinsey (2025) and HYBRIT (2025) believe that green steel is becoming cost-competitive as manufacturing matures and pricing will come into line with traditional steel. This model used the current average market premium of +25% to reflect short-term situations.
- Secondary stainless steels (304 and 316L) were projected to be 10% cheaper than virgin grades, considering scrap intake, processing efficiency, and alloying complexity.

To standardize for AHP input, prices were normalized inversely using the same formula structure as Equation (4), Appendix 3 Table 20 shows the results of this normalization.

### II. Scrap Value

Estimated values were obtained from, online scrap price aggregators (ScrapPrices, 2025; ScrapMonster, 2025; Scrap Metal Price Index: Netherlands - Metaloop, 2025), academic justification (Shamsuddin, 1986) and industry sources (International Aluminium Institute, 2024). See Table 7.

*Table 7: Scrap Value*

| Metal | Approx. Scrap Value (€/kg) | Notes |
|---|---|---|
| Recycled Al 6061 | 1.30 | Common, high recovery rate |
| Recycled Al 6082 | 1.30 | Similar to 6061 |
| Recycled Al 5083 | 1.20 | Slightly lower due to alloy impurities |
| Green Steel (S355) | 0.30 | Steel scrap is low in €/kg but recycable |
| Secondary AISI 304 | 0.75 | Driven by Ni content |
| Secondary AISI 316L | 1.00 | Higher due to Ni and Mo content |

Since a higher scrap value is better, scores were normalized using conventional min-max scaling (See Equation (3)), with the highest-value material receiving a score of 9 and the lowest receiving a score of 1. In Appendix 3 Table 21, dis results are displayed.

### III. Processing Cost

This study evaluates the corresponding processing cost by assigning a cost multiplier to each material, based on machinability ratings from Granta EduPack (2023), literature from Raabe (2023), and machineability index databases, tool wear, cutting time, and thermal resistance (Granta EduPack, 2023). Most materials, even recycled or green variations, are expected to have the same technical processing behaviour as their virgin counterpart. As a result, changes in processing cost multipliers are mostly determined by alloy composition and mechanical properties, rather than whether a material is recycled or green.

Recycled Aluminium 6061 has a multiplier of 1.0, indicating great machinability and minimal processing costs. Other materials were assessed against this baseline, as seen in Table 8.

*Table 8: Processing Costs*

| Metal | Processing Score | Notes |
|---|---|---|
| Recycled Al 6061 | 1 | Excellent machinability (baseline) |
| Recycled Al 6082 | 1.1 | Slightly higher strength |
| Recycled Al 5083 | 1.2 | Lower formability, marine grade |
| Green Steel (S355) | 1.1 | Good formability, slower than Al |
| Secondary AISI 304 | 1.5 | Tougher, more tool wear |
| Secondary AISI 316L | 1.7 | High Mo/Ni content, work hardening |

To standardize for AHP input, prices were normalized inversely using the same formula structure as Equation (4) , because lower cost is better. Refer to Appendix 3, Table 22 for the normalized scores.

**IV. Cost Stability / Market stability**

This sub-criterion was examined using London Metal Exchange (LME) commodities market data (2020-2023) (HKEX Company, 2025) pricing trends from Bloomberg, 2025, and EU CRM supply risk indexes.

Materials were assigned qualitative stability characteristics and mapped to a 1-5 scale, with 5 indicating very stable and 1 indicating highly unstable, Table 9.

*Table 9: Cost/Market Stability Score*

| Material | Stability Score | Notes |
|---|---|---|
| Recycled Al 6061 | 5 | Large scrap stream, low volatility |
| Recycled Al 6082 | 5 | Same as 6061 |
| Recycled Al 5083 | 4 | Slightly more variable due to niche use |
| Green Steel (S355) | 5 | Stable pricing with scaling $H_2$ supply |
| Secondary AISI 304 | 3 | Volatile due to Nickel dependency |
| Secondary AISI 316L | 1 | High volatility (Nickel and Molybdenum) |

Since higher stability is better, scores were normalized using conventional min-max scaling Equation (3), with the highest-value material receiving a score of 9 and the lowest receiving a score of 1. Refer to Appendix 3 Table 23, for the normalized scores.

### 3.4.3 OPERATIONALIZATION OF SUPPLIER CRITERIA

Supply Chain Availability, Supplier Maturity, Certifications & Traceability, and Lead Time were chosen based on sustainability supply chain literature (Tercero, 2019; Reuter et al., 2005), European sourcing strategies (European Commission, 2025), and relevance to real-world industrial supply chains. These requirements ensure that materials are technically, environmentally, and commercial in the EU. Like other categories, supplier sub-criteria were normalized to AHP ratings (1-9), with higher scores indicating better supply performance and lower risk.

**I. Supplier Availability**

Data came from suppliers' sustainability reports and product lines. Hydro's CIRCAL and REDUXA programs provide certified recycled aluminium with over 75% post-consumer content (Hydro, 2025). AMAG Austria Metall makes high-quality recycled rolled aluminium products (AMAG, 2025). Outokumpu produces annual ESG reports and makes stainless steel with up to 90% recycled material (Outokumpu, 2025). SSAB, Tata Steel, and HYBRIT produce green steel through fossil-free production and EAF processing (SSAB, 2025). In EU-based operations and export channels, ITG Steel and Aperam sell 304 and 316L secondary stainless steel.

The availability score was allocated from 1 to 5, following the same logic as Section 3.3.2, IV. This values can be seen in Table 10. The results were normalized using standard min-max scaling Equation (3), with higher availability resulting in higher ratings, for this normalized values refer to Appendix 3 Table 24.

*Table 10: Supplier Availability Normalized Score*

| Supplier Availability | | | |
|---|---|---|---|
| Metal | Availability | Multiplier | Score |
| Recycled Al 6061 | Very High | 5 | 9 |
| Recycled Al 6082 | Very High | 5 | 9 |
| Recycled Al 5083 | Moderate | 3 | 1 |
| Green Steel (S355) | Very High | 5 | 9 |
| Secondary Steel 304 | Very High | 5 | 9 |
| Secondary Steel 316L | High | 4 | 5 |

### II. Supplier Maturity

The evaluation was based on a multi-factor approach and five indicators described in Table 11:

*Table 11: Supplier Maturity Indicators*

| Criterion | Description |
|---|---|
| 1. Technology Readiness | Whether the sustainable process is commercially available. |
| 2. Market Integration | How well their sustainable products are integrated into supply. |
| 3. Volume & Scalability | The current and potential production capacity of sustainable materials. |
| 4. Transparency & Certifications | Use of verified EPDs, LCA, ISO 14001, third-party audits, etc. |
| 5. Track Record | Years of experience and implementation of sustainable practices. |

Each material's maturity was evaluated using the average rating of its primary suppliers, citing the suppliers in Section 3.3.3, I. The maturity score was again allocated from 1 to 5, Appendix 3, Table 29. The results were normalized using standard min-max scaling Equation (3), with higher maturity resulting in higher ratings, refer to Appendix 3 Table 25.

### III. Certifications and Traceability

A mature certification and traceability system decreases the risk of greenwashing, facilitates customer choice, and simplifies reporting under frameworks like the EU Corporate Sustainability Reporting Directive (CSRD).

*Table 12: Certifications and Traceability Indicators*

| Evidence Domain | Typical Proof Points | Example Standards / Tools |
|---|---|---|
| Environmental management | Third-party audited management systems | ISO 14001, ISO 50001 |
| Product compliance | Safety / chemical / performance labels | CE-mark, EN material standards, REACH |
| Sustainability disclosures | Public cradle-to-gate data | Environmental Product Declarations (EPD), LCA |
| Digital traceability | Real-time or batch passports | Blockchain, QR material ID, $CO_2$ trackers |
| Reporting alignment | ESG transparency & audits | GRI, CDP, EU Taxonomy mapping |

The certification and traceability score was allocated from 1 to 5, see Appendix 3,Table 30. The results were normalized using standard min-max scaling with Equation (3), with higher certification and traceability resulting in higher ratings, for this normalized values, refer to Appendix 3 Table 26.

### IV. Lead Time

The study took into account average lead times for EU deliveries, stock availability and logistical predictability, manufacturing stage (pilot vs. commercial size), supplier delivery notes, usual order cycles, and regional logistics restrictions. Sources included supplier product pages, technical sales datasheets, and direct connection with firms such as AMAG, Hydro, Tata Steel, and Outokumpu. Refer to Appendix 3, Table 31 for a detailed summary of the approximate lead times.

*Table 13: Lead Time Score*

| Material | Typical Lead Time | Notes | Score |
|---|---|---|---|
| Recycled Al 6061 | 4–8 weeks | High stock availability | 5 |
| Recycled Al 6082 | 4–8 weeks | Same as 6061 | 5 |
| Recycled Al 5083 | 5–7 weeks | Less common stock, marine grade | 4 |
| Green Steel (S355) | 4–6 weeks (pilot) or 2026 | Still scaling production, limited slots | 1 |
| Secondary AISI 304 | 3–6 weeks | Very common stock | 5 |
| Secondary AISI 316L | 4–6 weeks | Higher complexity, slower availability | 3 |

The availability score was allocated from 1 to 5, see Table 13. To standardize for AHP input, prices were normalized inversely using the same formula structure as Equation (4) , because lower lead time is better, refer to Appendix 3 Table 27, for the normalized values.

## 3.5 SUMMARY OF CHAPTER 3

This chapter showed how to arrange and quantify sustainable metal alternatives using the AHP. An AHP hierarchy was created based on Chapter 2's environmental, supplier and financial criteria for high-precision manufacturing. The method involves creating a decision hierarchy, doing pairwise comparisons, computing weights, verifying consistency, and formulating a final scoring model. These measures guarantee transparency and thoroughness in tackling the sustainability, supplier, and financial issues associated with metal replacement.

A material selection framework for the operationalization of the criteria was addressed to measure and rank the metals in a reliable way. This makes the overall model tailored to the specifications of the study and not only AHP centred.

The next chapter, Chapter 4, builds on this by applying the AHP method to sub-criteria, showing the full matrices, combining all the weights, and making the final list of sustainable metal alternatives.

# Chapter 4: Model and Results

This chapter shows the findings of the Analytical Hierarchy Process AHP-based evaluation of sustainable metal alternatives, which utilized the structured framework and operationalized criteria created in Chapter 3. It directly meets the study purpose of identifying the best sustainable metal at NTS Hengelo by combining evaluation criteria with alternative material performance data. This matches Step 6 of the Research Process (Measurement) by Heerkens, van Winden, and Tjooitink (2017) and Steps 3 to 5 of the AHP, which define local priorities, merges global scores, and compare options (Saaty, 1987).

The chapter examines the performance of chosen sustainable metal alternatives using the AHP model. It follows a three-step process. First, pairwise comparisons evaluate each material's performance under each criterion and sub-criterion. Second, local priorities from these comparisons are combined with global criterion weights to create a combined performance score for every criteria. The materials are ranked to recommend the best option to NTS Hengelo based on the company's rankings and alternative scenarios, and are presented in an interactive Dashboard. This aligns with Step 7 of the Research process (Processing and Analysing Results).

## 4.1 CRITERIA WEIGHTS LEVEL 2

Using the AHP method, a pairwise comparison was done to find out how important the three main criteria were, these criteria are shown in Figure 5, stated as Level 2: Environmental, Financial, and Supplier criteria as seen in Figure 5.

Table 14 shows the results of the pairwise comparisons based on Section 3.3.

| Original Matrix | Environmental | Supplier | Financial |
|---|---|---|---|
| Environmental | 1 (0.100) | ¼ (0.077) | 1/5 (0.118) |
| Supplier | 4 (0.400) | 1 (0.308) | ½ (0.294) |
| Financial | 5 (0.500) | 2 (0.615) | 1 (0.588) |

*Table 14: Main Criteria Original Matrix*

The pairwise comparison matrix in Table 14 shows the relative significance of the three main criteria, as viewed by the company. Each entry was given a value based on expert assessment and transformed using Saaty's relative importance scale, as shown in Table 3 of Section 3.2.1. Following the AHP process outlined in Section 3.2.2, the matrix was normalized, as shown in Table 14, between parenthesis, by dividing each element by the sum of its appropriate column, as specified in Chapter 3 Equation (4). The final weights were calculated by averaging each row of the normalized matrix, as seen in Chapter 3 Equation (5). Figure 6 shows the obtained weights.

According to the Figure 6, financial factors account for the majority of decision weight (57%), indicating that cost is the most important criterion in the company's material selection process. Supplier-related criteria come in second with 33%, suggesting their influence, especially in areas like availability and reliability. Environmental problems contribute only 10%, indicating a lower priority than financial and supplier concerns.

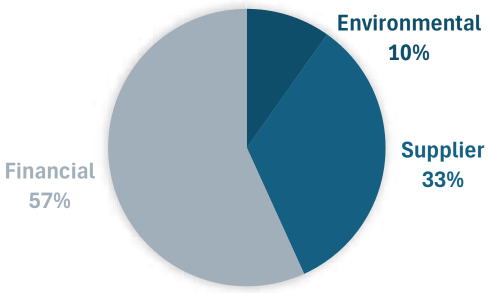



*Figure 6: Main criteria weights*

## 4.2 SUB-CRITERIA WEIGHTS LEVEL 3

After defining the relative importance of the three main criteria, the analysis was expanded to include sub-criteria within each major criterion. This section gives the findings of pairwise comparisons for the sub-criteria. These weights were determined by pairwise comparisons using the same AHP technique outlined in Section 3.2.1 and computed using the normalization and averaging method in Chapter 3 Equations (4) and (5). Figures 7, 8 and 9 show the outcomes of the priority weights for Environmental Performance, Supplier Availability, and Financial Feasibility.

As indicated in Figure 7, all environmental sub-criteria were given equal weight at 25%, demonstrating that the company values these criteria equally when evaluating environmental performance. This uniform distribution indicates a balanced sustainability perspective, with no single environmental indicator dominating the decision.

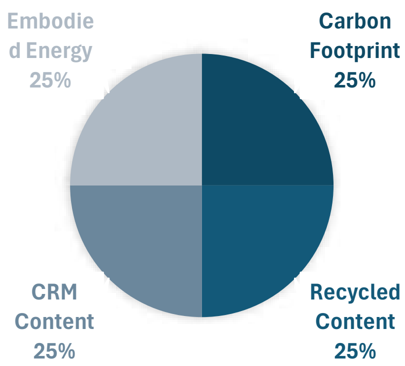



*Figure 7: Environmental criteria weights*

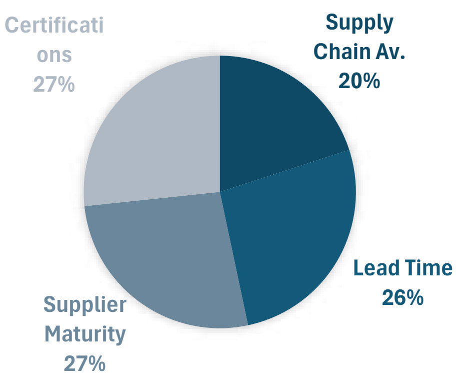



*Figure 8: Supplier criteria weights*

Figure 8 shows that supplier maturity and certifications were the most important sub-criteria in the supplier category, each accounting for 27% of the weight. These are closely followed by lead time (26%), with supply chain availability receiving a little lower weight of 20%. These findings suggest that the organization places a high priority on long-term supplier reliability and conformity with established standards, whereas logistical variables such as availability are slightly less important.

The financial sub-criteria, displayed in Figure 9, shows that market stability and processing cost were weighted the most at 32% each, followed by cost per kilogram at 28%. Scrap value was ranked as the least important, accounting for only 8%. This weighting represents the company's preference for stable pricing and production costs above end-of-life value recovery. It emphasizes a forward thinking, cost cutting management strategy.

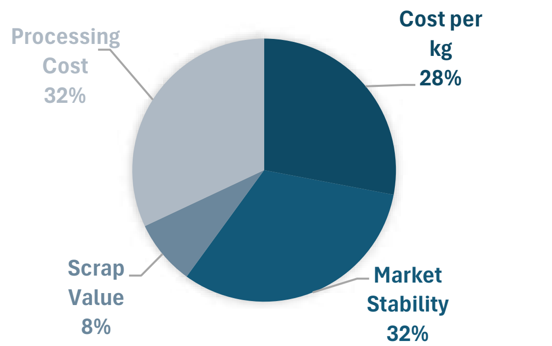



*Figure 9: Financial criteria weights*

## 4.3 SUSTAINABLE METAL PERFORMANCE LEVEL 4

This section evaluates alternative metal materials based on their performance across all weighted factors after determining the relative importance of the main criterion (Level 2) and sub-criteria (Level 3). Level 4 is the lowest tier of the AHP hierarchy, where actual options are assessed by aggregate environmental, financial, and supplier performance scores followed from Equation (9) in Section 3.2.4.

Sections 3.2.2 and 3.3 describe how to get each material's overall score by combining its normalized sub-criterion values with the weights from the prior levels. This process quantifies how effectively each material alternative meets the company's sustainability and management goals. The comparison supports an evidence-based selection of the most sustainable metal.

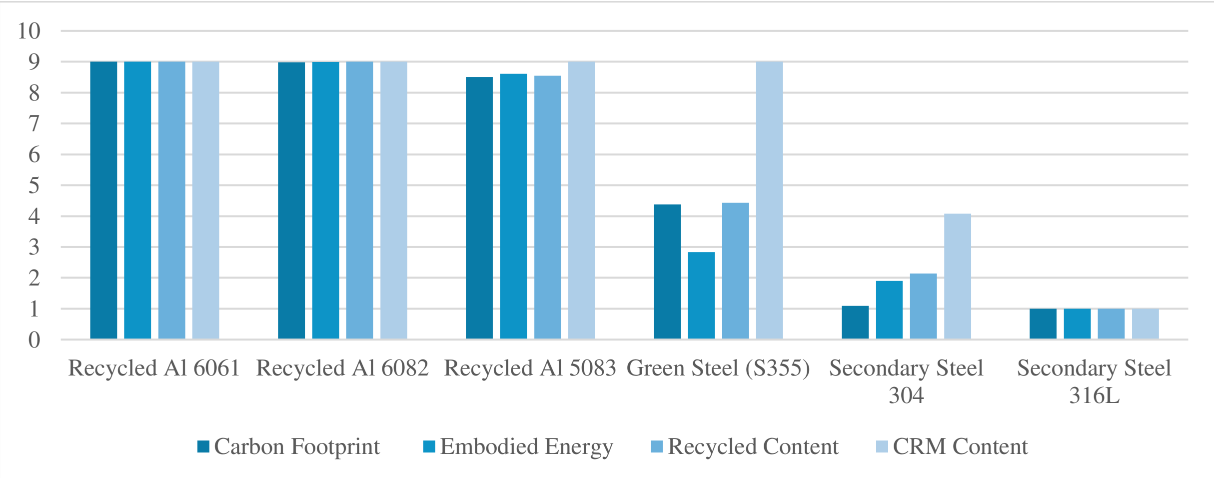



*Figure 10: Metal Performance on Environmental Criteria*

As indicated in Figure 10, the recycled aluminium grades (6061, 6082, and 5083) consistently rank better than other alternatives in all environmental sub-criteria. Green steel performed well in CRM content but received lower ratings in embodied energy. Secondary stainless steels received lower environmental rankings, due to alloying complexity and energy intensity.

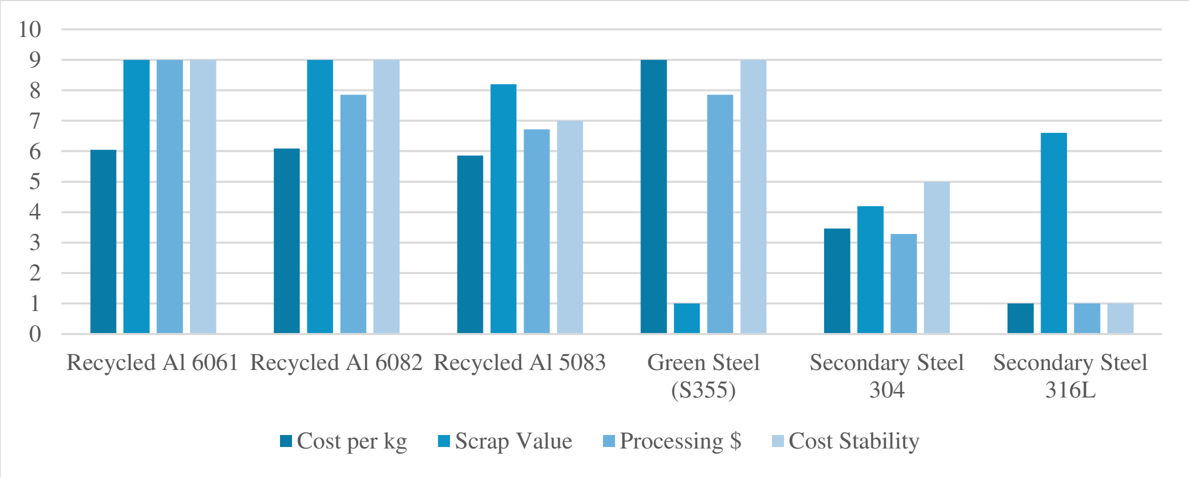



*Figure 11: Metal Performance on Supplier Criteria*

Fro Figure 11, the financial performance scores reflect the trade-offs between cost efficiency and circular value. While recycled aluminium grades regularly outperform in all four sub-criteria, green steel has outstanding cost stability but a poor scrap value due to immature recycling economics. Secondary stainless steels perform well in terms of processing costs and scrap recovery, but they struggle from high purchase price volatility and alloy complexity.

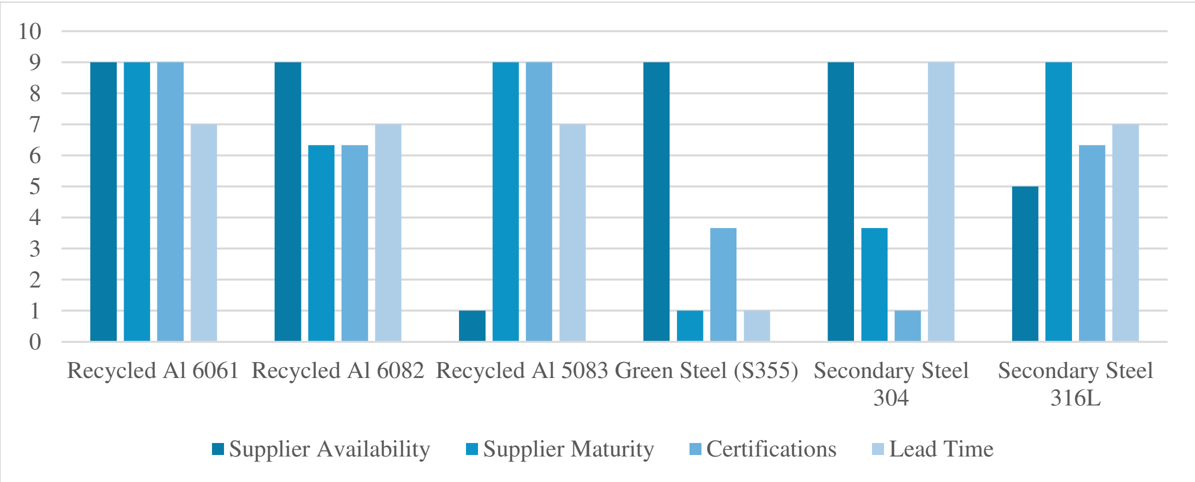



*Figure 12: Metal Performance on Financial  Criteria*

Supplier performance rankings, as seen in Figure 12, focus on the operational dependability and traceability of each sustainable metal's supply chain. Recycled aluminium grades perform consistently well, thanks to various EU-based suppliers who have excellent certification standards and moderate lead times. Secondary steels show strong maturity and lead time performance, while certification grade varies. Green steel and 5083 aluminium, on the other hand, receive lower scores due to restricted availability and early-stage supply models, despite their potential for long-term sustainability.

*Table 15: Final Rankings*

| Final AHP Score | |
|---|---|
| Recycled 6061 | 8.3528 |
| Recycled 6082 | 7.6751 |
| Recycled 5083 | 6.9395 |
| Green Steel | 6.1521 |
| Secondary 304 | 4.2914 |
| Secondary 316L | 3.2432 |

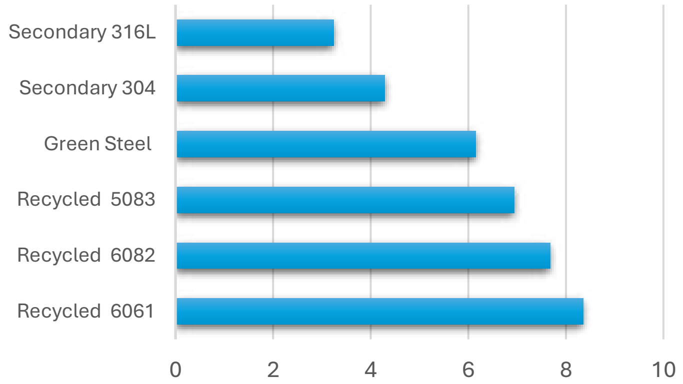



*Figure 13:Final Metal Performance*

According to Table 15 and Figure 13, Recycled Aluminium 6061 scored 8.35 in the final AHP rating, making it the best material for the company's weighted priorities. This means it balances environmental, financial, and supplier factors best. It is followed by Recycled Aluminium 6082 and Recycled 5083, with ratings of 7.68 and 6.94, respectively, indicating good recycled aluminium performance. Although less aligned with the company's cost and supply chain requirements, Green Steel scored 6.15 competitively, indicating its sustainability potential. However, Secondary Steel 304 and 316L scored the lowest, 4.29 and 3.24, indicating limited applicability under the current weighting structure. These rankings provide a data-driven basis for choosing the best material for strategic sustainability and procurement goals.

## 4.4 TRADE-OFFS AND INTERPRETATION

While Recycled Aluminium 6061 received the highest AHP score, its low utilization volume (2%) at NTS restricts its overall environmental impact. In contrast, Aluminium 6082, which scored almost the same accounts for roughly 40% of current metal usage (Figure 14). Thus, by selecting recycled 6082, NTS can reach or exceed the 4% sustainability objective with a single substitution while retaining technical compatibility.

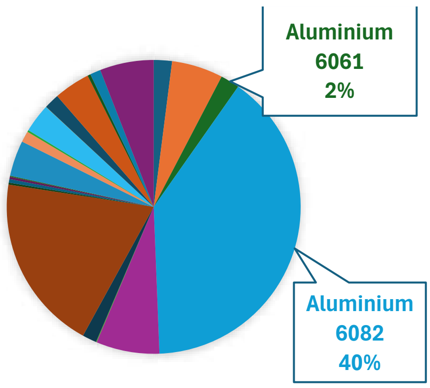
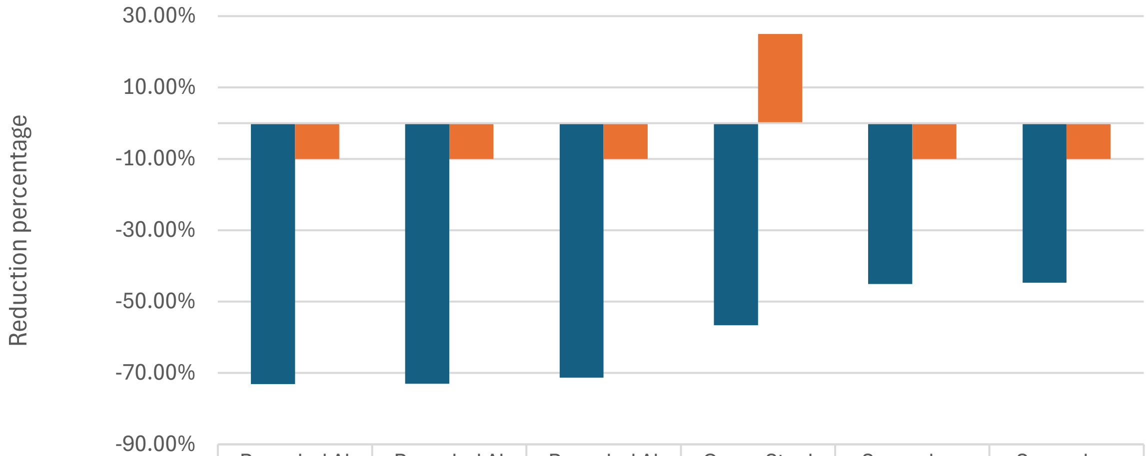



*Figure 14: Current Metal Volume in use at NTS*

Another important trade-off is regarding the replacement of traditional steel with green steel. While green steel's performance was consistent, its supplier maturity and lead time are currently less attractive. However, given its high environmental potential and future EU support, green steel may be considered for gradual implementation after commercial supply chains have stabilized. Similarly, stainless steel

304 and 316L have an acceptable supplier and scrap value performance, but their CRM percentage and embodied energy lower their environmental score. Suppliers such as HYBRIT and $H_2$ Green Steel are developing advanced traceability systems, but their current pilot-stage capability creates uncertainty for short-term adoption.

Another trade-off occurs between scrap value and initial cost. Recycled aluminium grades provide significant scrap value and long term environmental benefits, but their initial pricing is compared to lower cost structural steel. However, at NTS Hengelo, the majority of aluminium purchases are done on demand for specific uses, with customers handling scrapping. Material costs are generally just a small component of total product costs, with labour and added value having priority. As a result, material prices and scrap value are usually not the key decision-making variables for implementation.




| | Recycled Al 6061 | Recycled Al 6082 | Recycled Al 5083 | Green Steel (S355) | Secondary Steel 304 | Secondary Steel 316L |
|---|---|---|---|---|---|---|
| % CO2 Reduction | -73.06% | -73.00% | -71.31% | -56.66% | -45.03% | -44.69% |
| % Cost Reduction | -10% | -10% | -10% | 25% | -10% | -10% |

*Figure 15: CO2 vs Cost Reduction*

Figure 15 shows how carbon footprint reduction and expected cost reduction interact with each of the six sustainable metals. The recycled aluminium grades 6061, 6082, and 5083 have the highest overall performance, reducing $CO_2$ emissions by over 70% and reducing purchase cost by an estimated 10%. Their significant environmental benefit and financial savings demonstrate their cost-to-impact ratio.

While green steel (S355) has a significant 56.66% $CO_2$ reduction, it comes with a 25% cost increase due to its early market development and hydrogen-based manufacture. While promising, green steel is a long-term strategy rather than a cost-effective substitute. Secondary stainless steels (304 and 316L) offer a 45% $CO_2$ reduction and a 10% cost savings.

Although Recycled Aluminium 6061 received the best AHP score because to its environmental and cost features, its practical impact is limited by its low usage volume at NTS, which accounts for only 2% of overall metal consumption (Figure 14). In comparison, Recycled Aluminium 6082, which ranks second in the AHP model, accounts for roughly 40% of current utilization. Figure 15 shows that both alloys offer roughly equivalent $CO_2$ reductions (-73.06%) and cost savings (-10%). However, given 6082's high baseline usage, substituting a portion of this alloy can meet or exceed NTS's 4% sustainability replacement demand without requiring significant process adjustments. As a result, the emphasis on 6082 is a strategic implementation decision based on impact potential, feasibility, and alignment with internal usage patterns, rather than a performance ranking alone.

## 4.5 MODEL VALIDATION (SENSITIVITY ANALYSIS & CONSISTENCY RATIO)

A sensitivity study was performed to assess the AHP model's reliability and validity. Because the key factors heavily influence the final scores, multiple scenarios were created to reflect realistic stakeholder choices. Baseline (current estimate), Environment-Driven (future goal), Cost-Focused, Supplier Priority, and Equal Weights scenarios were created (Appendix 4, Figure 20). The model recalculated weighted scores and AHP ranks for all six candidate materials for each scenario. In Table 16 the scenarios are displayed.

The recalculations were carried out using an interactive automated Excel dashboard (see Section 4.5), which dynamically changes scores and rankings as a scenario is selected. This tool guarantees the reliability, consistency, and validity of the analytical process described in Section 3.3.

*Table 16: Sensitivity Analysis Scenarios*

| Scenario | Environmental | Supplier | Financial |
|---|---|---|---|
| Baseline (current) | 0.098 | 0.334 | 0.568 |
| Environment-Driven | 0.5 | 0.25 | 0.25 |
| Cost-Focused | 0.25 | 0.25 | 0.5 |
| Supplier Priority | 0.5 | 0.25 | 0.25 |
| Equal Weights | 0.33 | 0.33 | 0.33 |

In Table 16 we can see how the weights are distributed based on the five different scenarios. For the company, it is most important to look at the current scenario and the environment-driven scenario. This is because the targets and goals incline to a more environmentally driven future.

#### BASELINE (CURRENT SCENARIO)

The baseline scenario is precented throughout Chapter 4. It gives the greatest weight to financial factors (57%). Under this scenario, Recycled 6061 and Recycled 6082 have the greatest scores (8.35 and 7.68). This shows that cost-efficiency is the key motivation in the current decision-making framework.

#### ENVIRONMENT-DRIVEN SCENARIO

In a scenario where environmental problems are prioritized (50% weight), the top options are Recycled 6061 and Recycled 6082, but both of them increase (8.66 and 8.21). This solidifies their environmental performance and is consistent with future-oriented environmental goals.

#### COST-FOCUSED SCENARIO

Shifting the weight toward financial (50%) improves Recycled 6061's score to 8.54, confirming cost advantage. The list stays unchanged, demonstrating the model's reliability under cost-driven scenarios.

### SUPPLIER PRIORITY SCENARIO

Even with supplier-related parameters weighted the most heavily (50%), the model still finds Recycled 6061 and Recycled 6082 as the best possibilities. Their high supplier maturity and availability help them work well, demonstrating that they are capable of handling logistic demand.

**EQUAL WEIGHTS SCENARIO**

When each criterion is given equal weight (33%), the results remain consistent: Recycled 6061 leads with 8.46, followed by Recycled 6082 at 7.87. This supports their balanced performance in all three dimensions.

*Table 17: Scenario Scores*

| Metal | Current Scenario | Environmental-Driven | Cost-Driven | Supplier-Driven | Equal Weights |
|---|---|---|---|---|---|
| Recycled 6061 | 8.3528 | 8.6602 | 8.4536 | 8.6602 | 8.4614 |
| Recycled 6082 | 7.6751 | 8.2121 | 7.9184 | 8.2121 | 7.8723 |
| Recycled 5083 | 6.9395 | 7.7194 | 7.2247 | 7.7194 | 7.3307 |
| Green Steel | 6.1521 | 5.4064 | 6.115 | 5.4064 | 5.4336 |
| Secondary Steel 304 | 4.2914 | 3.5019 | 3.9155 | 3.5019 | 3.8625 |
| Secondary Steel 316L | 3.2432 | 2.6009 | 2.7129 | 2.6009 | 3.1032 |

The weights of all scenarios are presented in Table 17. In all scenarios, Recycled 6061 remains first, showing strong performance despite stakeholder focus. The close second place of Recycled 6082 shows the reliability of aluminium-based materials in terms of sustainability, cost, and supply criteria. These findings support the strategic fit of these options in  different scenarios.

**CONSISTENCY RATIO (CR)**

The Consistency Ratio (CR), an important metric for evaluating the logical coherence of expert judgments in AHP, was used to assess the consistency of the pairwise comparison matrix for the three primary AHP criteria (Environmental, Supplier, and Financial). As stated in Section 3.2.3, the CR for this matrix was calculated to be 0.0213 (see Appendix 3, Table 32). This result is significantly lower than the accepted threshold of 0.10 set by Saaty (1987), showing that the matrix is consistent. According to the literature, a CR value less than 0.10 indicates good consistency in pairwise comparisons, increasing trust in the ensuing weight computations and model outputs (Saaty, 1987; Kabir and Hasin, 2011).

## 4.6 DASHBOARD

To operationalize the Analytical Hierarchy Process (AHP) evaluation, an interactive dashboard  was created in Excel to help in scenario based decision-making. The dashboard combines all environmental, financial, and supplier performance scores before dynamically calculating the final AHP score using company defined weightings for each criterion group.

The company can choose from a variety of weight distribution scenarios, such as cost-focused, supplier-prioritized, or environment-driven, and instantly see how each metal alternative ranks against those criteria. This ensures that the tool adapts to changing strategic goals and purchasing preferences. It further encourages transparency by displaying the specific contributions of each criterion to the overall result.

This dashboard is particularly useful for NTS Hengelo because it enables easy comparison of sustainable metal alternatives, real-time updates when the weighting priorities change, clarity in trade-offs is essential for procurement teams to comprehend the effects of decisions on sustainability, costs, and supply risk.

Figure 16 depicts a static snapshot of the tool.

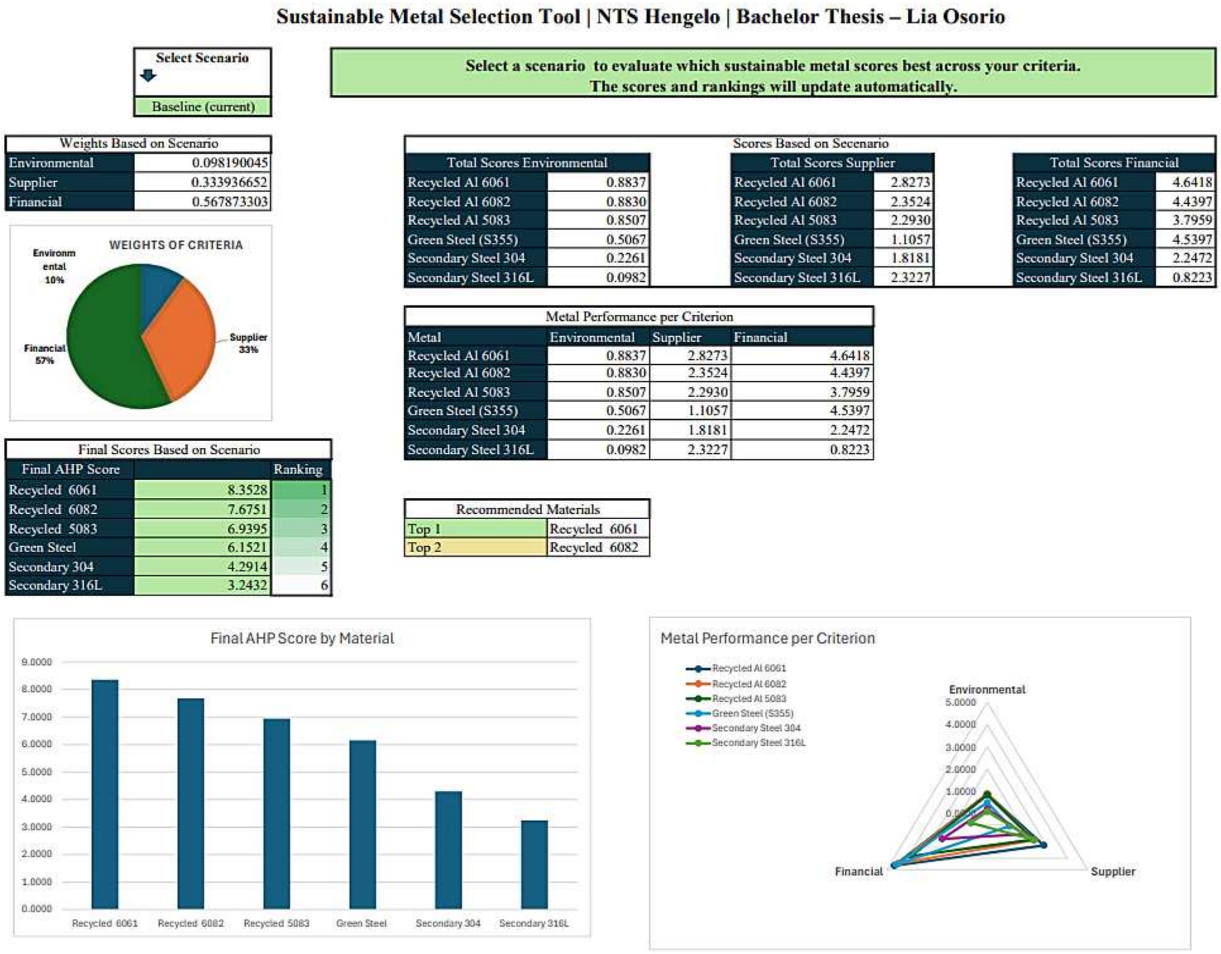



*Figure 16: Dashboard BS*

## 4.7 DASHBOARD VALIDATION

To guarantee the dashboard's practical relevance and functionality, informal validation was carried out with key stakeholders at NTS Hengelo. The tool was presented at progress meetings and internal reviews, and comment was received on its clarity, adaptability, and decision-making support. While the feedback was qualitative and unstructured, it provided significant validation that the dashboard met the company's needs.

The ability to dynamically evaluate multiple weighing scenarios (for example, cost-driven, supplier-priority, or environmental-focused) was emphasized by stakeholders as adding strategic value. It enabled users see how trade-offs between criteria affected rankings and allowed them to choose resources based on specific use cases. For example, numerous team members stressed the importance of seeing how recycled aluminium maintained a solid position in most scenarios, hence supporting its prioritizing. This informal validation revealed that the dashboard promotes procurement clarity and transparency, as planned. Furthermore, feedback indicated that the tool was useful not just for grading materials, but also for promoting internal conversation about sustainability trade-offs.

## 4.8 SUMMARY OF CHAPTER 4

This chapter presented the findings from the AHP model for sustainable material selection. The company emphasized financial criteria (0.588) over supplier (0.294) and environmental (0.118), which influenced the model's weight structure. The sub-criteria evaluation found that environmental criteria were given equal weight, whereas supplier maturity and certificates were preferred. Financial sub-criteria focused on processing costs and market stability.

The final AHP rankings indicated recycled aluminium 6061 as the best performing material across all levels, followed by recycled 6082 and 5083. A sensitivity analysis examined five different weighting situations and found that ranks remained constant proving the model's strength.

All computations were performed using an automated Excel dashboard, following the framework from Section 3.3, which ensured accuracy and transparency in scenario testing and final material evaluation.

# Chapter 5: Conclusion and Recommendations

This final chapter offers the findings and strategic recommendations derived from the AHP-based assessment of sustainable metal alternatives. It addresses the key study topic by combining the multi-criteria evaluation results and analysing the most important trade-offs for NTS Hengelo.

The chapter additionally describes the final phase in the methodological cycle based on Heerkens, van Winden, and Tjooitink (2017), Research Process model, Conclusions. After a methodical approach to problem analysis, criteria construction, method application, and outcome analysis, this chapter gathers the insights to drive practical decision-making.

## 5.1 CONCLUSION

This thesis set out to answer the question: *How can NTS Hengelo identify and select the most suitable sustainable metal alternative to replace at least 4% of its current metal usage to a more sustainable version?* To address this, a customized Analytic Hierarchy Process (AHP) model to help NTS Hengelo, was created to find the most appropriate sustainable metal to replace at least 4% of its present metal usage in the company. The model contains environmental, financial, and supplier criteria, these were broken down into sub-criteria based on information from industry databases, supplier, and literature.

Based on all of these criteria, six alternative materials were examined. Results showed that recycled aluminium 6061, 6082, and 5083 ranked as the best, due to their great carbon footprint reductions, high recycled content, strong supplier networks, and low costs. However, the best implementation strategy depends on more than just combine rankings.

The thesis shows that implementation is more than just selecting the best-ranked material. Strategic trade-offs, such as material use in the company, supplier availability, and CRM exposure, must be evaluated when determining the best implementation. For example, while Aluminium 6061 received the best grade, it has a small proportion of the company's total material usage (2%) this reduces its significance. On the other hand, aluminium 6082, which accounts for 40% of current volume and scored almost as high, provides a more feasible alternative path to fulfill the 4% sustainability requirement.

The framework and results help NTS Hengelo match its material sourcing decisions with EU sustainability targets, circular economy goals, and purchasing limitations, making this model go from an academic tool into a practical decision support model for future use.

## 5.2 RECOMMENDATIONS AND IMPLEMENTATION

To begin implementation, the recommendation is prioritizing recycled aluminium 6082 using an incremental substitution strategy, as outlined in Section 5.2.1. Because aluminium at NTS is normally ordered for specific goods rather than general use, it is easier to progressively replace 6082 in areas where it is already in use. Substitutions should begin with items that have been validated for technical compatibility, quality, and supplier availability.

Once the 4% sustainability objective is met with 6082, then what it is advised is looking into recycled aluminium 6061 for additional replacement alternatives. Despite having a better AHP score, its current low utilization (2%) limits its short-term strategic significance. Recycled aluminium 5083 should be explored for specific applications that require increased corrosion resistance while keeping high sustainability standards.

In addition, another recommendation is keeping track of green steel advances. As supply maturity and traceability increase, green steel may eventually replace conventional structural steel. To improve future decision-making accuracy, the recommendation is increasing internal monitoring of metal usage and cost data per alloy type. A more detailed spend and volume tracking system can help with sustainability projections as well as dynamic AHP model modifications. Furthermore, it is suggested starting to gather operational performance data, such as machining efficiency, delivery cycles, and scrap return rates, in order to gradually replace assumptions with actual company-specific figures. This would increase the reliability of model evaluations over time.

NTS can incorporate the early usage of recycled aluminium and green steel within a larger Corporate Sustainability Reporting Directive (CSRD) plan. This would assist connect sourcing with the EU's sustainable transformation goals and increase transparency.

A final recommendation is being strategically aligned with EU policies on critical raw materials (CRM), circular economy efforts, and carbon regulatory tools. This active alignment guarantees that sourcing and product development decisions are sustainable and future-proof.

### STEPWISE IMPLEMENTATION: FOCUS ON RECYCLED AL 6082

NTS Hengelo purchases aluminium 6082 only when it is required for certain products, so a step-wise adoption plan rather than a full substitution is better. The following step-wise approach shows how to adopt recycled aluminium 6082 while maintaining technical, operational, and supplier reliability:

**Step 1: Technical Compatibility Check**

Identify product groups that now use conventional aluminium 6082 and determine whether recycled alternatives meet the same mechanical, thermal, and surface quality requirements, based on supplier data. Because recycled 6082 has the same alloy composition and machining qualities, it is likely to be interchangeable in many applications..

**Step 2: Supplier Verification and Availability Mapping.**

Consult with major suppliers to ensure the availability of certified recycled 6082 with constant composition, delivery times, and documentation such as EPDs or ISO certificates. Check batch consistency and ensure compliance with internal quality procedures.

**Step 3: Pilot Application Selection**

Choose one or two low risk, high volume product families for pilot implementation. Prioritize the parts that are previously shown in 6082 machining, mechanical complexity ranges from minimal to moderate, have less surface finishing limitations, represent a scalable portion of NTS's overall aluminium volume.

**Step 4: Trial Purchase and Quality Testing.**

Conduct a small volume purchase of recycled 6082 for certain trial items. Perform several quality inspections and production trials, keeping into account any variances in tool wear, machining speed, or finish quality. Collect comments and document process stability.

**Step 5: Data Monitoring and Feedback.**

Monitor criteria, $CO_2$ footprint reduction, recycled content usage, cost variances, machining time, etc. Collaborate with the purchasing and manufacturing teams to gather feedback. Adjust supplier or volume based on the results.

**Step 6: Gradual Scale-Up**
If the trials exceed technical and operational standards, consider expanding adoption to other comparable items that use 6082. Define new milestones (10%, 15%, 20% of 6082 volume) to guide phased integration, taking into account purchasing cycles and supplier capacity.

## 5.3 LIMITATIONS AND FUTURE RESEARCH

This study presents the AHP approach for identifying sustainable metal alternatives. While it provides a transparent, criteria-based evaluation, some limitations must be recognized in order to contextualize the findings and drive future improvements.

First, the study's scope was narrowed to a selection of sustainable metals, namely aluminium and stainless steels, chosen for their relevance to NTS Hengelo's operations. Not all possible sustainable materials were considered, given time limits, data availability, and the company's present usage trends. Although the materials were pre-screened for technical compatibility in high-precision manufacturing environments, this assumption was based on alloy family information. Specific performance-critical components might need further technical validation via mechanical testing or process simulations.

Second, the model performance inputs were derived from secondary data sources, including Granta EduPack, industry studies, and supplier publications. These include environmental indices such as $CO_2$ footprint, embodied energy, and scrap value, as well as economic factors like cost and processing costs. While these sources provide information, they rely on generalized estimations that may not account for supplier-specific data in production processes. This thesis did not conduct a new Life Cycle Assessment (LCA); instead, it relied on previously published studies and EU environmental classification. As a result, live or updated LCA data should be used in future studies to increase the model's reliability and situational accuracy.

Third, environmental performance was analysed using known LCA values and EU Critical Raw Material (CRM) classifications, with the assumption that alloy compositions stay consistent between suppliers. However, the present model did not account for specific post-smelting alloy variations or CRM mass fractions (such as nickel, cobalt, molybdenum, and bauxite concentration). Including these characteristics would provide a more complete understanding of sustainability trade-offs, especially for alloys with similar scores but differing CRM or energy intensities.

Fourth, suppliers' performance was estimated rather than confirmed. The investigation only considered possible suppliers based on maturity, certification existence, and lead time approximations. A comprehensive supplier review, including direct evaluations of reliability, traceability practices, and regional sourcing, has to be completed.

Finally, the study is based on a formal AHP selection model, which excludes qualitative scenario analysis and non-metal alternatives. While the AHP technique gives a clear explanation for ranking based on company-defined priorities, incorporating a Life Cycle Costing (LCC) approach could assist decision-makers in understanding long-term economic trade-offs and total ownership consequences.

## REFERENCES


Aires, R. F. de F., & Ferreira, L. (2022). A New Multi-Criteria Approach for Sustainable Material Selection Problem. *Sustainability*, *14*(18), 11191. https://doi.org/10.3390/su141811191

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. Resources, *Conservation & Recycling*, 55(3), 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Al-Alimi, S., Yusuf, N. K., Ghaleb, A. M., Mohd Amri Lajis, Shazarel Shamsudin, Zhou, W., Altharan, Y. M., Hamza Salah Abdulwahab, Saif, Y., Djamal Hissein Didane, Ikhwan S T T, & Adam, A. (2024). Recycling aluminium for sustainable development: A review of different processing technologies in green manufacturing. *Results in Engineering*, *23*, 102566–102566. https://doi.org/10.1016/j.rineng.2024.102566

*Ansys Granta EduPack | Software for Materials Education*. (2021). Ansys.com. https://www.ansys.com/products/materials/granta-edupack

Ashby, M. F. (2011). *Materials Selection in Mechanical Design*. Book (4th ed.). Elsevier.

Bloomberg. (2025). Bloomberg.com. [Accessed on: 22-05-2025] https://www.bloomberg.com/europe

Bhole, G. P., & Deshmukh, T. (2018). *Multi Criteria Decision Making (MCDM) Methods and its Applications*. *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, 6(V), 899–914. https://doi.org/10.22214/ijraset.2018.5145

Bruschi, S., Bertolini, R., Ghiotti, A., Mahmood, H., & Zanella, C. (2024). Machinability of recycled aluminium alloys. *Manufacturing Letters*, *41*, 1669–1675. https://doi.org/10.1016/j.mfglet.2024.09.194

Chang, W.-S., & Lin, Y.-T. (2019). The effect of lead-time on supply chain resilience performance. *Asia Pacific Management Review*, *24*(4), 298–309. https://doi.org/10.1016/j.apmrv.2018.10.004

European Aluminium. (2025). European Aluminium. [Accessed on: 27-05-2025]. https://european-aluminium.eu/

European Commission. (2025). Critical Raw Materials Act . European Commission. . [Accessed on: 21-04-2025], from https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en.

Gleich, A. von. (2006). Outlines of a Sustainable Metals Industry. *Eco-Efficiency in Industry and Science*, 3–39. https://doi.org/10.1007/1-4020-4539-5_1

Government of The Netherlands (2019). *Circular Dutch economy by 2050*. Government.Nl. . [Accessed on: 2-04-2025] https://www.government.nl/topics/circular-economy/circular-dutch-economy-by-2050

Graedel, T., Allwood, J., Birat, J.-P., Buchert, M.-L.-M., Hagelűken, C., Buchert, M., Reck, B., Sibley, S., Sonnemann, & Guido. (2011). *What Do We Know About Metal Recycling Rates? What Do We Know About Metal RecyclingRates?* https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1605&context=usgsstaffpub

Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P., & Reck, B. K. (2015). Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences*, 112(14), 4257–4262. https://doi.org/10.1073/pnas.1500415112

Heerkens, H., Winden, A. v., & Tjooitink, J.-W. (2017). Solving Managerial Problems Systematically (First edtion). Noordhoff Uitgevers : Noordhoff Uitgevers BV. http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1491449

Herrmann, C., Kara, S., Stark, R., Seliger, G., & Bonvoisin, J. (2017). *Sustainable Production, Life Cycle Engineering and Management Sustainable Manufacturing Challenges, Solutions and Implementation Perspectives*. https://library.oapen.org/bitstream/handle/20.500.12657/27791/1002214.pdf?sequence=1#page=208

HKEX Company. (2025). *Market data | London Metal Exchange*. Lme. https://www.lme.com/Market-data

Hoffmann, C., Karel Eloot, & Wieland Gurlit. (2024, December 19). *Green-steel hubs: A pathway to decarbonize the steel industry*. McKinsey & Company. https://www.mckinsey.com/industries/metals-and-mining/our-insights/green-steel-hubs-a-pathway-to-decarbonize-the-steel-industry

Holloway, L. (1998). Materials selection for optimal environmental impact in mechanical design. *Materials & Design (1980-2015)*, *19*(4), 133–143. https://doi.org/10.1016/s0261-3069(98)00031-4

Hybrit. (2025). *Hybrit*. . [Accessed on: 09-05-2025] https://www.hybritdevelopment.se/en/

International Aluminium Institute | *Leading the Global Aluminium Industry*. (2024). International Aluminium Institute. . [Accessed on: 12-05-2025] https://international-aluminium.org/

*ISO 14001 Milieumanagement Systeem | Een handig overzicht*. (2025, May 2). Cuccibu. https://cuccibu.com/iso-14001-certificering/?gad_source=1&gad_campaignid=21904285891&gbraid=0AAAAAqWK9dS6OCHEWVtmtMqURkW1fWnY-&gclid=CjwKCAjwvO7CBhAqEiwA9q2YJQ-2LMe26YLSoYz-IRQU_3azAemhnLeKFWoyB1aJfdgb2ApCFHRJWRoCaIQQAvD_BwE

Jacquemin, L., Pierre-Yves Pontalier, & Sablayrolles, C. (2012). Life cycle assessment (LCA) applied to the process industry: a review. *The International Journal of Life Cycle Assessment*, *17*(8), 1028–1041. https://doi.org/10.1007/s11367-012-0432-9

Kasse, T., & Johansen, J. (2013). Maturity differences between customer and supplier—challenges, problems, and possible solutions. *Journal of Software Evolution and Process*, *26*(3), 295–305. https://doi.org/10.1002/smr.1582

Krupka, D. (2016). *Catalogue of European standards in the aluminium and aluminium alloys field*. https://european-aluminium.eu/wp-content/uploads/2022/10/catalogue-cen-tc-132-august-2016.pdf

Liu, Z., Geng, Y., Lindner, S., Zhao, H., Fujita, T., & Guan, D. (2012). Embodied energy use in China's industrial sectors. *Energy Policy*, *49*, 751–758. https://doi.org/10.1016/j.enpol.2012.07.016

López, C., Peña, C., & Muñoz, E. (2020). Impact of the Secondary Steel Circular Economy Model on Resource Use and the Environmental Impact of Steel Production in Chile. *IOP Conference Series: Earth and Environmental Science*, *503*(1), 012024. https://doi.org/10.1088/1755-1315/503/1/012024

Lopez, G., Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C. (2023). Towards defossilised steel: Supply chain options for a green European steel industry. *Energy*, *273*, 127236. https://doi.org/10.1016/j.energy.2023.127236

Mehrad, A., & Zangeneh, M. (n.d.). *Comparison between Qualitative and Quantitative Research Approaches: Social Sciences*. Retrieved June 7, 2025, from https://orcid.org/0000-0003-4364-5709

Mishan, E. J., & Euston Quah. (2020). Cost-Benefit Analysis. In *Routledge eBooks*. Informa. https://doi.org/10.4324/9781351029780

Muslemani, H., Liang, X., Kaesehage, K., Ascui, F., & Wilson, J. (2021). Opportunities and challenges for decarbonizing steel production by creating markets for "green steel" products. *Journal of Cleaner Production*, *315*, 128127–128127.

New lean alternative to nickel-based alloys for chemical, oil and gas. (2025). Outokumpu. . [Accessed on: 09-05-2025] https://outokumpu.com/en/expertise/2022/new-lean-alternative-to-nickel-based-alloys.

*NTS | NTS Hengelo: Ultra-precisie*. (2022, November 25). NTS. . [Accessed on: 05-02-2025] https://www.nts-group.com/nl/wie-we-zijn/onze-sites/nts-hengelo/

Nuss, P., & Eckelman, M. J. (2014). Life Cycle Assessment of Metals: A Scientific Synthesis. *PLoS ONE*, *9*(7), e101298. https://doi.org/10.1371/journal.pone.0101298

Ploumis, P. (2025). *Scrap Metal Prices, CME, LME, SHFE Metal Prices,Metal Market Data - ScrapPrices*. ScrapPrices.com. . [Accessed on: 12-05-2025] https://www.scrapprices.com/

Pusateri, V., Hauschild, M. Z., Kara, S., Goulas, C., & Olsen, S. I. (2024). Quantitative sustainability assessment of metal additive manufacturing: A systematic review. *CIRP Journal of Manufacturing Science and Technology*, *49*, 95–110. https://doi.org/10.1016/j.cirpj.2023.12.005

Raabe, D. (2023). The materials science behind sustainable metals and alloys. Chemical Reviews, 123(5), 2436–2608. https://doi.org/10.1021/acs.chemrev.2c00799

Raabe, D., Tasan, C. C., & Olivetti, E. A. (2019). Strategies for improving the sustainability of structural metals. *Nature*, *575*(7781), 64–74. https://doi.org/10.1038/s41586-019-1702-5

Recycling rates of metals: A status report. (2023). UNEP - UN Environment Programme. . [Accessed on: 12-05-2025] https://www.unep.org/resources/report/recycling-rates-metals-status-report

Responsiblesteel. (2025). *We're shaping a more responsible steel industry | ResponsibleSteel*. Responsiblesteel.org. . [Accessed on: 12-05-2025] https://www.responsiblesteel.org/

Reuter, M. A., A. van Schaik, O. Ignatenko, & Haan, G. J. de. (2005). Fundamental limits for the recycling of end-of-life vehicles. *Minerals Engineering*, *19*(5), 433–449. https://doi.org/10.1016/j.mineng.2005.08.014

Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, *9*(3-5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty, T. L., & Vargas, L. G. (2012). The Seven Pillars of the Analytic Hierarchy Process. *International Series in Operations Research & Management Science*, 27–46. https://doi.org/10.1007/978-1-4615-1665-1_2

ScrapMonster. (2025). *Current Scrap Metal Prices - United States, Europe, China & India*. ScrapMonster. https://www.scrapmonster.com/scrap-prices#google_vignette

Scrap Metal Price Index - *Netherlands - Metaloop*. (2025). Metaloop.com. . [Accessed on: 12-05-2025] https://www.metaloop.com/scrap-metal-price/netherlands/

Shamsuddin, M. (1986). Metal Recovery from Scrap and Waste. *JOM*, *38*(2), 24–31. https://doi.org/10.1007/bf03257917

Schwartz, A. J. (1998). *Money, Prices and the Real Economy*. https://www.iea.org.uk/sites/default/files/publications/files/upldbook413pdf.pdf#page=40

Suer, J., Traverso, M., & Jäger, N. (2022). Review of Life Cycle Assessments for Steel and Environmental Analysis of Future Steel Production Scenarios. *Sustainability*, *14*(21), 14131–14131. https://doi.org/10.3390/su142114131

Suer, J., Ahrenhold, F., & Traverso, M. (2022). Carbon Footprint and Energy Transformation Analysis of Steel Produced via a Direct Reduction Plant with an Integrated Electric Melting Unit. *Journal of Sustainable Metallurgy*, *8*(4), 1532–1545. https://doi.org/10.1007/s40831-022-00585-x

Taherdoost, H. & Madanchian. M. (2023). Multi-Criteria Decision Making (MCDM) Methods and Concepts. *Encyclopedia*, *3*(1), 77–87. https://doi.org/10.3390/encyclopedia3010006

Tercero, L. (2019). *Report on the future use of critical raw materials*. https://scrreen.eu/wp-content/uploads/2019/02/SCRREEN-D2.3-Report-on-the-future-use-of-critical-raw-materials.pdf

Thanasegaran, G. (2009). *Reliability and Validity Issues in Research: EBSCOhost*. Utwente.nl. https://web-p-ebscohost-com.ezproxy2.utwente.nl/ehost/detail/detail?vid=0&sid=0e041c6c-40cc-4781-9ff7-87d2c56b697e%40redis&bdata=JnNpdGU9ZWhvc3QtbGl2ZQ%3d%3d#db=bth&AN=43899561

Torrubia, J., Valero, A., & Valero, A. (2023). Energy and carbon footprint of metals through physical allocation. Implications for energy transition. *Resources, Conservation and Recycling*, *199*, 107281. https://doi.org/10.1016/j.resconrec.2023.107281

UNEP. (2011). *Towards a life cycle sustainability assessment: making informed choices on products*. UNEP - UN Environment Programme. https://www.unep.org/resources/report/towards-life-cycle-sustainability-assessment-making-informed-choices-products

Velenturf, A. P. M., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption*, *27*, 1437–1457. https://doi.org/10.1016/j.spc.2021.02.018

Yakubov, V., Ostergaard, H., Shishira Bhagavath, Lun, C., Hughes, J., Evren Yasa, Mani Khezri, Löschke, S. K., Li, Q., & Paradowska, A. M. (2024). Recycled aluminium feedstock in metal additive manufacturing: A state of the art review. *Heliyon*, *10*(5), e27243–e27243. https://doi.org/10.1016/j.heliyon.2024.e27243

# APPENDIX

## APPENDIX 1: COMPANY & SCOPES DATA

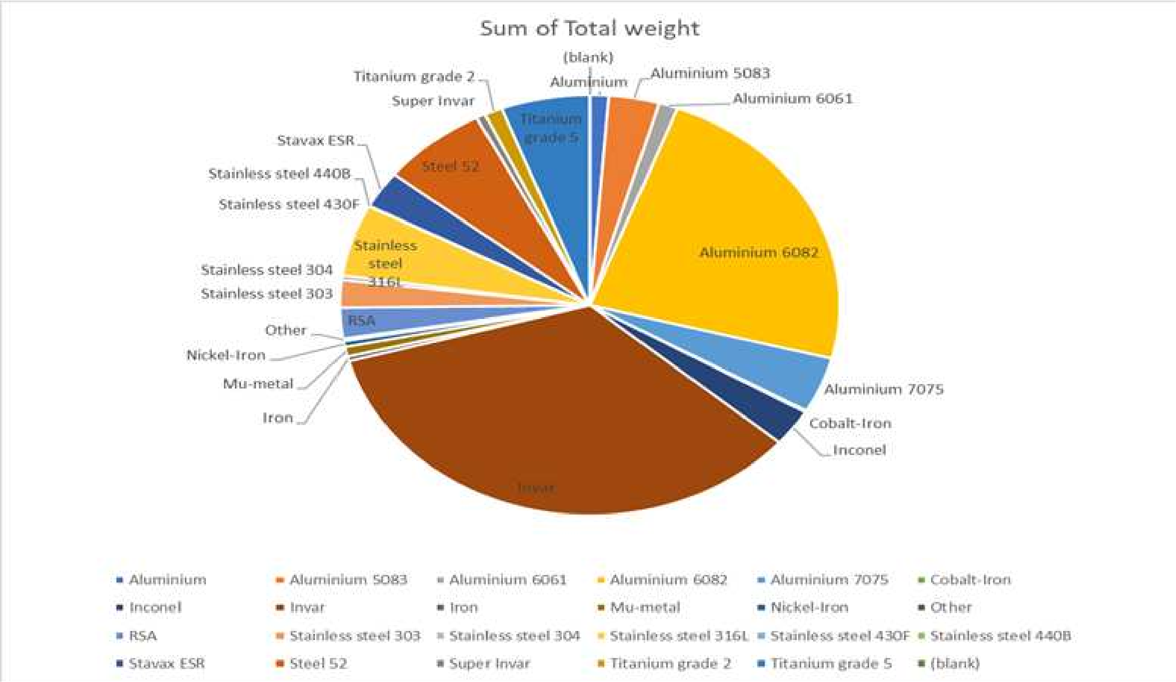



*Figure 18: Metals Used in The Company*

| Name | C | N | Mg | Al | Si | P | S | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Nb | Mo | Rest |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AISI 304 | <0.08 | <0.11 | | | <1.00 | <0.045 | <0.03 | | | 18.00-20.00 | <2.00 | BAL. | | 8.00-10.50 | | | | | |
| AISI 316L | <0.03 | <0.11 | | | <1.00 | <0.005 | <0.03 | | | 16.50-18.50 | <2.00 | BAL. | | 10.00-13.00 | | | | 2.00-2.50 | |
| St 52 | <0.22 | <0.02 | | >0.020 | <0.55 | <0.035 | <0.035 | <0.03 | <0.10 | <0.30 | <1.60 | BAL. | | <0.50 | <0.30 | | <0.005 | <0.08 | |
| Invar 36 | <0.15 | | | | <0.40 | <0.006 | <0.004 | | | <0.25 | <0.60 | BAL. | <0.05 | 35.0-37.0 | <0.5 | | | <0.5 | |
| Super invar | 0.02 | | | | 0.25 | | | | | | 0.4 | BAL. | 5.5 | 32 | | | | | |
| Inconel 718 | <0.08 | | | 0.20-0.80 | <0.35 | <0.0015 | <0.0015 | 0.65-1.15 | | 17.00-21.00 | <0.35 | BAL. | <1.00 | 50.00-55.00 | <0.30 | | 4.75-5.50 | 2.80-3.30 | <0.006 B |
| Mu metal | | | | | 0.1-0.4 | | | | | | 0.3-0.5 | BAL. | | 80 | | | | 5 | |
| Stavax | 0.35-0.42 | | | | <1.10 | | | | 0.15-0.45 | 13.10-14.35 | <1.00 | BAL. | | | | | | | |
| Ti Grade 2 | <0.08 | <0.05 | | | | | | BAL. | | | | <0.3 | | | | | | | <0.015<br><0.25 O |
| Ti Grade 5 (Ti-6Al-4V) | <0.08 | <0.05 | | 5.50-6.75 | | | | BAL. | 3.50-4.50 | | | <0.4 | | | | | | | <0.0125 H<br><0.2 O |
| Al 5083 | | | 4.00-4.90 | BAL. | <0.40 | | | 0.15 | | 0.05-0.25 | 0.40-1.00 | <0.40 | | | <0.10 | <0.25 | | | |
| Al 6061 | | | 0.80-1.20 | BAL. | 0.40-0.80 | | Korrelver-fijner | <0.15<br>korrelver-fijner | | 0.04-0.35 | <0.15 | <0.70 | | | 0.15-0.40 | 0.25 | | | <0.05 each<br><0.15 tot |
| Al 6082 | | | 0.60-1.20 | BAL. | 0.70-1.30 | | | <0.10 | | <0.25 | 0.40-1.00 | <0.50 | | | <0.10 | <0.20 | | | <0.05 each<br><0.15 tot |
| Al 7075 | | | 2.1-2.9 | BAL. | <0.40 | | | <0.20 | | 0.18-0.28 | <0.30 | <0.50 | | | 1.2-2.0 | 5.1-6.1 | | | <0.05 each<br><0.15 tot |
| RSA 426 | | | | BAL. | 24.0-28.0 | | | | | | | <0.7 | | | | | | | <0.1 each<br><0.3 tot |

*Figure 17: Metal Components*

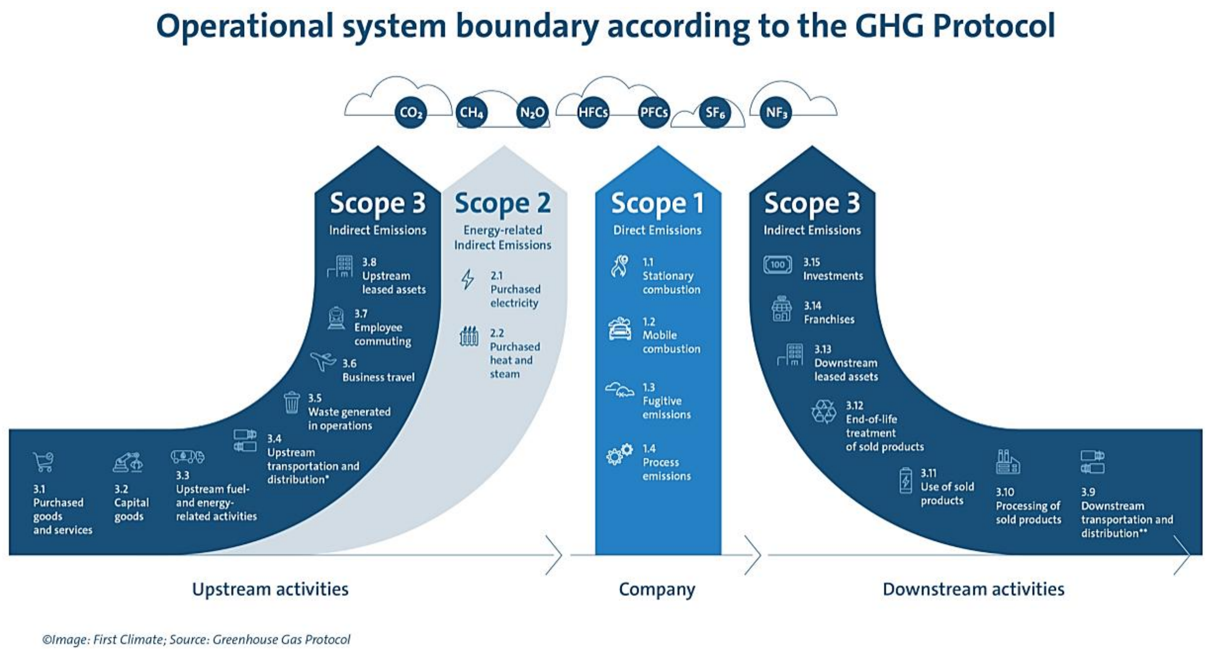



*Figure 19: Scope 1, 2 and 3*

# APPENDIX 2: RESEARCH DESIGN

*Table 18: Research Design*

| KQ | Research Type | Themes | Research Strategy | Data Gathering | Data Processing | Deliverables | Activity Plan |
|---|---|---|---|---|---|---|---|
| KQ1 | Descriptive | $CO_2$ emissions, production analysis | Qualitative | Company reports, emission data, interviews | Qualitative content analysis | Problem statement, emission baseline | Review literature → Identify $CO_2$ issues → Formulate problem statement |
| KQ2 | Exploratory | Sustainable metal options, emissions | Qualitative | Market scan, literature review, supplier data | Comparative emission analysis | List of viable sustainable metals | Scan market → Identify sustainable metals → Collect emissions data |
| KQ2.2 | Exploratory | Criteria identification (technical, environmental, financial) | Qualitative | Academic and industry literature, company needs | Thematic classification | Validated evaluation criteria | Review evaluation methods → Extract criteria → Align with company goals |
| KQ3 | Descriptive | Criteria operationalizatio n | Mixed | Material specifications, benchmarks | Indicator development, scoring methods | Operationalized criteria framework | Define indicators → Collect specification data → Develop score metrics |
| KQ4 | Descriptive | AHP framework setup | Mixed | AHP structure development | Model building in AHP tool | AHP decision model | Build hierarchy → Define alternatives → Link to criteria |
| KQ4.2 | Exploratory | Criteria weighting | Mixed | Expert input, stakeholder feedback | Weight calculation and validation | Final weighting matrix | Consult experts → Gather input → Assign and normalize weights |
| KQ5 | Descriptive | Sensitivity testing | Quantitative | Scenario modeling | Scenario impact modeling | Robustness check report | Change weights → Run AHP → Analyze shifts in rankings |
| KQ5.2 | Descriptive | Result visualization | Qualitative | Design vizualitation results, stakeholder | Graph ond/or tables with summary of results | Presentation-ready visuals | Create visuals → Gather feedback → Finalize presentation format |
| KQ6 | Descriptive | Trade-off assessment | Mixed | Performance and cost data, $CO_2$ comparison | Comparative matrix of trade-offs | Summary of trade-offs and recommendation s | Compare top options → Quantify trade-offs → Draft recommendations |

# APPENDIX 3: OPERATIONALIZATION OF CRITERIA

*Table 19: CRM Calculation and Normalized Score*

| CRM Content | | |
|---|---|---|
| Metal | CRM Content (%) | Score |
| Recycled Al 6061 | 0 | 9 |
| Recycled Al 6082 | 0 | 9 |
| Recycled Al 5083 | 0 | 9 |
| Green Steel (S355) | 0 | 9 |
| Secondary Steel 304 | 8 | 4 |
| Secondary Steel 316L | 13 | 1 |

*Table 20: Cost kg Calculation and Normalized Score*

| Cost per Kilogram | | | | |
|---|---|---|---|---|
| Metal | Virgin Avg (€) | Virgin | Sustainable Est. (€) | Score |
| Recycled Al 6061 | (2.74 + 3.77)/2 = 3.26 | 3.26 | 2.934 | 6 |
| Recycled Al 6082 | (2.71 + 3.76)/2 = 3.24 | 3.24 | 2.916 | 6 |
| Recycled Al 5083 | (2.84 + 3.89)/2 = 3.37 | 3.37 | 3.033 | 6 |
| Green Steel (S355) | (1.02 + 1.25)/2 = 1.14 | 1.14 | 1.425 | 9 |
| Secondary Steel 304 | (3.65 + 5.81)/2 = 4.73 | 4.73 | 4.257 | 3 |
| Secondary Steel 316L | (4.86 + 7.40)/2 = 6.13 | 6.13 | 5.517 | 1 |

*Table 21: Scrap Value Calculation and Normalized Score*

| Scrap Value per Kilogram | | | |
|---|---|---|---|
| Metal | Approx. Scrap Value (€/kg) | Approx. Value | Score |
| Recycled Al 6061 | 1.3 | 1.3 | 9 |
| Recycled Al 6082 | 1.3 | 1.3 | 9 |
| Recycled Al 5083 | 1.2 | 1.2 | 8 |
| Green Steel (S355) | 0.3 | 0.3 | 1 |
| Secondary Steel 304 | 0.75 | 0.7 | 4 |
| Secondary Steel 316L | 1 | 1 | 7 |

*Table 22: Processing Cost Calculation and Normalized Score*

| Processing Cost | | | |
|---|---|---|---|
| Metal | Processing Cost Impact | Multiplier | Score |
| Recycled Al 6061 | Low | 1 | 9 |
| Recycled Al 6082 | Low-Med | 1.1 | 8 |
| Recycled Al 5083 | Medium | 1.2 | 7 |
| Green Steel (S355) | Low | 1.1 | 8 |
| Secondary Steel 304 | Medium-High | 1.5 | 3 |
| Secondary Steel 316L | High | 1.7 | 1 |

*Table 23: Stability Calculation and Normalized Score*

| Cost Stability / Market Stability | | | |
|---|---|---|---|
| Material | Cost Stability | Multiplier | Score |
| Recycled Al 6061 | High | 5 | 9 |
| Recycled Al 6082 | High | 5 | 9 |
| Recycled Al 5083 | Moderate-High | 4 | 7 |
| Green Steel (S355) | High | 5 | 9 |

| | | | |
|---|---|---|---|
| Secondary Steel 304 | Moderate | 3 | 5 |
| Secondary Steel 316L | Low | 1 | 1 |

*Table 24: Availability Calculation and Normalized Score*

| Supplier Availability | | | |
|---|---|---|---|
| Metal | Availability | Multiplier | Score |
| Recycled Al 6061 | Very High | 5 | 9 |
| Recycled Al 6082 | Very High | 5 | 9 |
| Recycled Al 5083 | Moderate | 3 | 1 |
| Green Steel (S355) | Very High | 5 | 9 |
| Secondary Steel 304 | Very High | 5 | 9 |
| Secondary Steel 316L | High | 4 | 5 |

*Table 25: Maturity Calculation and Normalized Score*

| Supplier Maturity | | | |
|---|---|---|---|
| Metal | Supplier Maturity | Multiplier | Score |
| Recycled Al 6061 | High | 5 | 9 |
| Recycled Al 6082 | High - Mefium | 4 | 6 |
| Recycled Al 5083 | High | 5 | 9 |
| Green Steel (S355) | Medium | 2 | 1 |
| Secondary Steel 304 | Medium - High | 3 | 4 |
| Secondary Steel 316L | High | 5 | 9 |

*Table 26: Certification Calculation and Normalized Score*

| Certifications / Treaceability | | | |
|---|---|---|---|
| Metal | Certification | Multiplier | Score |
| Recycled Al 6061 | High | 5 | 9 |
| Recycled Al 6082 | High - Medium | 4 | 6 |
| Recycled Al 5083 | High | 5 | 9 |
| Green Steel (S355) | Medium - High | 3 | 4 |
| Secondary Steel 304 | Medium | 2 | 1 |
| Secondary Steel 316L | High - Medium | 4 | 6 |

*Table 27: Lead Time Calculation and Normalized Score*

| Lead Time | | | |
|---|---|---|---|
| Metal | Typical Lead Time | Multiplier | Score |
| Recycled Al 6061 | 4–8 weeks | 4 | 7 |
| Recycled Al 6082 | 4–8 weeks | 4 | 7 |
| Recycled Al 5083 | 5–7 weeks | 4 | 7 |
| Green Steel (S355) | 4–6 weeks (pilot) or 2026+ (H2GS) | 1 | 1 |
| Secondary Steel 304 | 3–6 weeks | 5 | 9 |
| Secondary Steel 316L | 4–6 weeks | 4 | 7 |

*Table 28: Supplier Availability Scores*

| Metal | Availability in EU | Notes / Example Suppliers | Score |
|---|---|---|---|
| Recycled Al 6061 | Very High | AMAG Austria Metall AG / E MAX / Hydro / Apple Steels | 5 |
| Recycled Al 6082 | Very High | AMAG Austria Metall AG / E MAX / Hydro / Apple Steels | 5 |
| Recycled Al 5083 | Moderate | AMAG Austria Metall AG / Hydro / Apple Steels | 3 |
| Green Steel (S355) | Very High | H2 Green Steel / SSAB / Tata Steel / HYBRIT | 5 |
| Secondary AISI 304 | Very High | Apple Steels / Aperam / Outokumpu / ITG Steel | 5 |
| Secondary AISI 316L | High | Apple Steels / Aperam / Outokumpu / ITG Steel | 4 |

*Table 29: Supplier Maturity Scores*

| Material | Supplier Maturity | Notes / Example Suppliers | Score |
|---|---|---|---|
| Recycled Al 6061 | High | AMAG Austria Metall AG / E MAX / Hydro / Apple Steels | 5 |
| Recycled Al 6082 | High - Mefium | AMAG Austria Metall AG / E MAX / Hydro / Apple Steels | 4 |
| Recycled Al 5083 | High | AMAG Austria Metall AG / Hydro / Apple Steels | 5 |
| Green Steel (S355) | Medium | H2 Green Steel / SSAB / Tata Steel / HYBRIT | 2 |
| Secondary AISI 304 | Medium - High | Apple Steels / Aperam / Outokumpu / ITG Steel | 3 |
| Secondary AISI 316L | High | Apple Steels / Aperam / Outokumpu / ITG Steel | 5 |

*Table 30: Certifications and Traceability Scores*

| Material | Certification / Traceability Strength | Notes & Example Certifications | Score |
|---|---|---|---|
| Recycled Al 6061 | High | Hydro CIRCAL (EPD, ISO 14001), AMAG (EPD), E-MAX (ISO 50001) | 5 |
| Recycled Al 6082 | High – Medium | Same supplier set as 6061; some mills lack ISO 50001 | 4 |
| Recycled Al 5083 | High | Hydro / AMAG EPDs & QR material passports | 5 |
| Green Steel (S355) | Medium-High | SSAB & HYBRIT pilot EPDs; $H_2$ Green Steel planning ISO-cert launch (2026) | 3 |
| Secondary AISI 304 | Medium | Outokumpu Circle Green EPDs; some traders lack full disclosure | 2 |
| Secondary AISI 316L | High-Medium | Outokumpu (ISO 14001/50001, EPD); Aperam Recyco traceability | 4 |

*Table 31: Approximate Lead Time*

| Material | Supplier | Approx. Lead Time (Weeks) | Notes |
|---|---|---|---|
| Recycled 6061 | AMAG / Hydro | 4–6 | Regular production with EPD-certified output; AMAG has strong EU presence. |
| | E-MAX | 4–8 | Dependent on billet casting cycles and order volume. |
| | Apple Steels | 6–10 | International sourcing from India with scrap format variability. |
| Recycled 6082 | AMAG / Hydro | 4–6 | Good availability; Hydro CIRCAL can offer quick turnaround in Europe. |
| | E-MAX | 4–8 | Often linked to specific extrusion needs. |
| | Apple Steels | 6–10 | Scrap-based, longer due to export time and limited control. |
| Recycled 5083 | AMAG / Hydro | 5–7 | Plate and rolled formats may take longer due to rolling schedules. |
| | Apple Steels | 6–10 | Scrap only; requires reprocessing. |
| Green Steel | H2 Green Steel | 2026+ | First commercial deliveries expected mid-2026. |
| | SSAB (HYBRIT) | 4–6 | Limited fossil-free steel in pilot availability; bulk delivery later. |
| | Tata Steel | 6–10 | Depending on conversion to electric arc furnace (still transitioning). |
| Secondary 304 | Outokumpu / Aperam | 3–5 | Widely available; short lead due to stock and EU-based mills. |
| | ITG Steel | 5–8 | Reseller; may require sourcing time from multiple sites. |
| | Apple Steels | 6–10 | International shipping and handling. |
| Secondary 316L | Outokumpu / Aperam | 4–6 | More niche than 304, but good availability from primary EU suppliers. |
| | ITG Steel / Apple Steels | 6–10 | Scrap or secondary format; longer if reprocessing is needed. |

## APPENDIX 4: MODEL AND RESULTS

*Table 32: Principal Eigenvalue and Critical Ratios Calculation*

| CI calculation | Environmental | Supplier | Financial | Sum | Sum/Weight |
|---|---|---|---|---|---|
| Environmental | 0.098 | 0.083 | 0.114 | 0.295 | 3.007 |
| Supplier | 0.393 | 0.334 | 0.284 | 1.011 | 3.026 |
| Financial | 0.491 | 0.668 | 0.568 | 1.727 | 3.041 |
| | | | | ʎ max = | 3.025 |

| Metric | Value |
|---|---|
| Principal Eigenvalue (λ) | 3.0247 |
| Consistency Index (CI) | 0.0123 |
| Random Index (RI) | 0.5800 |
| Consistency Ratio (CR) | 0.0213 |

*Table 33: Principal Eigenvalue for Environmental Criteria*

| Environmental Criteria | | | | | | |
|---|---|---|---|---|---|---|
| Eigenvalue calculation | Carbon Footprint | Recycled Content | CRM Content | Embodied Energy | sum | sum/weight |
| Carbon Footprint | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 1.0000 | 4.0000 |
| Recycled Content | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 1.0000 | 4.0000 |
| CRM Content | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 1.0000 | 4.0000 |
| Recyclability | 0.2500 | 0.2500 | 0.2500 | 0.2500 | 1.0000 | 4.0000 |
| | | | | | ʎ max = | 4.0000 |

*Table 34: Principal Eigenvalue for Supplier Criteria*

| Supplier Criteria | | | | | | |
|---|---|---|---|---|---|---|
| Eigenvalue calculation | Supply Chain Av. | Lead Time | Supplier Maturity | Certifications | sum | sum/weight |
| Supply Chain Av. | 0.2000 | 0.2000 | 0.2000 | 0.2000 | 0.8000 | 4.0000 |
| Lead Time | 0.2667 | 0.2667 | 0.2667 | 0.2667 | 1.0667 | 4.0000 |
| Supplier Maturity | 0.2667 | 0.2667 | 0.2667 | 0.2667 | 1.0667 | 4.0000 |
| Certifications | 0.2667 | 0.2667 | 0.2667 | 0.2667 | 1.0667 | 4.0000 |
| | | | | | ʎ max = | 4.0000 |

*Table 35: Principal Eigenvalue for Financial  Criteria*

| Financial Criteria | | | | | | |
|---|---|---|---|---|---|---|
| Eigenvalue calculation | Cost per kg | Market Stability | Scrap Value | Processing Cost | sum | sum/weigh t |
| Cost per kg | 0.2800 | 0.2800 | 0.2800 | 0.2800 | 1.1200 | 4.0000 |
| Market Stability | 0.3200 | 0.3200 | 0.3200 | 0.3200 | 1.2800 | 4.0000 |
| Scrap Value | 0.0800 | 0.0800 | 0.0800 | 0.0800 | 0.3200 | 4.0000 |
| Processing Cost | 0.3200 | 0.3200 | 0.3200 | 0.3200 | 1.2800 | 4.0000 |
| | | | | | ʎ max = | 4.0000 |

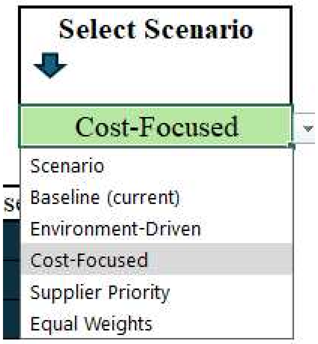
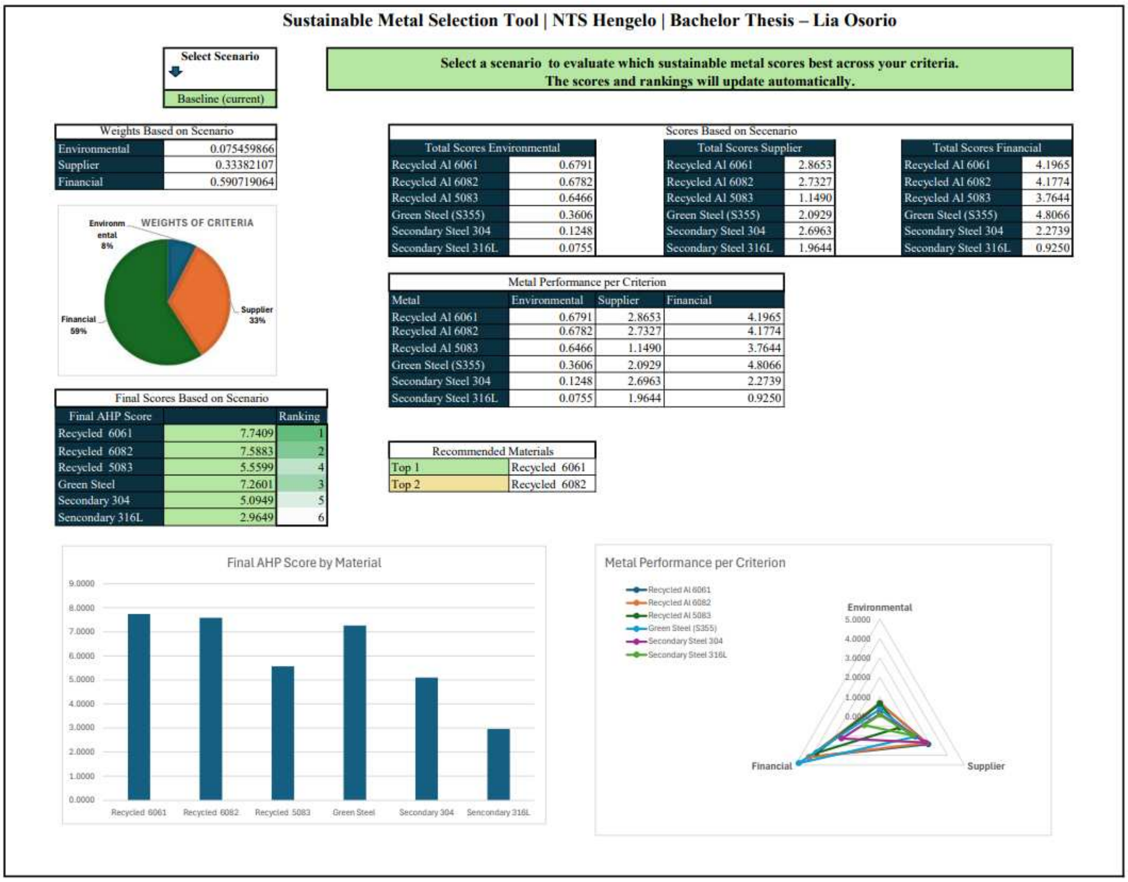



*Figure 20: Scenario Choices*



**Sustainable Metal Selection Tool | NTS Hengelo | Bachelor Thesis – Lia Osorio**

| Select Scenario |
|---|
| Baseline (current) |

**Select a scenario to evaluate which sustainable metal scores best across your criteria.
The scores and rankings will update automatically.**

| Weights Based on Scenario | |
|---|---|
| Environmental | 0.075459866 |
| Supplier | 0.33382107 |
| Financial | 0.590719064 |



| Final Scores Based on Scenario | | |
|---|---|---|
| Final AHP Score | | Ranking |
| Recycled 6061 | 7.7409 | 1 |
| Recycled 6082 | 7.5883 | 2 |
| Recycled 5083 | 5.5599 | 4 |
| Green Steel | 7.2601 | 3 |
| Secondary 304 | 5.0949 | 5 |
| Sencondary 316L | 2.9649 | 6 |

Scores Based on Secenario

| Total Scores Environmental | | Total Scores Supplier | | Total Scores Financial | |
|---|---|---|---|---|---|
| Recycled Al 6061 | 0.6791 | Recycled Al 6061 | 2.8653 | Recycled Al 6061 | 4.1965 |
| Recycled Al 6082 | 0.6782 | Recycled Al 6082 | 2.7327 | Recycled Al 6082 | 4.1774 |
| Recycled Al 5083 | 0.6466 | Recycled Al 5083 | 1.1490 | Recycled Al 5083 | 3.7644 |
| Green Steel (S355) | 0.3606 | Green Steel (S355) | 2.0929 | Green Steel (S355) | 4.8066 |
| Secondary Steel 304 | 0.1248 | Secondary Steel 304 | 2.6963 | Secondary Steel 304 | 2.2739 |
| Secondary Steel 316L | 0.0755 | Secondary Steel 316L | 1.9644 | Secondary Steel 316L | 0.9250 |

Metal Performance per Criterion

| Metal | Environmental | Supplier | Financial |
|---|---|---|---|
| Recycled Al 6061 | 0.6791 | 2.8653 | 4.1965 |
| Recycled Al 6082 | 0.6782 | 2.7327 | 4.1774 |
| Recycled Al 5083 | 0.6466 | 1.1490 | 3.7644 |
| Green Steel (S355) | 0.3606 | 2.0929 | 4.8066 |
| Secondary Steel 304 | 0.1248 | 2.6963 | 2.2739 |
| Secondary Steel 316L | 0.0755 | 1.9644 | 0.9250 |

| Recommended Materials | |
|---|---|
| Top 1 | Recycled 6061 |
| Top 2 | Recycled 6082 |



*Figure 21: Dashboard*