UNIVERSITY DEGLI STUDI DI PADOVA

Department of Industrial Engineering DII

Master's Degree in Energy Engineering

Comparative Life Cycle Assessment of Separator Tank Structural Materials

Supervisor: Prof. Anna Stoppato

Graduated: Farzaneh Akbari, 2043089

Academic Year 2023/2023

I express my heartfelt gratitude to my family. To my mother, father, and sister, your unwavering support, love, and encouragement have been my greatest motivation. Thank you for being the pillars of strength in my academic journey.

List of Content

Abstract

I collaborated with a company to conduct an environmental study, following UNI EN ISO 14040:2021 and UNI EN ISO 14044:2021 guidelines. The study employed Sima-Pro LCA software and the ReCiPe 2016 Endpoint (H) version 1.07 methodology. The findings provide crucial insights for guiding environmentally conscious decisions in hydronic systems. The study aims to compare the environmental impacts of coated iron and stainless-steel versions of the Hydraulic Separator. The results indicate that stainless steel has approximately 64% more impact during the usage phase. Despite improvements within defined boundaries for a 15-year period, the study emphasizes the importance of considering the potential extended life expectancy associated with stainless steel. Furthermore, it is essential to highlight that the uncertainty analysis performed is focused exclusively on data uncertainty and does not encompass the assumptions made during the study. The uncertainty estimate, specific to the impact category of Climate Change, accounts for mean, median, standard deviation (SD), coefficient of variation (CV), and the two values defining the 95% confidence interval (2.50% and 97.5%). In addition, the study comprehensively explores various impact categories, including Global Warming over a 100-year interval (GWP100). The assessment also covers Freshwater Ecotoxicity, Marine Ecotoxicity and Human Carcinogenic Toxicity. The study highlights the significant impact during the usage phase, emphasizing the need for sustainable practices and energy efficiency improvements. It underscores the importance of holistic life cycle assessments, considering material choices, design improvements, and user behavior. Ultimately, the assessment's reliability hinges on end users' energy supply/generation practices.

Chapter 1
Introduction

In an era where environmental consciousness is imperative, the choice of materials for a wide range of applications holds significant ecological consequences. This study embarks on a journey of exploration, delving into the environmental implications of materials, particularly in the context of separators. In various industrial and operational settings, separators serve as essential components, and it is noteworthy that iron and stainless-steel tanks are predominantly utilized as their housing, contributing to a consistent presence in their application. Recent engineering analyses reveal that the use of iron and stainless-steel separators not only aligns with environmental sustainability but also offers enhanced structural integrity and corrosion resistance, crucial factors in ensuring long-term functionality. From an engineering standpoint, these materials demonstrate superior performance in comparison to other metals, meeting stringent industry standards for durability and reliability. Moreover, ongoing research indicates advancements in manufacturing processes that further reduce the environmental footprint associated with the production of iron and stainless-steel separators. This innovative engineering approach not only strengthens their environmental credentials but also solidifies their position as preferred materials in various industrial sectors, showcasing a harmonious blend of engineering excellence and environmental responsibility [20].

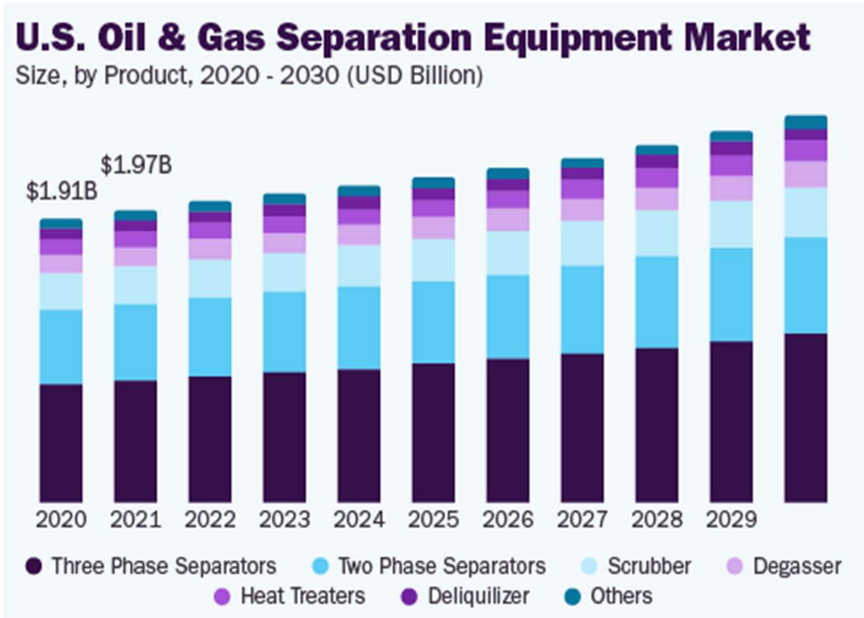

Figure 1.1: The oil and gas separation equipment market [2]

For instance, in the oil and gas industry, separators are crucial for the separation of oil, gas, and water, ensuring efficient resource extraction and reducing environmental contamination [2].

In wastewater treatment plants, separators play a pivotal role in separating solids from liquids, purifying water, and safeguarding ecosystems. In wastewater treatment plants, separators are like important guardians. They play a key role in keeping our environment safe and making sure we use water wisely. These plants have a big job that is turning dirty water into clean water we can use again. Separators, a crucial part of this process, act as protectors by removing things like dirt and pollutants from the water. This helps improve the quality of the water, making it safe to put back into rivers or use in different industries. But separators do more than clean water. They also help keep our environment in balance. By separating solid stuff from the water, they stop harmful things from getting into rivers and lakes. This is very important for keeping our water and the animals that live in it healthy. Now, when it comes to making separators, using tough materials like iron and stainless steel is a smart choice. These materials make separators strong and able to withstand the tough conditions in wastewater treatment. So, not only do they help clean water, but they also last a long time, making our efforts to treat water more sustainable. [37]. Additionally, in the food and beverage industry, separators are employed to separate liquids from solids or separate different liquid components, maintaining product quality and safety, offering a reliable choice for their usage across industries. Iron and stainless steel, with their distinct physical characteristics, offer functional advantages that make them prominent choices for separator systems. Iron, appreciated for its magnetic properties, is an excellent candidate for applications requiring magnetic separation, efficiently separating ferrous materials from non-ferrous materials, providing a consistent method of material separation. Its strength and cost-effectiveness further contribute to its popularity in separator tank construction, ensuring reliability in the materials used [15].

Stainless steel, on the other hand, is notable for its remarkable corrosion resistance, making it a top choice for separator systems that come into contact with corrosive substances. Its non-porous and easy-to-clean surface lends itself well to applications where hygiene and sanitation are paramount, maintaining a high standard of cleanliness and reliability. Additionally, stainless steel's durability ensures a long service life, and its recyclability aligns with environmentally responsible practices, contributing to the reliability of the material choices. Moreover, stainless steel has an impressive array of features that enhance its suitability for separator systems, which we will discuss in the following. First, the high strength of stainless steel, which has a high strength-to-weight ratio ensures structural integrity and longevity in separator applications, and its ability to withstand extreme temperatures ensures consistent performance in separators operating under varying environmental conditions. Stainless steel's resistance to the corrosive effects of a broad spectrum of chemicals makes it ideal for separator systems in chemical processing industries, offering a reliable material choice across chemical sectors [3], [19]. Second, its smooth, shiny finish not only contributes to a professional appearance but also aids in maintaining cleanliness in separator systems, ensuring reliable cleanliness.

As we explore these materials and their applications in separator tanks, it becomes evident that their physical characteristics and resistance properties significantly impact their environmental footprints. Understanding the advantages and challenges posed by iron and stainless steel in separator systems is essential, especially considering growing environmental concerns, climate change, resource scarcity, and the imperative need for sustainable practices by considering the fact that 9.1% of wastes is metal [16].

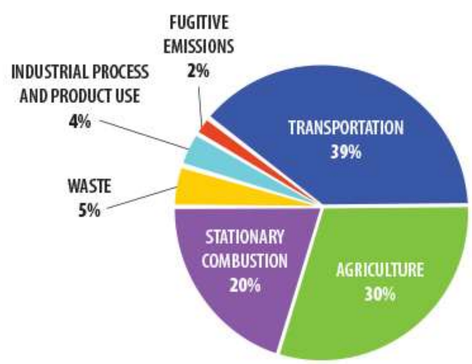

Figure 1.2.: Impact of the materials in the environmental footprint [16]

The importance of caring for our environment and making informed material choices is paramount, particularly when it comes to separator systems that play a vital role in numerous industries. The ecological implications of the materials chosen for separator tanks have far-reaching consequences, impacting ecosystems, economies, and society at large. It is our duty to contemplate the profound implications of these choices and seek environmentally responsible alternatives [9].

In this context, we delve into the environmental implications of the prevalent use of iron and stainless steel in separator tanks, shedding light on their advantages and challenges [3], [15]. Life

Cycle Assessment (LCA) investigations, inquiries that encompass environmental considerations, offer valuable insights into this technology. LCA-based studies play a significant role in assessing the environmental impacts from the curdle to gate[1] of products and systems, enabling equitable comparisons of various technologies.

1.1. Literature Review

In the field of industry related to metals and Life Cycle Assessment (LCA), numerous studies have been conducted, primarily focusing on several key areas which are Technological Advancements, Environmental Impact Reduction, Resource Efficiency, Economic Viability, Life Cycle Thinking, Policy and Regulatory Frameworks, Sustainability Metrics and Hybrid Systems. A growing emphasis has been placed on Environmental Impact Reduction, considering not only direct environmental impacts but also indirect effects, potential trade-offs, and the entire life cycle of metal projects. Based on the findings presented in this article [4], the U.S. iron industry, responsible for 83% of coal demand in the manufacturing sector, utilizes coal as both a primary fuel and feedstock for coke production. This results in significant greenhouse gas emissions, with direct emissions in 2019 reaching 72 million metric tons of CO2 equivalent, equivalent to 6% of total U.S. manufacturing sector emissions [4]. The compelling evidence of iron's substantial environmental impact motivates the exploration of alternative materials like steel.

1.1.1. Materials and Methods

- Life-cycle assessment

[1] refers to the assessment of environmental impacts throughout the entire life cycle of a product, from raw material extraction (cradle) to the point where the product leaves the factory gate (gate). This assessment includes all stages such as raw material production, manufacturing, transportation, and sometimes use and end-of-life considerations.

LCA calculations were accomplished by using software SimaPro version 7.2.4 in compliance with ISO 14040 (2006) that defines four main steps within an LCA study: goal and scope definition, inventory modeling, impact assessment, and final interpretation.

1) Goal and scope definition

The goal of the study was to assess the environmental impacts of integrated iron and steel industries in US and to compare the impacts associated with the sub-processes as well as the impacts associated with the final products. The system boundary was assigned as “cradle to gate”. Upstream processes, transportation, production processes and utility services were included to cradle to gate boundary. The upstream processes are acquisitions of raw materials, energy, and auxiliary materials. The transportation stage indicates the transportation of materials, such as raw materials, auxiliary materials, and fuels. The production processes for steel production are divided into two parts, the main production system and the utility services. The main production system comprises of the following sub-processes: coke making (CM), sintering (S), blast furnaces (BF), basic oxygen furnaces (BOF), casting (C) and hot rolling (HR). The utility services include energy and water facilities and mechanical workshop. The energy facility comprises boiler, turbo generator, turbo blower, pure water, waste heat, and oxygen plants producing steam, electricity, compressed air, steam and oxygen respectively. Water facility supplies pure water, service water and sea water. Mechanical workshop is responsible for repair and manufacturing of machine parts. The mechanical workshop had been excluded during the LCA evaluations conducted for the sub-processes and products as the contribution of this unit to specific processes or products cannot be disintegrated.

2) Data inventory

The data inventory stage involves the quantification of flows and materials and energy required to produce the functional unit of interest. In the present study, a field study was carried out in one of the three integrated iron and steel production facilities in US in order to collect the inventory data. The selected facility has the features to reveal the average values of integrated iron and steel industry in US having the share of about 35% in steel production via integrated means. Thus, this facility is considered as a representative sample of US integrated iron and steel industry in terms of manufacturing technologies and production capacity. The information about acquisitions of raw materials, energy and auxiliary materials were not obtained from the facility, but instead was taken from the inventories in the database of SimaPro. Among the databases involved, primarily Ecoinvent database was preferred. In case the information was not available in this database, the other databases (Dutch Input Output Database 95, ELCD, EU&DK Input Output Database, Industry data 2.0, USA Input Output Database 98 and USLCI) were used. The data not specific to country were directly taken from the databases whereas country-specific ones were selected according to the suitability to the country conditions such as geographical similarities. For example, the electricity provided by the network was adapted using the percentages of energy sources specific to electricity production in USA to reflect country specific conditions.

The functional unit, enabling alternative products to be compared was selected as 1 ton of final steel product. The final steel products are of basically two types, one being semi-finished products, namely, slab and billet; and the other being finished products, namely, hot rolled coil and hot rolled wire rod.

3) Life cycle impact assessment methods

The impact assessment steps were Characterization, Damage Assessment, Normalization and Single Score. A method covering the category indicators at endpoint level was favored in this study. By this way, the results of midpoint level can also be seen and to ease the interpretation step endpoint results were used. IMPACT 2002þ method that combines the advantages of the IMPACT 2002 methodology, CML 2002 Ecoinvent database, and IPCC List (IPCC, 2001), was selected in this study as the assessment method. The IMPACT 2002þ method offers a feasible execution of a combined midpoint/damage approach, linking all types of life cycle inventory results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, nonrenewable energy, and mineral extraction) to four damage categories. Nevertheless, the damage factors for the impact categories of aquatic acidification and aquatic eutrophication are under development in IMPACT 2002þ version 2.1 in SimaPro 7.1 software. So, the effects on the damage categories of aquatic acidification and aquatic eutrophication are not calculated. The weighting factor of 1 was used as default value as suggested by the IMPACT 2002þ. The detail information of IMPACT 2002þ method could be found in the document entitled “IMPACT 2002þ. [38]

4) Interpretation

The last phase of the LCA process is life cycle interpretation. The objective of this step is to analyze results and reach conclusions based on the findings of the preceding 3 phases. In the present study, normalized and single score results were used for the evaluation of the results from impact assessment stage in accordance with the goal of the study.

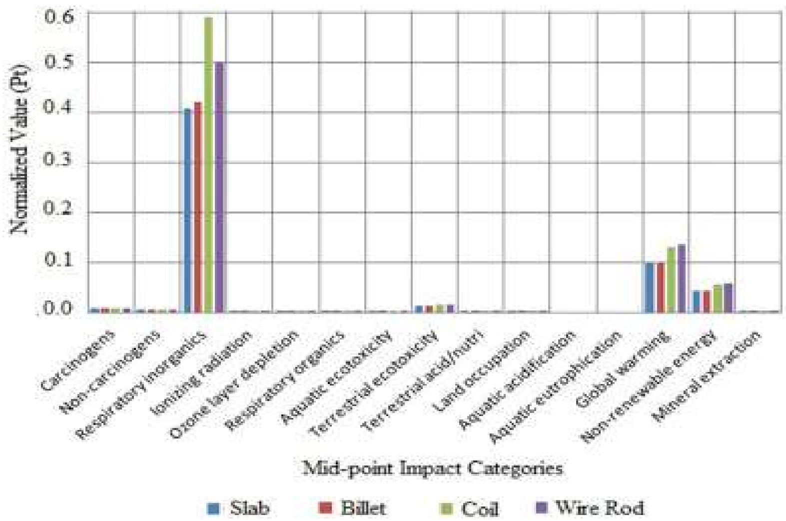

Figure 1.3.: environmental impacts per one ton of production

1.1.2. Results and Discussion

1) Sub-process based environmental impacts.

The study assessed environmental impacts in the liquid steel production process, focusing on sub-processes. Results showed that coke making (CM), sinter production (S), blast furnaces (BF), and basic oxygen furnace (BOF) had varying impacts. In CM, it exhibited the second-highest impact on 'Resources' (non-renewable energy), and contrary to expectations, it mainly contributed to 'Global Warming,' with coke oven gas recycling reducing global warming potential. S had a significant impact on 'Respiratory Inorganics' (Human Health), with major contributors being emissions from the process (50.2%), recycled sinter dust (28.3%), and iron ore (5.3%), and noteworthy global warming impact despite no avoided products. In BF, it showed the highest impact on 'Human Health' due to respiratory effects, with 'Respiratory Inorganics' dominating, mainly from sinter (31.9%) and pellet (25.2%) inputs.

Process	Product	Human health	Ecosystem quality	Climate change	Resources	Total
Coke	Coke	1.46E-01	2.1E-02	−6.13E-02	1.09E-01	2.15E-01
Sinter	Sinter	3.51E-01	1.06E-02	5.87E-02	1.65E-02	4.37E-01
BF	LI	2.70E-01	1.00E-02	1.35E-02	7.30E-03	3.00E-01
BOF	LS	4.10E-01	1.57E-02	9.49E-02	4.14E-02	5.62E-01
Casting	Billet	4.35E-01	1.67E-02	1.02E-01	4.33E-02	5.97E-01
	Slab	4.24E-01	1.63E-02	1.00E-01	4.32E-02	5.84E-01
HR	WR	5.15E-01	1.94E-02	1.35E-01	5.91E-02	7.29E-01
	Coil	6.06E-01	2.18E-02	1.30E-01	5.66E-02	8.15E-01

EI-environmental impact BF- Blast Furnace BOF- Basic Oxygen Furnace HR- Hot Rolling LI –Liquid Iron LS-Liquid Steel WR-Wire Rod.

Figure 1.4.: Summary of the normalized impact assessment results (Pt)

The BF gas was a major CO2 contributor, and its recycling reduced environmental impact. In BOF, the highest impact was on 'Respiratory Inorganics,' similar to S and liquid iron (LI) production. Liquid steel (LS) production downstream had the most significant total environmental impact, with one ton of LS having the highest overall impact. LI had the highest impact on 'Human Health.' S followed in impacts on 'Human Health' (80.1%) and 'Climate Change' (13.4%). CM had a priority in depleting non-renewable energy sources (67.6%), followed by LS. [32], [38].

1.2. Thesis Scope

The primary objective of this groundbreaking study is to conduct a meticulous assessment of the sustainability implications associated with the transition from the prevalent usage of Equicall 45l 332101 iron to the potentially more eco-friendly Equicall X50l 332002 stainless steel, with a specific focus on the variant Equicall X50l 332002, as a viable alternative material for separator tanks. Our overarching goal is to undertake a comprehensive life cycle assessment (LCA) that spans from the cradle to the grave, ensuring a thorough examination of the environmental and ecological effects stemming from this material switch. In order to achieve the highest degree of accuracy and relevance in our analysis, we sourced data from G3 Company. Through a collaborative effort, we categorized and input this information into SimaPro, employing a mass balance approach to ensure the inclusion of both waste streams and the final product in our assessment. This strategic use of SimaPro allowed us to delve deeper into the intricacies of the environmental impact, considering various factors that contribute to the life cycle of separator tanks. Furthermore, to provide a more holistic perspective, we have incorporated detailed data on energy consumption throughout the entire process. This addition to our study enables a nuanced understanding of the ecological footprint associated with the material switch, encompassing the energy-intensive phases of manufacturing, assembly, and transportation [5]. Our comprehensive LCA will extend its evaluation to include the sourcing of primary materials, the manufacturing process, assembly, packaging, and the transportation involved in both the arrival of primary materials and the final product's delivery to end-users. Additionally, we will explore various energy backup systems, further contributing to the nuanced analysis of the ecological effects associated with scaling up the system. By delving into the intricacies of the life cycle, our study aims to provide not only a detailed understanding of the environmental impact but also insights into potential areas for improvement and optimization. This wealth of information is poised to guide informed decision-making in terms of material selection for separator tanks, promoting sustainable practices and contributing significantly to the ongoing global commitment to environmental conservation. Through our research, we aspire to establish a benchmark for environmentally conscious decision-making in the domain of separator tank materials.

Chapter 2
Separator tank

Separators are devices or equipment used to separate different components or phases within a mixture, such as a fluid or gas. There are various types of separators, each designed for specific separation tasks. These types are based on the mechanisms and principles used for separation. In the following count some common types of separators are Vertical Hydraulic Separators, Gravity Separators, Cyclone Separators, Centrifuges and Gas-Liquid Separators [14], [36].

In this project, our focus is on the investigation of vertical hydraulic separators paired with buffer tanks, with the aim of identifying the most environmentally sustainable choice of metal for the tank, considering its LCA.

Figure 2.1.: Vertical Hydraulic Separators [10]

In hydronic heating systems, vertical hydraulic separators play a pivotal role in hydraulic separation, effectively isolating hot supply water from the cooler return water. This separation optimizes the efficiency of the heating source, promoting its peak performance. Integrated with the separator, buffer tanks act as thermal reservoirs, strategically storing excess hot water and releasing it as needed. This buffering function, integral to the heating system, plays a critical role in maintaining a steady temperature profile. By acting as a stabilizer, it effectively counteracts temperature fluctuations, resulting in a more consistent and reliable performance. This not only enhances comfort but also significantly contributes to the overall energy efficiency of the heating system. In practical terms, the buffering function serves as a regulator, absorbing excess heat when it is generated and releasing it when the system demands additional warmth. This dynamic equilibrium ensures that the temperature remains within the desired range, preventing abrupt spikes or drops that could compromise both the system's effectiveness and the user's comfort.

Beyond its immediate impact on temperature control, the buffering function indirectly influences energy efficiency. By minimizing temperature swings, the system operates more smoothly, reducing the need for frequent adjustments or excessive energy consumption. This optimized performance not only benefits the end user by providing a consistently comfortable environment but also aligns with sustainable energy practices by promoting a more efficient use of resources.

In essence, the buffering function acts as a stabilizing force within the heating system, fostering a harmonious balance between temperature regulation, comfort, and energy efficiency. Its nuanced role goes beyond mere temperature control, making it a key element in the quest for optimized and sustainable heating solutions.

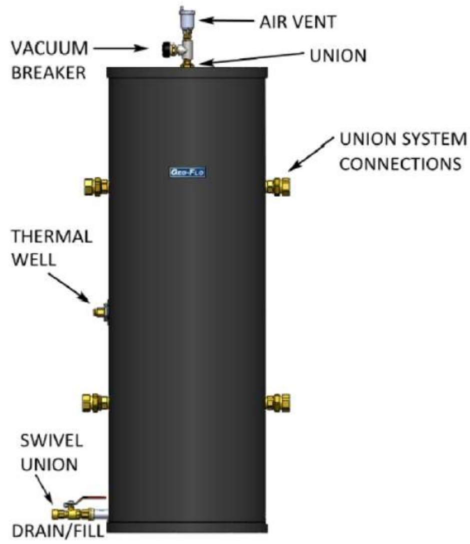

Figure 2.2.: Buffer Tank

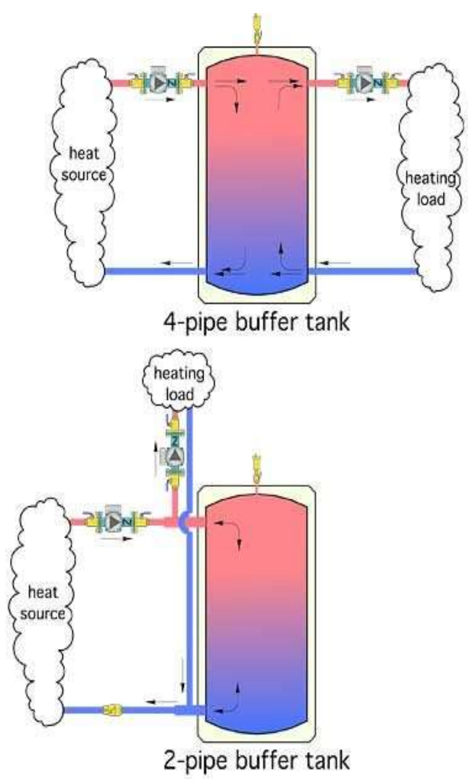

Figure 2.3.: Pipe Buffer Tank

Some hydraulic separators also feature air and dirt removal mechanisms. Within some hydraulic separators, the incorporation of air and dirt removal mechanisms stands out as a key feature, acting as a shield against potential threats to the system's efficiency and durability. This added functionality serves to counteract the adverse impacts that air and dust can have on the overall performance of the heating system. Air, when present in the hydraulic system, can disrupt efficient heat transfer, and create air pockets, impeding the smooth circulation of heating fluid. The integrated air removal mechanism actively expels trapped air, ensuring optimal fluid flow and heat exchange. This not only safeguards the system's efficiency but also reduces the risk of uneven heating and potential damage to components. Concurrently, the inclusion of a dirt removal mechanism addresses the influence of impurities like dust and debris on the hydraulic system. Over time, these contaminants can accumulate, leading to blockages, increased friction, and accelerated wear on components. The dirt removal feature proactively combats these issues, preventing the buildup of impurities and facilitating an unobstructed flow of the heating fluid. In doing so, it plays a pivotal role in sustaining efficiency and extending the lifespan of the entire heating system. The incorporation of air and dirt removal mechanisms in hydraulic separators strategically tackles the challenges posed by air and dust without redundancy. By addressing these issues at their source, these separators not only ensure the consistent operation of the heating system but also contribute to its long-term reliability and durability [29]. They are constructed predominantly from materials like carbon steel because it is generally compatible with common hydraulic fluids. The material's chemical composition is suitable for use in hydraulic systems without negatively interacting with the fluids. This ensures that the dust and air removal mechanisms remain effective without introducing contaminants or compromising the hydraulic fluid's integrity. The separator and buffer tank are often coated or painted to shield against corrosion, ensuring equipment longevity. These versatile components are designed for secure installation on carbon steel walls, an imperative step in guaranteeing the effective operation of hydraulic separators and buffer tanks [23].

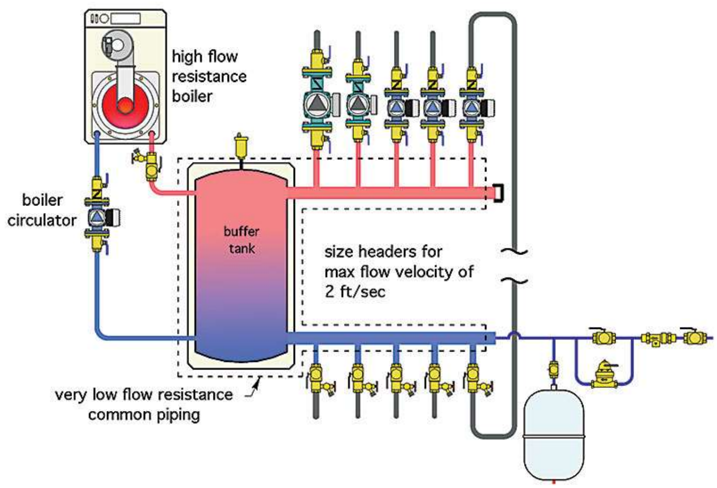

Figure 2.4.: schematic of the power plant

2.1. Iron Tank

In the context of separation processes, an iron tank is a crucial component used in various industrial applications. These tanks, often made from iron or iron-based materials, are chosen for their strong engineering properties, which provide both economic and environmental benefits. In separation processes, iron tanks are favored due to their resistance to rust and corrosion. This resistance means they require less maintenance and replacement, which, in turn, reduces overall costs. Their structural strength allows them to withstand demanding conditions within separators, such as exposure to different fluids, wide temperature variations, and varying pressure levels. This durability improves reliability and cost-effectiveness, aligning with principles of sustainability. collaboration between engineers and material scientists to make environmentally responsible material choices [22].

Physical Feature	Description
Material Composition	Steel with specific alloy components
Corrosion Resistance	Resistant to corrosion under various conditions
strength	High tensile strength (75,000 psi) and excellent structural integrity
Temperature Range	Operates within a wide temperature range (-40°C to 800°C)
Pressure Capacity	Can handle high pressures (up to 5000 psi)
Coatings	May have additional protective coatings (e.g., epoxy)

Figure 2.5.: Physical characteristics of Iron [6]

From a practical standpoint, the selection of iron tanks highlights the importance of choosing materials that can withstand the substances they will encounter, a fundamental aspect of engineering design.

2.2. Stainless Steel Tank

Stainless steel tanks, recognized for their corrosion resistance, durability, and hygienic features, are versatile containers widely used across diverse industries. Commonly constructed from corrosion-resistant alloys like 304 or 316 stainless steels, these tanks find applications in sectors such as food and beverage, pharmaceuticals, chemicals, and water treatment.

Their non-reactive nature and resistance to corrosion make stainless steel tanks suitable for various environments. The smooth surface facilitates easy cleaning, ideal for industries with stringent hygiene requirements. Additionally, their long lifespan and ability to withstand harsh conditions reduce the need for frequent replacements. These tanks come in specialized types, including storage tanks for long-term storage, mixing tanks for blending liquids or solids, and pressure vessels for managing internal pressures, showcasing their versatility across industries.

Environmental considerations highlight the high recyclability of stainless steel, contributing to resource conservation and reducing the environmental footprint. Proper disposal and recycling practices further minimize waste sent to landfills. The longevity and inherent durability of stainless-steel tanks contribute to a reduction in replacements, aligning with resource efficiency goals. Energy efficiency is demonstrated over their long-term use, offsetting the initial energy investment during manufacturing. Environmentally friendly cleaning practices enhance sustainability, and conscientious end-of-life considerations ensure minimal waste volume sent to landfills. In economic aspects, while stainless steel tanks may have higher upfront costs, their long-term benefits often justify the investment. The total cost of ownership (TCO), lowered by extended lifespan and low maintenance, contributes to cost-effectiveness. Industries with corrosion-resistant storage needs witness a favorable return on investment (ROI). Customization and adaptability enhance operational efficiency, and the higher resale value of used tanks influences economic decisions [35]. In the specialized domain of the separator industry, stainless steel tanks play a vital role in oil and gas separation processes. Their unparalleled corrosion resistance, exceptional durability, and high strength in pressure vessels ensure reliability in harsh conditions. Customization capabilities facilitate efficient separation processes, and easy cleaning and hygienic design maintain process purity. The resistance to scaling and fouling minimizes the need for frequent maintenance, contributing to optimal operational efficiency. Long-term cost savings, compliance with industry standards, environmental compliance, and recyclability align with sustainable practices.

2.3. Separators in dual-flow hydronic systems

In hydronic heating systems, separators play a crucial role in ensuring the efficient and effective operation of the system. Dual-flow hydronic systems often incorporate separators to manage the flow of water and remove air or other impurities. In this system as we mentioned there are two circuits. The primary flow refers to the main flow of the fluid within a system, typically associated with the transport of heat or energy from the source to the destination serves the main purpose of distributing thermal energy from the source to the various heating or cooling components within the system and in the following. The secondary flow, on the other hand, refers to a separate circulation loop within the system, often designed to enhance the overall efficiency or provide additional functionality and allow for temperature control in different areas or zones. This can contribute to energy efficiency and occupant comfort. In the intricate design and operation of dual-flow hydronic systems, the Reynolds number (Re) assumes a main role as an essential engineering parameter, providing critical insights into fluid flow characteristics. The Reynolds number significantly influences separator design, particularly in turbulent flows where advanced features are systematically integrated to efficiently manage air and impurity removal. where fluid motion is characterized by chaos and irregularity. Calculated using parameters like fluid velocity, density, and viscosity, the Reynolds number aids in identifying the specific flow regime, be it laminar, transitional, or turbulent. In turbulent flows, characterized by high Reynolds numbers, rapid and irregular fluid movement poses challenges to effective separation. This influence extends to factors such as separation efficiency, pressure drop, sizing, and geometry considerations. Turbulent flows generally result in higher pressure drops, necessitating a careful balance between achieving efficient separation and managing energy requirements. In the design process, engineers must optimize fluid dynamics by considering the Reynolds number, adapting internal structures, such as baffles or plates, to accommodate turbulence and enhance separation efficiency. Consequently, a comprehensive understanding of the Reynolds number is essential for tailoring separator designs that navigate the intricacies of turbulent flows, ensuring optimal performance and efficient phase separation in various industrial applications. thereby optimizing heat transfer and overall system performance. The Reynolds number is calculated as the ratio of inertial to viscous forces [18].

$$Re = \frac{\rho . v . D}{\mu}$$

where ρ denotes fluid density, v represents fluid velocity, D stands as the characteristic dimension, and μ signifies dynamic viscosity. The Reynolds number guides the categorization of flow regimes. For instance, in the primary circuit with a flow rate of 5 $\frac{m^3}{h}$ and a pipe diameter of $0.05m$, the Reynolds number undergoes meticulous analysis to ascertain whether the flow exhibits laminar characteristics (Re < 2000) or turbulent behavior (Re > 4000). This analytical process is methodically replicated for the secondary circuit featuring a flow rate of 8 $\frac{m^3}{h}$. The Reynolds number significantly influences separator design, particularly in turbulent flows where advanced features are systematically integrated to efficiently manage air and impurity removal, thereby optimizing heat transfer and overall system performance [14]. Beyond Reynolds' number considerations, the dual-flow hydronic system encompasses key components seamlessly integrated into a comprehensive cycle. Initiated by a boiler or heat source, the primary circuit employs a pump to circulate fluid through a strategically positioned primary circuit separator, facilitating the removal of air and impurities. The resultant clean fluid advances to the distribution system, where it is systematically directed into the secondary circuit for delivery to distinct zones or loads. Here, another separator ensures the effective removal of air and impurities before the fluid reaches terminal units such as radiators or fan coils, facilitating heat transfer to the surrounding space. The fluid, having successfully completed its cycle, retraces its path through the return piping to the boiler or chiller, thereby culminating the dual-flow hydronic cycle [28].

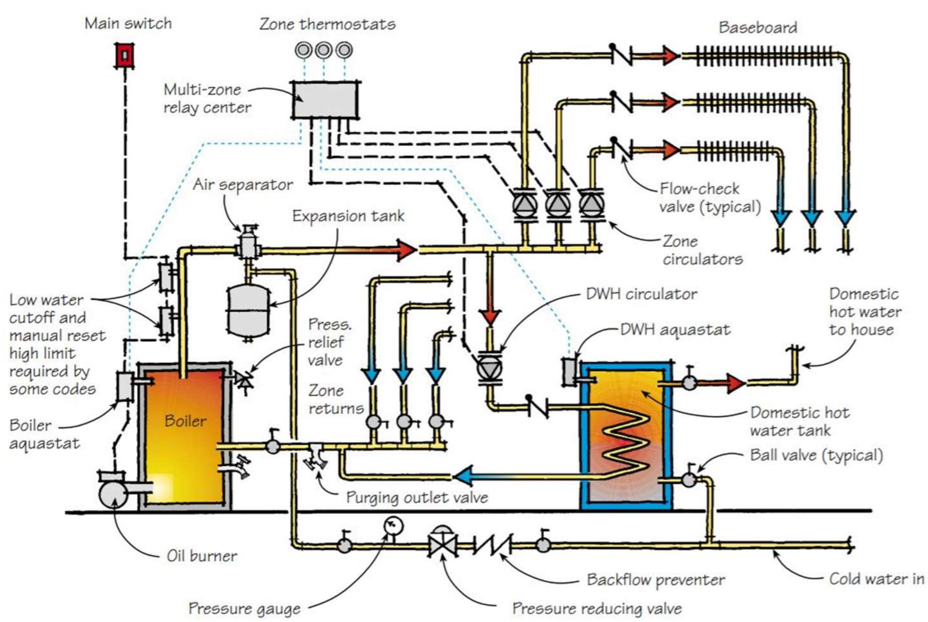

Figure 2.6.: dual-flow hydronic Power Plant Diagram

This comprehensive approach, seamlessly integrating Reynolds number considerations with the precise sizing and strategic placement of separators, ensures the efficient and reliable operation of the entire dual-flow hydronic system. By incorporating Reynolds number considerations, which relate to the fluid flow characteristics such as velocity and viscosity, the design of the system is fine-tuned to match the specific requirements of the fluid dynamics involved. The sizing of separators plays a pivotal role in maintaining optimal flow conditions within the hydronic system. Strategically placed separators efficiently remove air and impurities, preventing their accumulation and potential disruption to the system's performance. This not only enhances heat transfer efficiency but also minimizes the risk of equipment damage caused by the adverse effects of air pockets or debris. Moreover, the strategic placement of separators is carefully orchestrated to align with the fluid dynamics and heat exchange requirements of the dual-flow hydronic system. This thoughtful placement ensures that separators effectively capture and remove air bubbles and particles, safeguarding the integrity of the fluid and contributing to the system's overall reliability. The synergistic combination of Reynolds number considerations, precise separator sizing, and strategic placement not only optimizes heat transfer throughout the system but also serves as a protective measure against potential operational disruptions. By minimizing the risk of equipment damage, this approach contributes significantly to the system's longevity, reducing the likelihood of premature wear and tear on critical components. In addition to its role in equipment protection, this comprehensive approach upholds the equilibrium of the hydronic cycle. By promoting a balanced and efficient flow of the heat transfer fluid, it prevents imbalances that could lead to uneven heating, system inefficiencies, or excessive energy consumption. The result is a dual-flow hydronic system that not only meets performance expectations but also operates with enhanced durability and longevity [17].

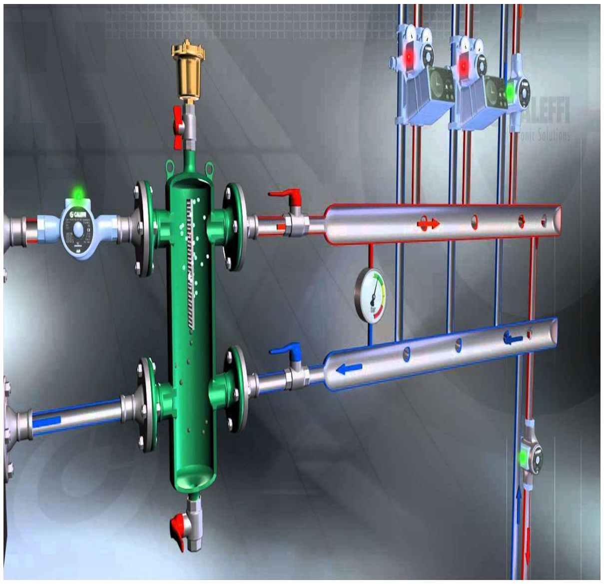 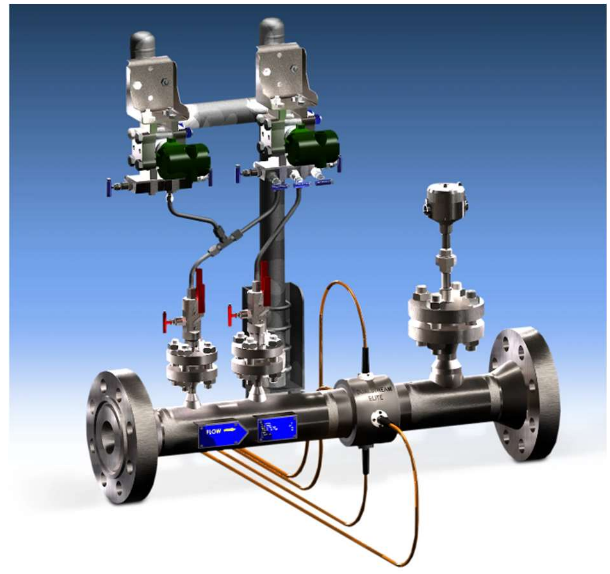

Figure 2.7.: dual-flow hydronic Power Plant Diagram

Chapter 3

Life Cycle Assessment

This section offers a broad overview of the Life Cycle Assessment methodology, in accordance with the standards outlined in ISO 14040 and 14044. ISO 14040 and ISO 14044 are two international standards that form the basis for life cycle assessment (LCA), a method used to assess the environmental impacts of a product, process, or service throughout its entire life cycle. These standards were developed by the International Organization for Standardization (ISO) to provide a consistent and standardized approach to conducting life cycle assessments.

a) ISO 14040: Environmental management - Life cycle assessment - Principles and framework:

   ISO 14040 sets out the general principles and framework for conducting life cycle assessments. It provides guidance on the goals and scope of an LCA, as well as the definition of the functional unit (the unit of analysis), system boundaries, and life cycle stages. This standard emphasizes the importance of transparency, consistency, and accuracy in conducting life cycle assessments. It outlines the key steps of an LCA, including goal and scope definition, inventory analysis, impact assessment, and interpretation of results.

b) ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines:

ISO 14044 complements ISO 14040 by providing specific requirements and guidelines for conducting a life cycle assessment. It is intended to ensure the reliability and consistency of LCA studies. The standard outlines the detailed steps involved in each phase of an LCA, including data collection, inventory analysis, impact assessment, and interpretation. It also provides guidance on selecting appropriate impact categories and characterization models. ISO 14044 emphasizes the need for data quality and data validation, encouraging practitioners to use reliable and relevant data in their assessments. It also addresses uncertainty and sensitivity analysis to enhance the robustness of LCA results. Together, ISO 14040 and ISO 14044 form a comprehensive framework for conducting life cycle assessments. The goal is to enable organizations to make informed decisions about the environmental performance of their products or processes, considering all stages from raw material extraction to end-of-life disposal. Compliance with these standards helps ensure the credibility and comparability of LCA results across different studies, industries, and regions.

These internationally recognized guidelines provide a robust framework for conducting LCA, ensuring a systematic and holistic approach to evaluating the environmental impact across a product's entire life cycle. By adhering to these standards, practitioners gain a reliable methodology to assess environmental considerations in a thorough and standardized manner.

3.1. Definition

Life cycle assessment is one of the methods being developed for better understand and address the possible impacts associated with any goods or services, it quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues. According to the ISO 14040 [1],” LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product’s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave).”

Figure 3.1.: Life Cycle Thinking Schema

Life cycle assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise and others [1], [34].

When conducting an LCA, the design or development phase is usually excluded, since it is often assumed not to contribute significantly. However, one has to note that the decisions in the design or development phase highly influence the environmental impacts in the other life cycle stages. The design of a product strongly predetermines its behavior in the subsequent phases (e.g., the design of an automobile determines the fuel consumption and emissions for kilometer driven in the use phase and has a high influence on the feasible recycling options in the end-of-life phase). If the aim of an LCA is the improvement of goods and services, one of the most important LCA applications, then the study should be carried out as early in the design process as possible and concurrent to the other design procedures. This applies analogously to the design or improvement of a process within a life cycle of a product, especially if interactions with other processes or life cycle stages can occur [1], [34].

For policy development, LCA aligns with Integrated Product Policies, considering a product's entire life cycle. Governments can leverage LCA data to create regulations and incentives that promote environmentally friendly practices throughout the supply chain. LCA informs decision-makers by offering detailed insights into a product's environmental impacts. This knowledge guides the formulation of policies and standards that align with broader environmental objectives.

In marketing, LCA supports environmental claims and ecolabeling, enhancing transparency for consumers. Verified LCA data fosters trust and empowers eco-conscious purchasing decisions.

The creation of Environmental Product Declarations (EPDs) is facilitated by LCA, providing a standardized report on a product's environmental performance, and contributing to the dissemination of eco-friendly practices [13], [34].

3.2. Structure

A Life Cycle Assessment Consists Of 4 Phases:

a) Definition of Goal and Scope;

b) Inventory Analysis;

c) Impact Assessment;

d) Interpretation.

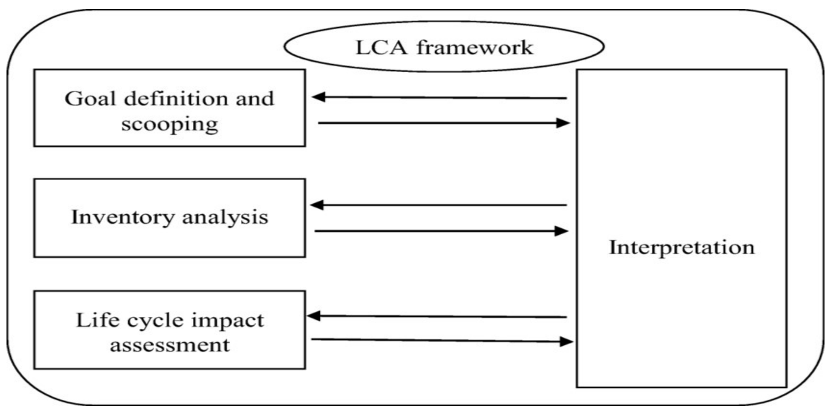

Figure 3.2.: Life Cycle Assessment Stages [1]

Life Cycle Assessment (LCA) conceptualizes the life cycle of a product as its product system, which undertakes one or more specified functions. The defining characteristic of a product system lies in its function and cannot be solely defined by the final products it yields. These product systems are further divided into a series of unit processes, interconnected through flows of intermediate products and/or waste for treatment. They are also linked to other product systems through product flows and connected to the environment via elementary flows.

Breaking down a product system into its constituent unit processes enables the identification of inputs and outputs within the overall system. In many instances, some inputs become integral components of the output product, while others (termed ancillary inputs) are utilized within a unit process but do not contribute to the final output product. This systematic breakdown facilitates a comprehensive understanding of the flow of materials and energy throughout the product system's life cycle [1].

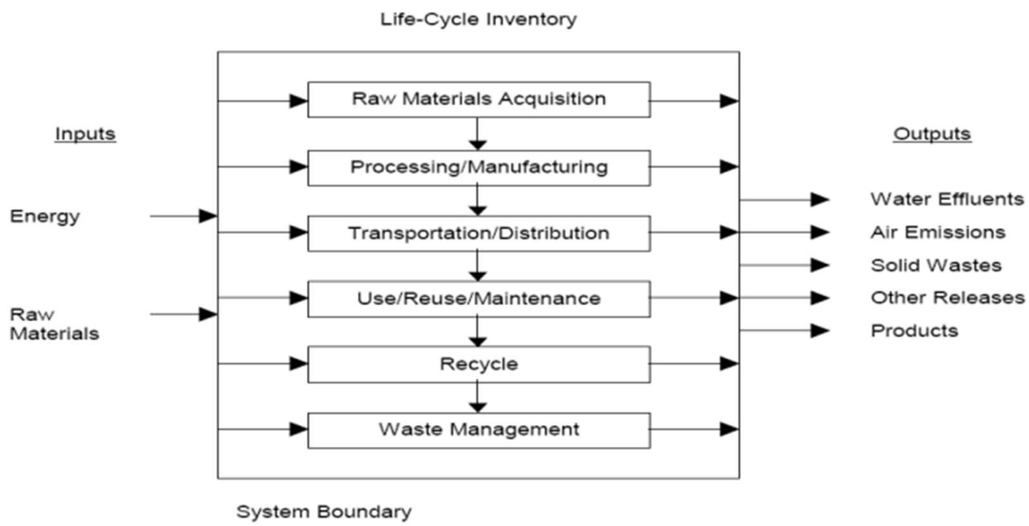

Figure 3.3.: Example of Product System[2]

In the context of Life Cycle Assessment (LCA) and environmental impact assessments in general, primary, and secondary sources of data refer to the origin and nature of the data used in the analysis.

a) Primary Sources of Data:

- Direct Measurements: Primary data are collected through direct measurements or observations specific to the product, process, or system being assessed. This may include on-site measurements, surveys, or experiments conducted to gather information about resource use, emissions, and other relevant parameters.

[2] http://www.ecoil.tuc.gr/LCA-2.pdf

- Manufacturer Data: Information provided by the manufacturer of the product or system under evaluation. This may include production data, material composition, energy consumption, and waste generation.

b) Secondary Sources of Data:

- Existing Databases: Secondary data are obtained from existing databases, literature, or previously conducted studies. These sources provide general data that may be applicable to a range of products or processes. Examples include environmental databases, government reports, and academic publications.
- Industry Averages: When specific data for a particular product or process is unavailable, industry averages serve as a valuable secondary source in Life Cycle Assessment. These averages are derived from aggregating data across entire industries or specific processes, often obtained through industry-wide surveys or comprehensive data collection efforts. Essentially, industry averages provide a generalized representation of the environmental impact associated with certain activities or sectors. While not as precise as product-specific data, they offer a practical alternative for assessing environmental impacts when detailed information is lacking. Utilizing industry averages ensures that the LCA retains a level of reliability and comprehensiveness even in situations where specific data is scarce, enabling a more informed evaluation of the overall environmental footprint. [1].

3.2.1. Goal and Scope Definition

Conducting a Life Cycle Assessment (LCA) involves modeling the life cycle of a product, service, or system. Recognizing that this model simplifies a complex reality, the challenge lies in minimizing distortions. A key strategy is the careful definition of the LCA's goal and scope. This includes specifying reasons for the assessment, defining the product and its life cycle, determining the functional unit for comparisons, outlining system boundaries, and addressing co-production. Additionally, the practitioner establishes data quality requirements, assumptions, and limitations, along with procedures for Life Cycle Impact Assessment (LCIA) and subsequent interpretation. The intended audiences, communication of results, potential peer review, and the required report format are also part of this crucial definition [1], [7], [34].

3.2.2. Inventory Analysis

The most demanding task in performing an LCA is data collection depending on the time and budget you have available, there are several strategies to collect data. It is useful to distinguish between two types of data:

a) Foreground data, in the context of Life Cycle Assessment (LCA), encompasses specific and detailed information that is crucial for modeling a particular system. This type of data is essential for creating a comprehensive and accurate representation of a product or specialized production system within the LCA framework. Essentially, foreground data is the detailed information that directly pertains to the specific attributes, characteristics, and processes of the system under assessment.

b) Background data, which is data to produce generic materials, energy, transport, and waste management. Background data is valuable in cases where obtaining specific, product-related information is challenging or impractical. It allows for a more generalized understanding of the environmental impacts associated with certain activities, providing a baseline for comparison when detailed, foreground data is not available.

Inventory analysis is the process of collecting and calculating data to measure the key inputs and outputs of a product system. It involves tracking the inventory flows, which include water, energy, and raw materials as inputs, and emissions to air, land, and water as outputs. The inventory analysis is iterative, meaning that as more data is gathered and the system is better understood, there may be a need to change the data collection methods. This change is important to make sure that the study's goals are still met, and it may result from finding new data needs or constraints. It is essential that the data collected matches the functional unit defined in the goal and scope definition [1], [31].

3.2.3. Life Cycle Impact Assessment

During the impact assessment step of an LCA study, all used raw materials and emissions during the life cycle of a product are translated to environmental impacts. In simple terms, when we want to understand the impact of our actions on the environment, we usually follow a chain of events from what we do to what happens in the end. According to the language used by many people who work on Life Cycle Assessment (LCA), we can describe these parts in a certain way. The main idea here is to connect the information we gather about what we are doing with specific environmental impacts and indicators. The process helps us get a grasp of these impacts. The Life Cycle Impact Assessment (LCIA) involves a series of steps that are crucial in this overall process.

The following steps, comprise the LCIA:

a) Selection and Definition of Impact Categories

In Life Cycle Impact Assessment (LCIA), an impact category refers to a specific environmental aspect or area of concern that may be affected by the life cycle of a product, process, or activity. Impact categories help quantify and evaluate potential environmental impacts in a structured manner, allowing for a comprehensive analysis of different aspects of sustainability. Examples of common impact categories include [24]:

- Global Warming Potential (GWP): Measures the contribution of greenhouse gas emissions to climate change, usually expressed in terms of carbon dioxide equivalents.
- Human Toxicity: Evaluates the potential harm to human health caused by exposure to toxic substances during the life cycle.
- Eutrophication: Assesses the impact of nutrient discharge on aquatic ecosystems, which can lead to excessive plant growth and oxygen depletion.
- Acidification: Examines the release of acidic substances that can contribute to soil and water acidification, negatively impacting ecosystems.
- Ozone Depletion: Assesses the potential harm to the ozone layer caused by emissions of ozone-depleting substances.
- Resource Depletion (e.g., minerals, fossil fuels): Evaluates the depletion of non-renewable resources during the life cycle.
- Land Use Change: Examines the impact of changes in land use, such as deforestation or urbanization, on biodiversity and ecosystems [31], [33].

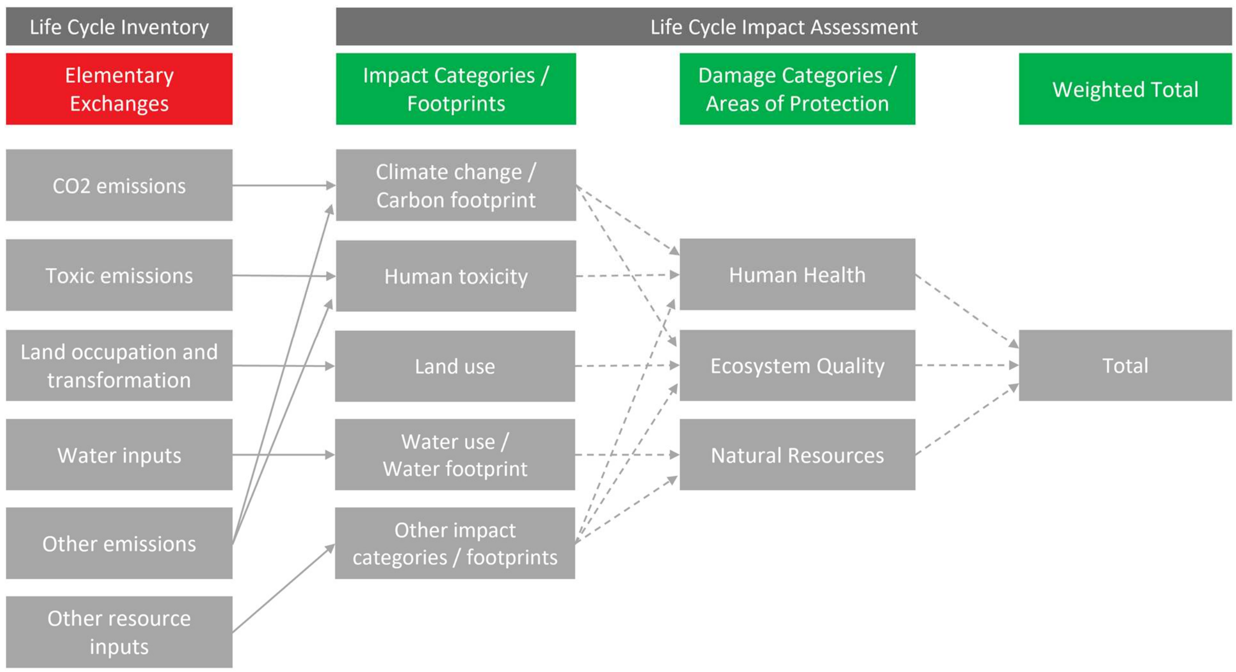

Figure 3.4.: Commonly used life cycle impact categories

b) Classification

In Life Cycle Impact Assessment (LCIA), classification is the essential step where the potential environmental impacts identified in the inventory analysis are categorized and assigned to specific impact categories. The purpose of classification is to organize the various environmental burdens into distinct groups based on their nature and characteristics. This step provides a structured framework for further assessment and analysis. The International Organization for Standardization (ISO) provides guidelines for conducting LCIA, specifically in ISO 14044. According to ISO 14044, the classification phase involves allocating the inventory data to predefined impact categories. The allocation is typically based on cause-and-effect relationships and the specific environmental mechanisms involved.

c) Characterization

Characterization refers to the calculation of the magnitude of the contribution of each classified input and output to their respective impact categories, and aggregation of the contributions within each category. This is carried out by multiplying the inventoried values by the relevant characterization factor for each impact category considered. The characterization factors are substance- or resource-specific. They represent the impact intensity of a substance relative to a common reference substance for an impact category [15].

$$Inventory\ Data \times Characterization\ Factor = Impact\ Indicators$$

d) Normalization

Normalization is a critical step in the life cycle assessment (LCA) methodology, specifically within the life cycle impact assessment (LCIA) phase. During normalization, the results obtained from the LCIA are multiplied by normalization factors. The purpose of this step is to calculate and compare the magnitudes of contributions to impact categories relative to a reference unit. The reference unit serves as a benchmark for comparison, representing a standardized quantity of a resource or a common environmental impact. The key objective of normalization is to express environmental impacts in a dimensionless manner, facilitating a straightforward and meaningful comparison between different products or processes. By applying normalization factors, the impacts of a product or process are transformed into dimensionless, normalized results. These results provide insights into the proportional contributions of various systems to each impact category, making it easier to compare their environmental performances. Normalized results enable decision-makers to assess the relative environmental burdens of different products or processes, leading to more informed and sustainable choices. The dimensionless values obtained through normalization enhance the interpretability and comparability of LCA results, contributing to effective decision-making in support of environmentally friendly and resource-efficient practices [27].

e) Grouping

Grouping refers to the practice of categorizing similar environmental impacts into broader classes or clusters. This helps simplify the assessment process, making it more manageable and facilitating a clearer understanding of the overall environmental performance. Grouping is especially relevant during the classification phase of LCIA [1], [33], [34].

f) Weighting

Weighting entails multiplying the normalized results of each of the impact categories with a weighting factor that expresses the relative importance of the impact category. The weighted results all have the same unit and can be added up to create one single score for the environmental impact of a product or scenario. Simply put, weighting means applying a value judgment to your LCA results. It is a controversial step since the weighting factors you choose can influence the results and conclusions of your LCA. Weighting is useful for several reasons. First, it presents LCA results as a single score, which allows you to easily compare the environmental impact of different products or scenarios. This facilitates decision-making since it is immediately clear whether a product's impact is higher than, lower than, or like the alternatives. Second, weighting can be very helpful for communication purposes. It is much easier to explain a single score for environmental impact than it is to explain 3 to 18 different scores per product or scenario. Researchers emphasized that the weighting of environmental impacts is primarily based on value choices; different individuals, organizations, and societies may have different preferences. The weighting process enables the ranking of alternatives and helps stakeholders make sound decisions. Different weighting sets have been developed over the last few decades. A variety of weighting techniques are available for normalization, namely: distance to target[3], panel weighting[4] , monetary weighting[5] , and binary weighting[6] [8].

3.2.4. Interpretation

Interpretation of the life cycle serves as the final stage in the Life Cycle Assessment (LCA) process. During this phase, the findings obtained from both the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) undergo identification, validation, and assessment. In adherence to the ISO standard, the interpretation phase aims to produce results consistent with the predetermined goals and scope. This involves drawing conclusions, elucidating limitations, and

[3] weighting factors depend on the distance between the current impact level from a desired state based on regulations.

[4] consideration of the opinions of a group of people, stakeholders, and experts

[5] weighting according to economic value

[6] for zero weights or equal weights

presenting recommendations [1]. The primary goal is to deliver a clear, comprehensive, and coherent presentation of LCA results that aligns with the study's specified objectives and scope.

Chapter 4
Case study

4.1. Goal and Scope Definition

Mixa S.r.l. put together an environmental comparison study for G3 Hydronic Systems. G3 is a company that looks into, plans, makes, and sets up hydronic systems for keeping places cool and making hot water. They started offering hydraulic systems and kits to create thermotechnical plants, carefully designed to work well with most hydronic systems already in use. The report was worked on between October 2023 and December 2023. The study follows specific rules for taking care of the environment, figuring out how things affect it and making a plan. These are laid out in UNI EN ISO 14040:2021. Also, there are rules and tips for doing the environment study, deciding what to look at, and how to talk about the results, outlined in UNI EN ISO 14044:2021. The objective of this study is to conduct a comparative Life Cycle Assessment (LCA) for the Hydraulic Separator EQUICOLL 20L, evaluating the environmental impacts associated with two material options. One is made from coated iron and the other from stainless steel. The primary motivation behind this analysis is to ascertain whether transitioning to stainless steel offers environmental advantages, positioning it as a more sustainable alternative compared to the current iron structure (Equicoll 45l 332101). The study findings will play a crucial role in guiding internal material choices and influencing customers towards options with reduced environmental impact.

4.1.1. Description of The Analyzed Products

The EQUICOLL 20L is a hydraulic tank equipped with micro-storage designed for heating and cooling systems. This model includes insulation cups and connections specifically prepared for the direct attachment of CS series collectors DX/SX type. Its internal piping configuration is uniquely tailored, making it well-suited for use with heat pumps that serve both heating and cooling applications[7].

			Iron		INOX	
RIF.	**DESCRIPTION**	**Q.**	**MATERIAL**	**WEIGHT (gr)**	**MATERIAL**	**WEIGHT (gr)**
1	Packaging cap	2	CARDBOARD	94	CARDBOARD	94
2	serial	1	ADHESIVE LABEL	1	ADHESIVE LABEL	1
3	Insulating shell	1	POLYETHYLENE FOAM	700	POLYETHYLENE FOAM	700
4	Tank	1	IRON	14210	INOX AISI 304	14210
4.1	Handle	4	IRON	39	INOX AISI 304	39
4.2	Fillet	4	IRON	106	INOX AISI 304	106
5	Adhesive closure band	1	ADHESIVE POLY-ETHYLENE FOAM	5	ADHESIVE POLY-ETHYLENE FOAM	5
6	Rivest packaging	1	CARDBOARD	282	CARDBOARD	282
7	label. 100*80	1	ADHESIVE LABEL	1	ADHESIVE LABEL	1
8	Instruction manual	1	CARDBOARD	30	CARDBOARD	30
9	trapping packaging	2400 (mm)	POLYPROPYLENE	60	POLYPROPYLENE	60
Total weight			15546 gr		15546 gr	
Dimension			360*546*180 cm		360*546*180 cm	

Figure 4.1.: Description of the Package

[7] https://www.g3sistemi.com/wp-content/uploads/2022/06/CATALOGO-2022-DEF-low.pdf

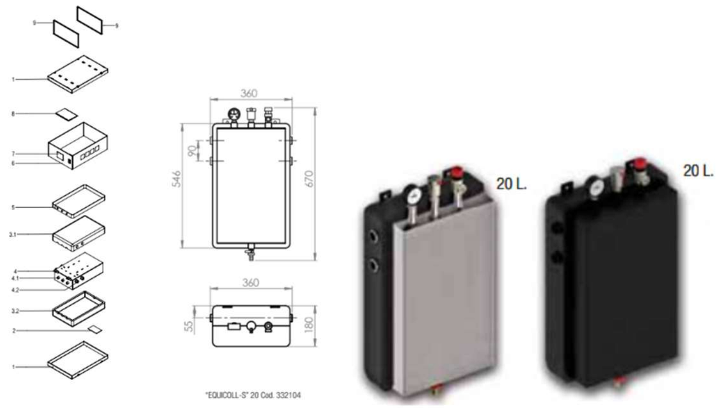

Figure 4.2.: Schematic of the Package

The product's function lies in its role as a water storage tank dedicated to the heating and cooling system. The functional unit consists of a single tank capable of storing 20 liters of water for the heating or cooling system. The system's boundaries are defined as cradle-to-grave, encompassing the entire life cycle of the product. The life cycle processes involve the extraction of raw materials, the processing of these materials into semi-finished products, and the subsequent transportation of these semi-finished products. The assembly phase follows, succeeded by the processes of packaging and storage. Product distribution comes next, leading to the utilization phase where the tank fulfills its function within the heating and cooling system. Post utilization, the life cycle proceeds with disassembly, preparing the tank for recycling and disposal stages. This comprehensive approach ensures that every stage, from the extraction of raw materials to the end-of-life processes, is considered in evaluating the product's environmental impact.

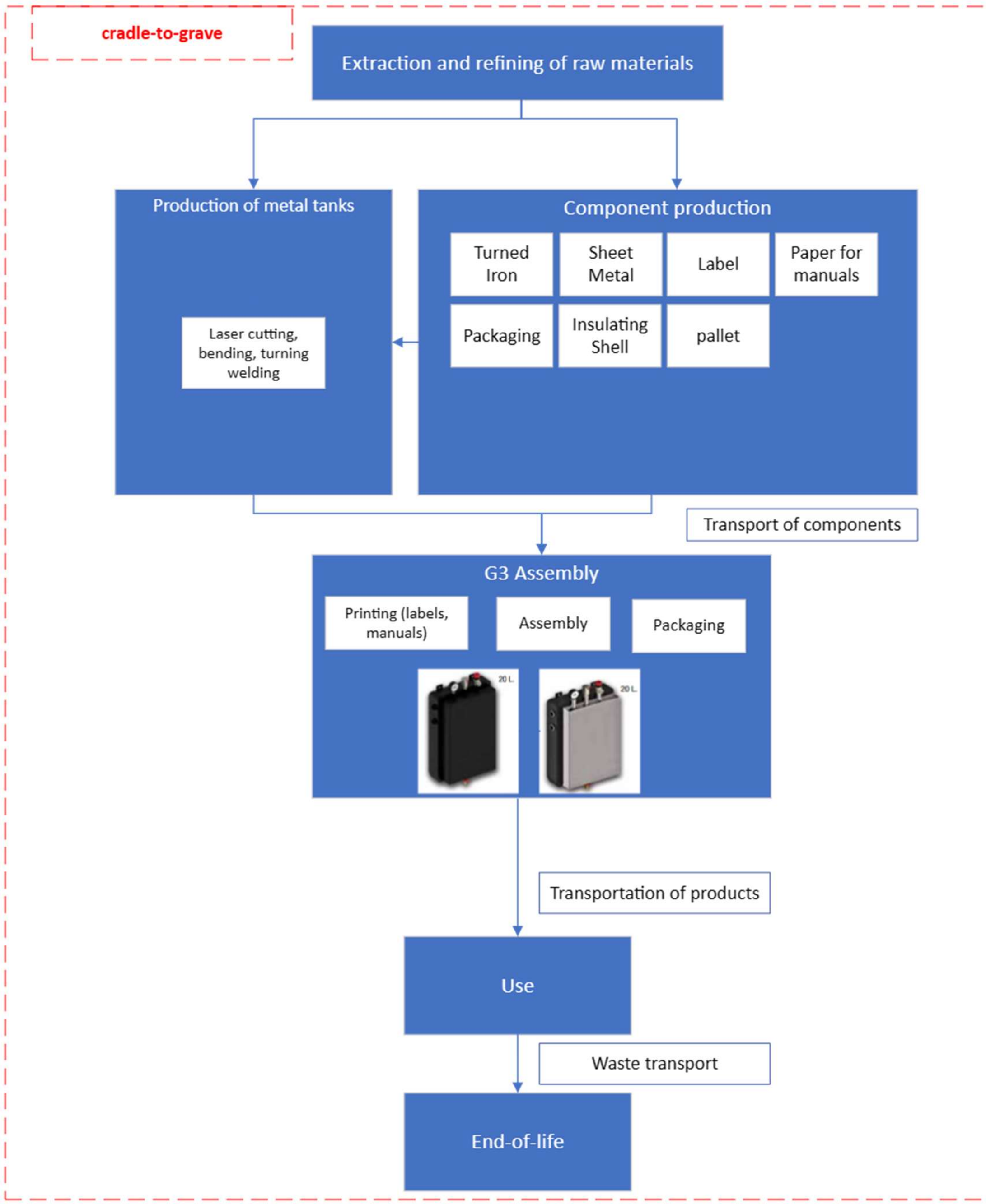

Figure 4.3.: Scope of LCA

4.1.2. Exclusion Criteria and Data Quality

The exclusion criteria encompass various components such as Research and Development, packaging of raw materials, transportation of products to customers, transportation of waste, infrastructure of facilities, human labor and transportation, plants and machinery, and maintenance phases. Moving on to data quality considerations, temporal coverage ensures that primary datasets and inventories are not older than one year. Geographical coverage generally refers to an average Italian context, contingent on data availability. Technological coverage relies on primary data from company technical sheets and secondary data representing average technologies in the European Union. Ensuring accuracy, representative and precise primary data are utilized whenever possible, with consumption and loads calculated based on values provided by the G3 company. Completeness is achieved through an iterative process of data collection and modeling, with gaps transparently disclosed, and validation checks conducted. Representativeness is addressed concerning temporal, geographical, and technological coverage, portraying entire systems composed of clearly defined products. Coherence is paramount, with consistency in assumptions, modeling choices, and data source selection, ensuring a robust comparative assessment. Reproducibility is facilitated through the documentation of assumptions and the implementation of secondary data, enabling the replication of underlying models. The uncertainty of information is addressed through a dedicated uncertainty analysis, ensuring a comprehensive evaluation of residual uncertainties throughout the assessment. "Continuing with the exploration of data processing in the absence of certain data points, our approach involved a thorough examination of existing literature studies and database processes. This exhaustive analysis aimed to identify potential sources that could effectively compensate for missing data, ensuring that no pertinent system processes were inadvertently excluded from the defined boundaries. A comprehensive account of the data used, and the assumptions made during this process is meticulously detailed in the preceding inventory chapter [30].

Following the completion of the sensitivity analysis, it was determined that there was no need for revisions to the established system boundaries. The insights gained from these analyses, including their methodologies and implications, are thoroughly documented, providing a transparent view into the decision-making process and the robustness of the system boundaries. Moving on to allocation principles and procedures, a meticulous consideration was given to the consumption associated with the assembly and packaging of the final product. Additionally, the energy expended for the heating, air conditioning, and lighting of production facilities essential for the annual production of 1000 units of the specified products was factored in. To address these energy-intensive aspects, a judicious allocation was determined, attributing 20% of the total consumption to the production under examination. This allocation methodology ensures a fair representation of the environmental footprint associated with the targeted production scale, contributing to a comprehensive understanding of the overall sustainability impact."

4.1.3. Types of Impacts and Methods

As defined by ISO 14040, "the LCA impact assessment phase is intended to assess the extent of potential environmental impacts using LCI results. In general, this process involves associating inventory data with specific categories of environmental impacts and category indicators and deepening the understanding of these impacts." Below, in addition to the description of the selected impact categories, are the results for the two different products analyzed. The LCIA results are relative expressions and do not foresee impacts on category purposes, threshold exceedances, safety margins or risks. The impact assessment was carried out utilizing the Sima-Pro LCA software developed by PRé Consultants, employing the ReCiPe 2016 Endpoint (H) version 1.07 methodology. The data banks employed for the study encompass Ecoinvent 3 with allocation, cut-off by classification, and system, the EU – DK Input Output Database, and Industry Data 2.0. The impact categories considered encompass:

- Human health
- Ecosystem quality
- Resource depletion

Area of protection	Endpoint	Abbr.	Name	Unit
Human health	Damage to human health	HH	Disability adjusted loss of life years	Year
Ecosystem quality	Damage to ecosystem quality	ED	Time integrated species loss	Species ´ yr
Resource depletion	Damage to resource availability	RA	Surplus cost	Dollar

Figure 4.4.: Overview of the endpoint categories, indicators, and characterization

4.2. Life Cycle Inventory Analysis

4.2.1. Process Flows

The definition of all mass and energy inputs to the process involves a comprehensive description and quantification of the substances and energy flows that enter the system during its operational phases [1].

4.2.2. Inventory Table

In a Life Cycle Assessment (LCA), the inventory table serves as a comprehensive summary of the environmental inputs and outputs associated with a product or process throughout its entire life cycle. This table typically includes distinct stages such as raw material extraction, manufacturing, transportation, use, and end-of-life disposal, listing specific parameters such as materials, energy, or emissions, along with corresponding units and quantities. Through the compilation of this data, the inventory table enables a systematic analysis of the environmental impact of a product or process, aiding in the identification of key areas for improvement and facilitating informed decision-making towards more sustainable practices [1].

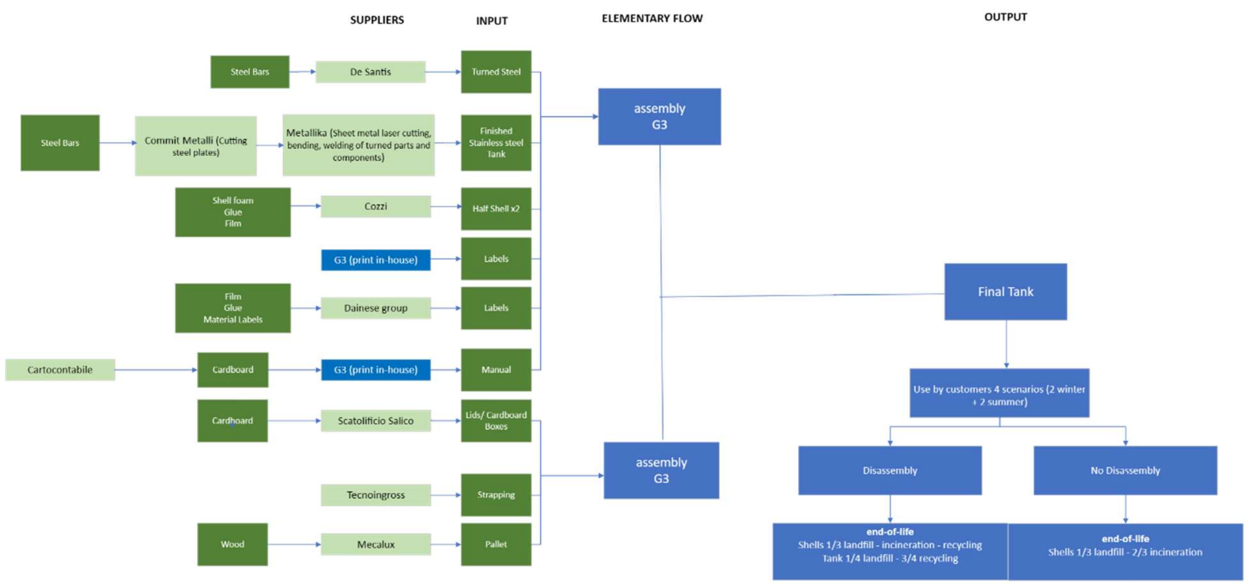

Figure 4.5.: schematic of inventory data

In the following thesis, valuable insights are presented through the analysis of data pertaining to Inventory and Processes, shedding light on their intricate relationship. The first column contains input data selected in Sima-Pro, based on data from the company and certain assumptions. The second column represents the total quantity of materials, while the final column indicates the weight of the material per unit of the product.

Description	Quantity	U.M.	Quantity for One Label
Brass turned			
Input			
Brass removed by turning, average, computer numerical controlled {GLO}| market for | Cut-off, S	145040	g	1,52
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs	1,06
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	200	g	1,06
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	2000	g	1,06
Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	76,90176	tkm	1,09
Output			
Brass turned	145040	g	-
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	1,06
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	2000	g	1,21
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	200	g	1,21
Stainless steel turned parts			
Input			
Cast iron removed by turning, average, computer numerical controlled {GLO}| market for | Cut-off, S	145040	g	1,52
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs	1,06
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	200	g	1,06
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	2000	g	1,06

Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	76,90176	tkm	1,09
Output			
Turned steel	145040	g	-
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	1,06
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	2000	g	1,21
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	200	g	1,21
Painted tank			
Output			
Painted iron tank	218077,44	g	-
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	1,06
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	768	g	1,21
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	1188	g	1,21
Input			
Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, S	218077,44	g	1,22
Steel, unalloyed {GLO}| market for | Cut-off, S		g	1,22
Welding, arc, steel {GLO}| market for | Cut-off, S		m	1,22
Powder coat, steel {GLO}| market for | Cut-off, S	8,79	m2	1,22
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	1,06
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	670	g	1,06
Polypropylene, granulate {GLO}| market for | Cut-off, S	98	g	1,22
Injection moulding {GLO}| market for | Cut-off, S	98	g	1,22
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	1188	g	1,06
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, S	19,19081	tkm	1,22
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, S	2,11530096	tkm	1,09
Stainless steel tank			
Output			
AIAI 304L steel tank	218077,44	g	-
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	1,06
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	768	g	1,21
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	1188	g	1,21
Input			

Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, S	218077,44	g	1,22
Steel, unalloyed {GLO}| market for | Cut-off, S		g	1,22
Welding, arc, steel {GLO}| market for | Cut-off, S		m	1,22
Powder coat, steel {GLO}| market for | Cut-off, S	8,79	m2	1,22
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	1,06
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	670	g	1,06
Polypropylene, granulate {GLO}| market for | Cut-off, S	98	g	1,22
Injection moulding {GLO}| market for | Cut-off, S	98	G	1,22
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	1188	g	1,06
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, S	11,99426	tkm	1,22
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, S	2,11530096	tkm	1,09
Insulating shell with film			
Insulating shell with film	14,1	kg	-
Input			
Polyethylene, low density, granulate {GLO}| market for | Cut-off, S	14	kg	1,22
Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, S	14	kg	1,22
Acrylic filler {RER}| market for acrylic filler | Cut-off, S	20	g	1,22
Paper, woodfree, uncoated {RER}| market for | Cut-off, S	80	g	1,22
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	4	kg	1,06
Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	5,1042	tkm	1,09
Output			
Insulating shell with film	14	kg	-
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	4	kg	1,21
Outer adhesive band			
Input			
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	2500	g	1,22
Acrylic filler {RER}| market for acrylic filler | Cut-off, S	250	g	1,22
Paper, woodcontaining, supercalendered {RER}| market for paper, woodcontaining, supercalendered | Cut-off, S	5250	g	1,22
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	1500	g	1,06

Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	2,679	tkm	1,09
Output			
Adhesive outer band for shells with film	8000	g	-
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	1500	g	1,21
Labels			
Input			
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	2100	g	1,22
Acrylic filler {RER}| market for acrylic filler | Cut-off, S	200	g	1,22
Paper, woodfree, uncoated {RER}| market for | Cut-off, S	720	g	1,22
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	188	g	1,06
Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	0,1508	tkm	1,09
Output			
Labels	3020	g	-
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	188	g	1,21
Printing paper			
Input			
Paper, woodfree, uncoated {RER}| market for | Cut-off, S	4375	g	1,09
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	150	g	1,06
Transport, freight, light commercial vehicle {Europe without Switzerland}| market for transport, freight, light commercial vehicle | Cut-off, S	0,0362	tkm	1,09
Output			
Labels	4375	g	-
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	150	g	1,21
Packaging - Reggette			
Input			
Polypropylene, granulate {GLO}| market for | Cut-off, S	9196	g	1,22
Injection moulding {GLO}| market for | Cut-off, S	9196	g	1,22
Core board {GLO}| market for | Cut-off, S	784	g	1,22
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	820	g	1.06
Transport, freight, lorry 7.5-16 metric ton, euro6 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO6 | Cut-off, S	0,1728	tkm	1,09
Output			
Packaging - Reggette	9196	g	-
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	1604	g	1,21

Packaging - Pallet			
Input			
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	1,06
Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Cut-off, S	0,38	tkm	1,09
Output			
Packaging - Pallet	15000	g	-
Packaging – Stretch Film			
Input			
Core board {GLO}| market for | Cut-off, S	24000	g	1,22
Packaging film, low density polyethylene {GLO}| market for | Cut-off, S	100544	g	1,22
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	4256	g	1,06
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	1	Pcs.	
Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Cut-off, S	2,3008	tkm	1,09
Output			
Packaging - Pallet	15000	g	-
Core board (waste treatment) {GLO}| recycling of core board | Cut-off, S	28256	g	1,21
Packaging – lids and cardboard box			
Input			
Corrugated board box {RER}| market for corrugated board box | Cut-off, S	47014	g	1,06
EUR-flat pallet {RER}| market for EUR-flat pallet | Cut-off, S	3	Pcs.	1,06
Polyethylene terephthalate, granulate, amorphous {Europe without Switzerland}| polyethylene terephthalate, granulate, amorphous, recycled to generic market for amorphous PET granulate | Cut-off, S	510	g	1,22
Injection moulding {GLO}| market for | Cut-off, S	510	g	1,22
Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Cut-off, S	2,3008	tkm	1,09
Output			
Packaging - Lids and cardboard box	47014	g	-
PET (waste treatment) {GLO}| recycling of PET | Cut-off, S	510	g	1,21
Printed manual			
Input			
Printing paper	37,19	g	-
Printed paper, offset {RoW}| offset printing, per kg printed paper | Cut-off, S	37,19	g	1,32

Output			
Printed manual	37,19	g	
Printed labels			
Input			
Labels	1	g	-
Printed paper, offset {RoW}| offset printing, per kg printed paper | Cut-off, S	1	g	1,32
Output			
Printed labels	1	g	1,32
Insulating Shell Assembly			
Input			
Insulating shell with film	705	g	-
Output			
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	4	g	1,21
Headband assembly			
Input			
Adhesive outer band for shells	16	g	-
Output			
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	5	g	1,21
Label assembly			
Input			
Printed labels	1,007	kg	-
Output			
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S	0,240	g	1,21
Equicoll X 20l			
AISI 304L steel tank	13629,84	g	-
Stainless steel turned parts	580,16	g	-
Assembly - Insulating Shells	701	g	-
Assembly - Headband	11	g	-
Assembly - Labels	11534	g	-
Printed manual	37,19	g	-
Electricity, low voltage {IT}| market for | Cut-off, S	0,318	kWh	1,07
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler fan burner non-modulating <100kW | Cut-off, S	5,513	kWh	1,07
Packaging - Equicoll X 20l			

Packaging – lids and cardboard box	470,14	g	-
Packaging - Reggette	60	g	-
Packaging - Pallet	15000/12	g	-
Packaging - Stretch film	318/12	g	-
Equicoll 20l			
Painted iron tank	13629,84	g	-
Brass turned	580,16	g	-
Assembly - Insulating Shells	701	g	-
Assembly - Headband	11	g	-
Assembly - Labels	11534	g	-
Printed manual	37,19	g	-
Electricity, low voltage {IT}| market for | Cut-off, S	0,318	kWh	1,07
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler fan burner non-modulating <100kW | Cut-off, S	5,513	kWh	1,07
Packaging - Equicoll 20l			
Packaging – lids and cardboard box	470,14	g	-
Packaging - Reggette	60	g	-
Packaging - Pallet	15000/12	g	-
Packaging - Stretch film	318/12	g	-

Figure 4.6.: inventory data of assembly

In the tables presented herewith, one can discern the applied phase in use. In this context, there are two tables: one for Iron and one for Inox. We explore two scenarios for each material, considering different years and hours for the use phase. Using data gathered from the brochure, the total energy for each case is calculated using the following equation:

$$\frac{\text{Hour} \times \text{Year} \times \text{delta}_T \times \text{Internal Surface Area}}{\text{Thickness} \times 1000}$$

Season	Iron									
Scenario 1		Hour	Year	delta_T	Thermal Conductivity	unit	Thickness	Internal Surface Area	TotalEnergy	unit
Winter	Scenario 1	4398	15	15	0,04	W/mK	3,441	0,523	6,013	KWh
	Scenario 2	1107	15	15	0,04	W/mK	3,441	0,523	3,007	KWh
Summer	Scenario 1	1107	15	19	0,04	W/mK	3,441	0,523	1,917	KWh
	Scenario 2	0	15	19	0,04	W/mK	3,441	0,523	0	KWh
Total	Scenario 1.1								7,930	KWh
	Scenario 1.2								3,007	KWh
Scenario 2		Hour	Year	delta_T	Thermal Conductivity	unit	Thickness	Internal Surface Area	TotalEnergy	unit
Winter	Scenario 1	4398	**20**	15	0,04	W/mK	3,4411	0,523	8,017	KWh
	Scenario 2	1107	20	15	0,04	W/mK	3,4411	0,523	4,008	KWh
Summer	Scenario 1	1107	20	19	0,04	W/mK	3,4411	0,523	2,556	KWh
	Scenario 2	0	20	19	0,04	W/mK	3,4411	0,523	0	KWh
Total	Scenario 2.1								10,573	KWh
	Scenario 2.2								4,008	KWh

Figure 4.6.: inventory data of using of Iron tank

Season		Inox								
Scenario 1		Hour	Year	delta_T	Thermal Conductivity	unit	Thickness	Internal Surface Area	TotalEnergy	unit
Winter	Scenario 1	4398	15	15	0,04	W/mK	3,441	0,523	6,013	KWh
	Scenario 2	1107	15	15	0,04	W/mK	3,441	0,523	3,007	KWh
Summer	Scenario 1	1107	15	19	0,04	W/mK	3,441	0,523	1,917	KWh
	Scenario 2	0	15	19	0,04	W/mK	3,441	0,523	0	KWh
Total	Scenario 1.1								7,930	KWh
	Scenario 1.2								3,007	KWh
Scenario 2		Hour	Year	delta_T	Thermal Conductivity	unit	Thickness	Internal Surface Area	TotalEnergy	unit
Winter	Scenario 1	4398	**30**	15	0,04	W/mK	3,4411	0,523	12,025	KWh
	Scenario 2	1107	30	15	0,04	W/mK	3,4411	0,523	6,013	KWh
Summer	Scenario 1	1107	30	19	0,04	W/mK	3,4411	0,523	3,834	KWh
	Scenario 2	0	30	19	0,04	W/mK	3,4411	0,523	0	KWh
Total	Scenario 2.1								15,85	KWh

Figure 4.7.: inventory data of using of Inox tank

After the utilization phase, we encounter the crucial end-of-life stage in the product lifecycle. The end-of-life stage in the product lifecycle means the conclusion of its operational utility, often characterized by discontinuation, decommissioning, and consideration for sustainable disposal or recycling practices. With regard to the end-of-life of packaging, the following situation has been assumed for paper and plastic: 70% of the material is sent for recycling, 20% for incineration/waste-to-energy and 10% goes to landfill, also based on the ISPRA Report [35]. The transport factor is set at 25 KgKm for every kilo of waste.

As far as wood is concerned, since there is no recycling, it is assumed that 50% of the waste is sent to incineration/waste-to-energy and 50% goes to landfills. The transport factor is the same. In continuation, a comprehensive table accompanies pertinent information, providing a detailed overview of the concluding phase and its associated details. The distribution of the scenarios is attributed on the basis of a research in the literature on the end-of-life of the materials in question and referring to the ISPRA 2022 Report.

Component	% Recycling	% Landfill	% Incineration
Turned	80	20	0
Reservoir	80	20	0
Manual	70	10	20
Shell	70	10	20
Sash	0	50	50
Labels	0	50	50

Figure 4.8.: inventory data of using of Inox tank

In the subsequent text, I specified the names of the companies where we handle various stages of the process, along with their respective distances from the G3 company.

Description The Process	Name of Company	Address	Distance	Method of Transportation
Production/distribution of cardboard for packaging	Scatolificio Salico	Via Volta, Dosson, Treviso	26	Road
Label production (140x100)	Dainese Group	Via Luovigni, Col Ceresa, Vicenza	47	Road
Label production (80x100)	Dainese Group	Via Luovigni, Col Ceresa, Vicenza	47	Road
Label Distribution	Dainese Group	Via Luovigni, Col Ceresa, Vicenza	47	Road
Production/distribution of the insulating shell	Cozzi	Via san sovino, paraviago, Milano	282	Road
Cutting steel plates	Commit metalli	Via Alessandro Volta, Veggiano, Padova	30	Road
Cutting iron plates	Commit siderurgica	Via dell'industria, veggiano, padova	30	Road
sheet metal laser cutting, bending, welding of turned parts and components	Zoccarato Industria coatings	Via Frattina, Campodarsego, Padova	24	Road
Sandblasting and painting (exteriors only)	Metallika	Via ronchi, Piombino Dese, Padova	11	Road
Production of turned steel	De santis	Via Sammaccio, Notaresco, Teramo	474	Road
Production of turned iron parts	De santis	Via Sammaccio, Notaresco, Teramo	474	Road

Production/distribution of plastic elements for packaging	Cozzi		282	Road
Production/distribution of wooden elements for packaging	Cartocontabile	Via dei faggi, castelfranco veneto, treviso	8	Road

Figure 4.9.: List of Companies

Chapter 5
Interpretation of Results

The comprehensive Life Cycle Assessment (LCA) conducted in this study has played a pivotal role in discerning and elucidating the environmental critical issues associated with two diverse materials. Through rigorous analysis, the LCA has allowed for a nuanced comparison of the environmental footprints of these materials, highlighting key differences and areas of concern. The detailed findings and insights gleaned from this comparative study are graphically depicted in the included Figure, facilitating a visual understanding of the environmental performance of the two products throughout their life cycles. Furthermore, this study delves into not only the environmental impacts but also explores the broader implications for sustainability and resource management. By examining factors such as resource consumption, energy usage, and waste generation, a holistic perspective on the life cycles of the materials is presented.

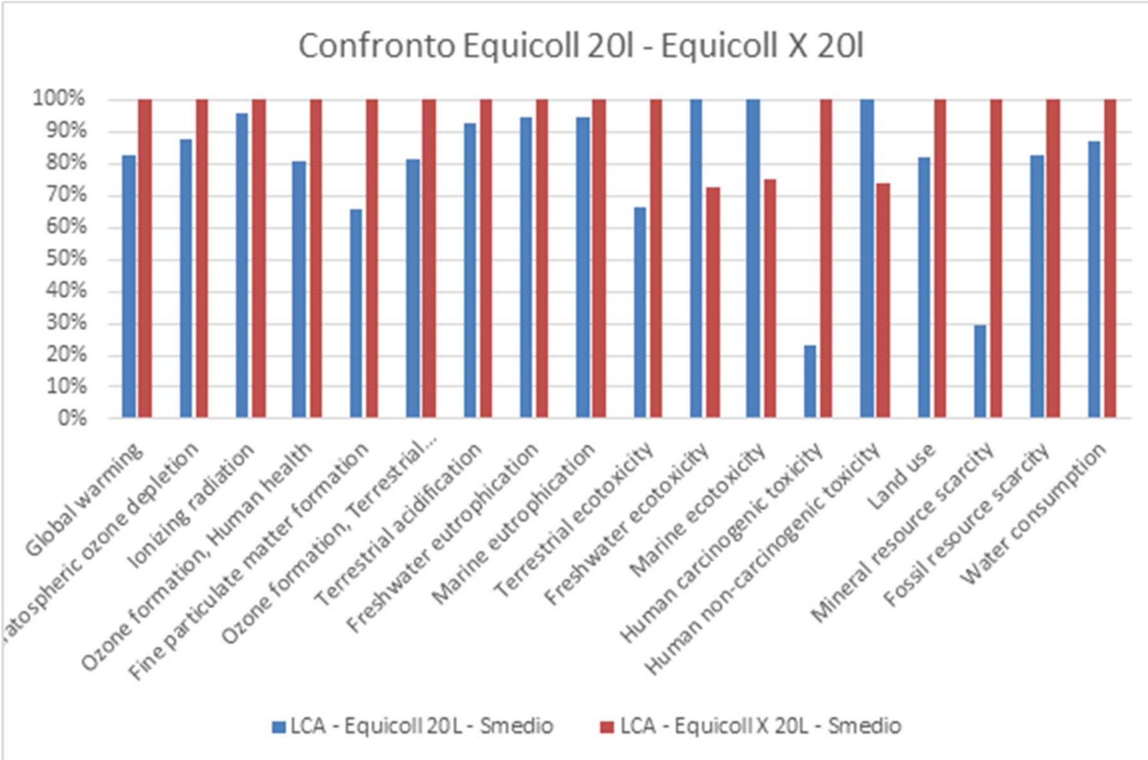

Figure 5.1.: Comparison of the Environmental Impacts

From this method, normalizing the results shows that the relevant categories are:

- Global warming (kg CO2 eq): greenhouse gases are converted into CO2 equivalents with GWP factors, considering a 100-year interval (GWP100);
- Freshwater ecotoxicity (kg 1,4 DBC / kg);
- Marine ecotoxicity (kg 1,4 DBC / kg);
- Human carcinogenic toxicity (kg 1,4 DBC / kg).

Referring to the text "LCA Life Cycle Analysis" the most widely used category, Global warming, is described below. The Global warming category represents the increase in climate-altering gases in the atmosphere that generate the greenhouse effect. The greenhouse effect is a natural phenomenon that ensures global warming and is linked to the presence of certain atmospheric gases such as carbon dioxide, ozone, water vapor and methane. These gases act as a kind of transparent glass that, by enveloping the planet, allows radiation from the Sun to filter through, while hindering the return of some of the infrared (IR) radiation reflected from the Earth and the lower atmosphere, thus retaining heat. Through the greenhouse effect and its influence on the Earth's radiation balance, the temperature of the planet is determined and consequently the distribution and functioning of climate systems. Considering the close relationship between the increase in the concentration of greenhouse gases and the increase in the temperature of the planet, it is likely that most of these changes are attributable to human action. The phenomenon involves the entire planet and is therefore to be considered a problem on a global scale, compared to other phenomena related to air pollution. The results of the LCIA are in line with the defined objective and scope of the LCA. The results reported, in both cases, refer to an average scenario of use of the product: the 4 use scenarios were averaged and a value of 940.80 kWh of total consumption of the use phase was applied to the count throughout the life cycle for both Equicoll 20l and Equicoll X 20l products. The last phase of the LCA consists of the interpretation which, through the analysis of the results and contributions, makes it possible to highlight the environmental criticalities of the analyzed product, draw conclusions, explain limitations and provide recommendations. The following figures show the network diagrams

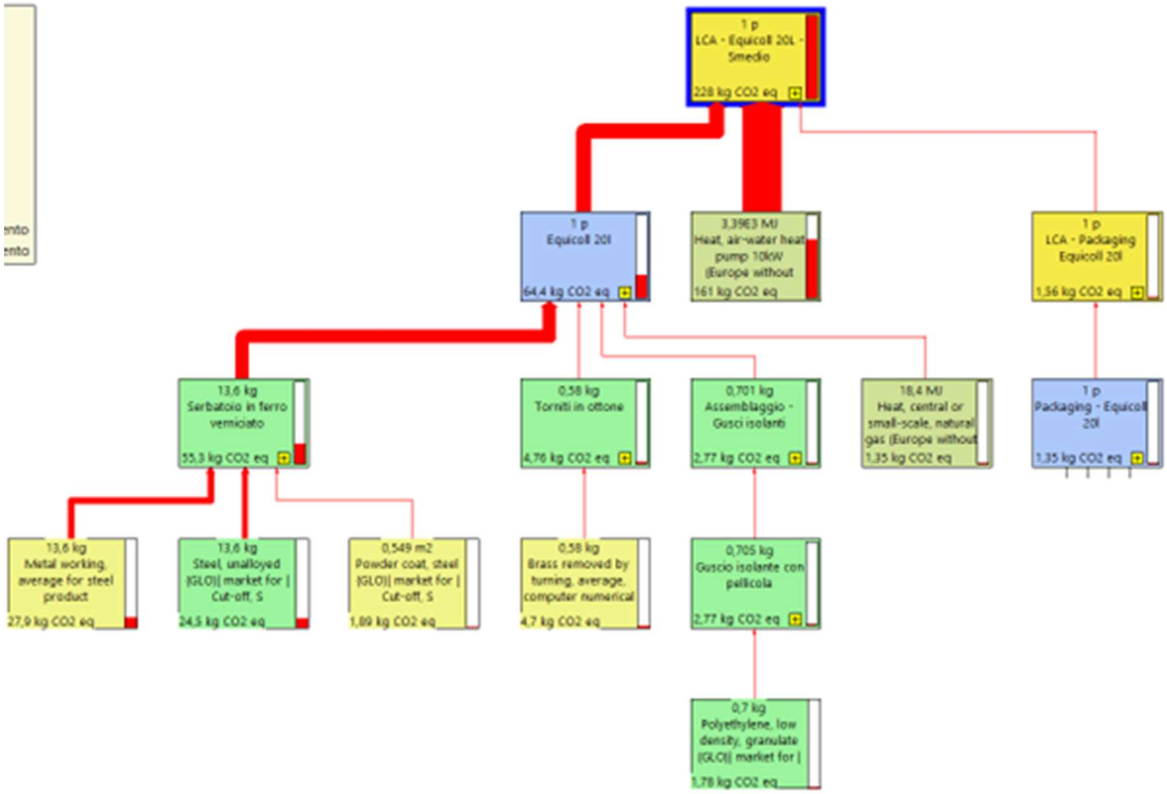

Figure 5.2.: Tree Diagram for Equicoll 20l - Global warming (kg CO2 eq)

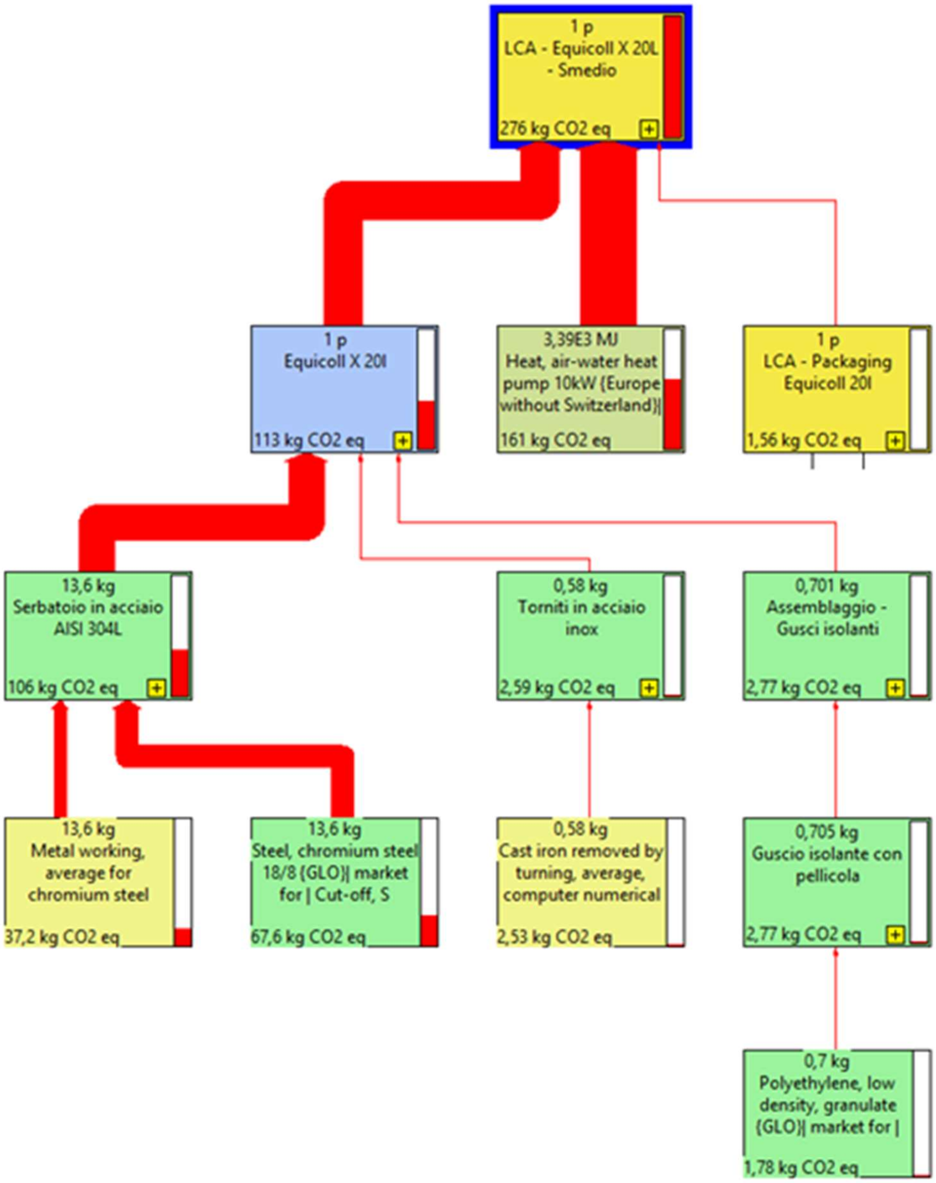

Figure 5.3.: Tree Diagram for Equicoll X 20l - Global warming (kg CO2 eq)

Network diagrams give us the opportunity to analyze the contribution of each stage of the life cycle of the products covered by this study [21]. It is clear that, in both cases, it is the phase of use of the product that weighs more, net of the fact that stainless steel has an impact of about 64% more than Iron.

5.1. Sensitivity Analysis

Sensitivity analysis, within the context of Life Cycle Assessment (LCA), is a methodical examination that involves systematically varying and manipulating specific factors to gauge their influence on the overall environmental impact of the system under examination. This analytical approach is employed to discern the sensitivity and responsiveness of the LCA results to variations in input parameters, assumptions, or methodological choices. In the pursuit of comprehensively understanding the robustness and reliability of LCA outcomes, sensitivity analysis is indispensable. It serves as a tool for assessing the uncertainties inherent in the LCA process and enhances the transparency and credibility of the evaluation. By systematically altering key factors, such as input data, system boundaries, or impact assessment methods, sensitivity analysis allows researchers and practitioners to identify critical parameters that significantly influence the outcomes of the LCA. In an academic context, sensitivity analysis is integral to ensuring the rigor and validity of LCA studies. Researchers often employ sensitivity analysis to explore the implications of different modeling assumptions and input data uncertainties on the final results. Through this process, scholars can provide a more nuanced interpretation of their findings and communicate the reliability and robustness of the LCA outcomes to the academic community and stakeholders. Furthermore, sensitivity analysis contributes to the advancement of LCA methodology by shedding light on the sensitivity of specific impact categories or indicators, thereby guiding researchers and decision-makers toward more informed choices in data collection, modeling, and interpretation. In essence, sensitivity analysis within LCA serves as a methodological cornerstone, offering a systematic approach to assess the impact of varying factors on the overall environmental performance evaluation, fostering transparency, and promoting continuous improvement in the field of life cycle assessment. Given in the previous point that the life phase that has the greatest impact is that of use, it is decided to carry out the sensitivity analysis on the most critical factor, which is precisely the consumption of electricity [11]. The analysis focuses on the use phase of the system, as it is identified as the life phase with the greatest impact. The use phase often involves the operation of the system and, in this case, the energy consumption associated with it. The main objective of the sensitivity analysis in our case is to understand how variations in electricity consumption can influence the overall environmental impact of the system. This insight helps decision-makers and stakeholders identify areas where improvements or optimizations can be made. The methodology involves systematically varying the electricity consumption within a specified range and observing the corresponding changes in the environmental impact indicators so given in the previous point that the life phase that has the greatest impact is that of use, it is decided to carry out the sensitivity analysis on the most critical factor, which is precisely the consumption of electricity. This may be done through mathematical modeling, simulation, or data analysis. The impact of electricity consumption is quantified in terms of its environmental implications. This could include factors such as greenhouse gas emissions, resource depletion, or other relevant environmental indicators.

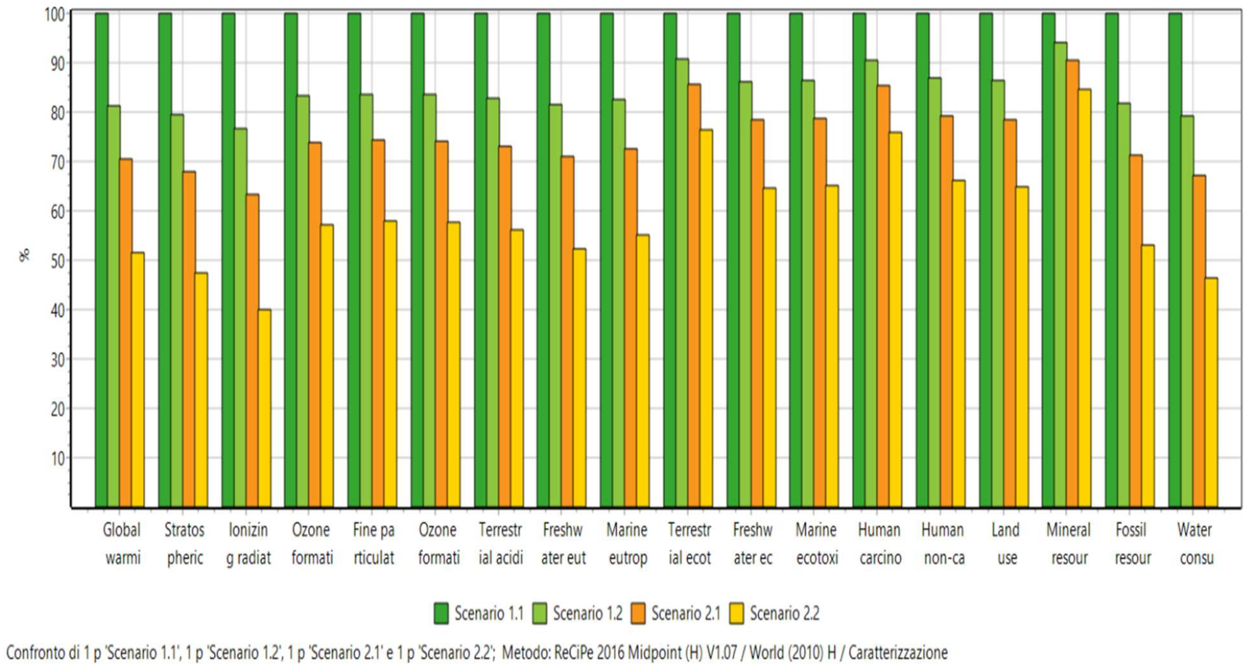

Figure 5.3.: Sensitivity analysis for Equicoll 20l

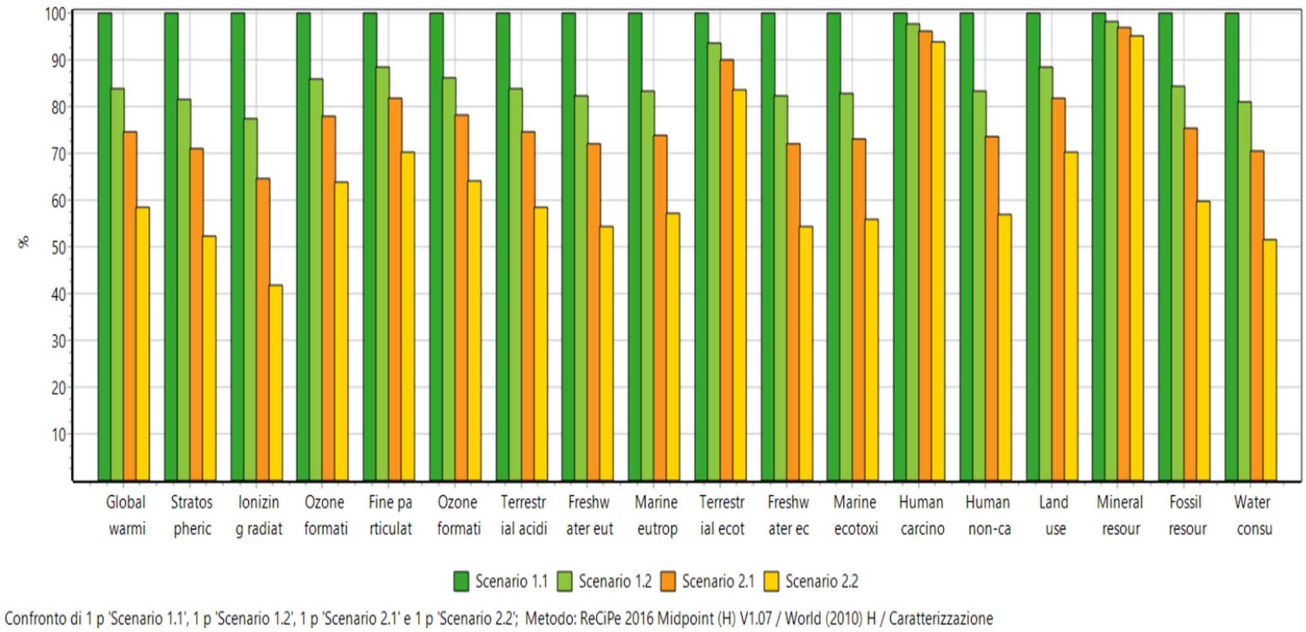

Figure 5.4.: Sensitivity analysis for Equicoll X 20l

The graphs affirm that alterations in assumed electricity consumption significantly impact the proportion of emissions linked to the utilization phase. The observed correlation underscores the sensitivity of emission percentages to changes in electricity consumption assumptions. Thus, validating the pivotal role of electricity-related factors in influencing overall emissions during the use phase.

5.2. Data Quality Control

Assessment of the data quality and reliability of the LCA model implemented in the present study was performed through completeness, sensitivity, and consistency checks. The purpose of this analysis is to establish the extent to which methodological choices affect the results and, if necessary, the need to integrate the data collected and review the assumptions made

1) Completeness check

The completeness check qualitatively evaluates the information and data used in the different phases of the LCA study to ensure that it is complete with respect to the defined objectives, scope, system boundaries and quality criteria. This verification is useful to ensure that all key aspects of the life cycle have been taken into account and all available data has been analysed.

The control was carried out mainly through the comparison with the company involved in the project, the involvement of experts in the field and the analysis of available specialized studies.

All processes within each individual phase of the life cycle have been modelled to represent each specific situation. All available data for each process unit have been verified. In some cases, these were data collected directly by the companies that collaborated in the study (specific data) and in others, instead, data from selected literature and/or databases. Below is a table for verification [25]:

STAGES	PROCESSES	DATA COLLECTED IN THE FIELD	DATA INTEGRATED WITH EXTERNAL INFORMATION (literature/databases)	FULL DATA
Procurement of raw materials and components	Tank	X	X	X
	Turned	X	X	X
	Shells	X	X	X
	Paper for manual	X	X	X
	Transport	X	X	X
Packaging	Paper/ Cardboard	X	X	X
	Wood	X	X	X
	Plastic	X	X	X
	Transport	X	X	X

Product Assembly	Energy consumption (electrical and thermal)	X	---	X
Product Usage	Electricity consumption	X	X	X
End of product life	---	---	X	X
Packaging End-of-Life	---	---	X	X

Figure 5.5.: Completeness Check Table

2) Sensitivity control

The purpose of the sensitivity check is to assess whether and how some specific methodological choices, assumptions, or allocations, may affect the results of the study and how the results vary if alternative choices are possible. The control is reported in section 1.

3) Consistency checker

The consistency check ensures that the quality of the data, the assumptions and the methods used have been consistent with the objective and scope of the study. This was done by following the method outlined in the ILCD Manual [16]:

CONSISTENCY CHECK	JUSTIFICATION
Data quality	It is considered sufficient; specific data were compared and validated with literature data; the lack of data was compensated for by in-depth bibliographic research in the Ecoinvent database.

Choice of method	The methodological choices made are consistent with the ISO 14040 and 14044 and ISO 14067 standards taken as a reference in this study.
Impact assessment	The impact categories and methodologies chosen are consistent with the objective and scope of the study.
Evaluation of inconsistencies	No inconsistencies were detected from the analyses of the results, input and output flows, and networks of results

Figure 5.6.: Completeness Check Table

4) Estimation of uncertainty

Uncertainty estimation helps LCA recipients assess the validity and applicability of the data obtained by determining how data uncertainties affect the reliability of the results. In this case, the analysis was carried out with the support of SimaPro software using the Monte Carlo method, which is based on an algorithm that generates a series of random data that are not correlated with each other and with the probability distribution that the phenomenon is supposed to investigate [26]. The software simulates the calculation of the results for a predetermined number of cycles and evaluates the distribution of the results obtained and from these the uncertainty about the final value. The uncertainty, in fact, derives from the log-normal standard deviation measurements present in each of the unitary processes of the database used to model the life cycle of the analyzed product. The uncertainty analysis in question only takes into account the uncertainty of the data, and not the assumptions made. The uncertainty estimate was made for the impact category Climate change, calculating for each the values of mean, median, standard deviation (SD), coefficient of variation (CV) and the two values that define the 95% confidence interval of the parameter, and therefore 2.50% and 97.5%. The results are presented in the figures below.

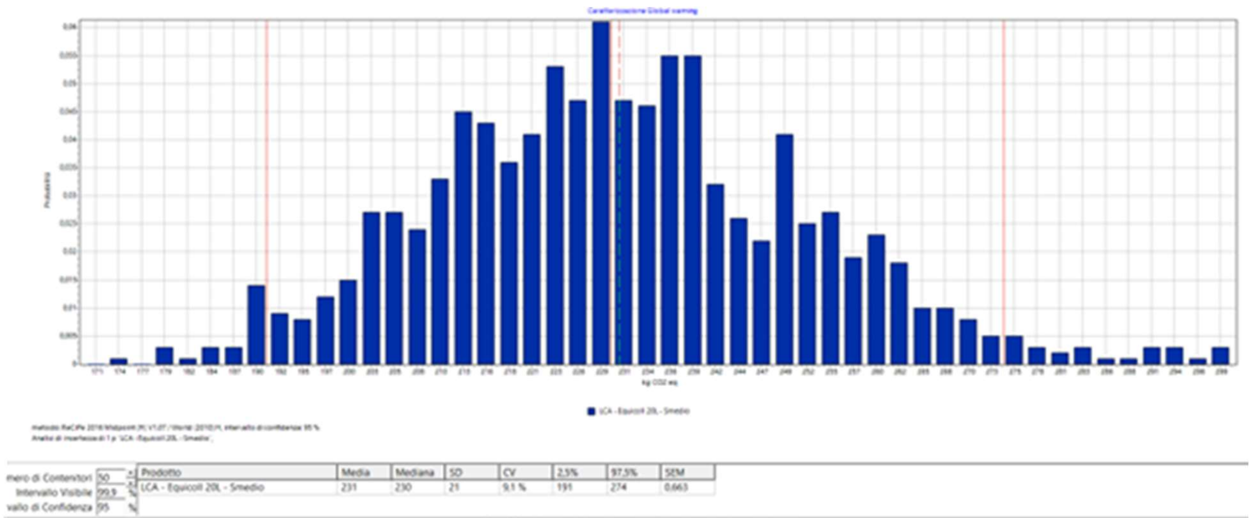

Figure 5.7.: Uncertainty estimation for Equicoll 20l

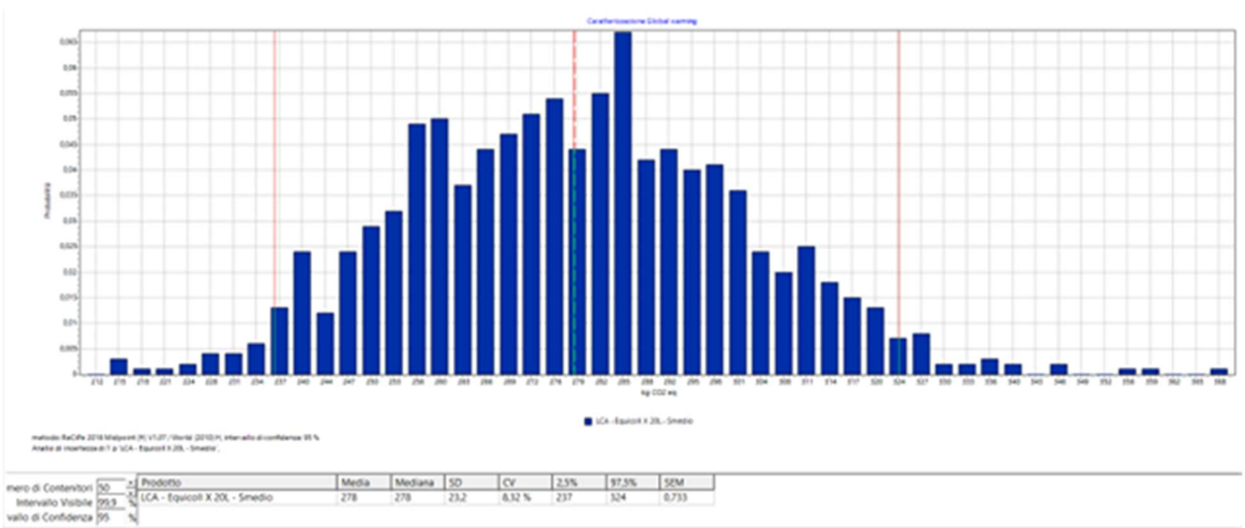

Figure 5.8.: Uncertainty estimation for Equicoll X 20l

5.3. Conclusions

In conclusion, the network diagrams utilized in this study have provided a comprehensive analysis of the life cycle stages of the products under investigation. Notably, the findings underscore that, in both cases, the usage phase significantly contributes to the overall environmental impact, with stainless steel exhibiting approximately 64% more impact than Iron during this phase. The comparative study between Equicoll 20l and Equicoll X 20l reveals that the configuration with elements and tanks not made of stainless steel falls between the two in terms of improvements within the defined boundaries, especially for a useful life period of 15 years. However, it is essential to consider the potential for a significantly extended life expectancy associated with the stainless steel solution, which cannot be fully accounted for within the chosen evaluation period. Beyond the choice of tank material, the study emphasizes that the use phase remains the primary driver of life cycle impacts. The high impact observed during the usage phase in life cycle assessments (LCAs) is primarily due to the intricate interplay of factors associated with how products operate and are utilized over time. One significant contributor is the substantial energy consumption required during the operational life of products. When we use items such as appliances, electronic devices, or vehicles, they draw a considerable amount of energy, and the source of this energy plays a pivotal role. If the energy comes from non-renewable or environmentally detrimental sources, it significantly amplifies the overall environmental footprint. Continuous and prolonged usage of products often results in wear and tear, leading to the need for maintenance, repairs, or even replacements. Each of these activities contributes additional environmental burdens, such as the extraction, production, and transportation of replacement parts or new products. Emissions, effluents, and by-products released during the operation of these products further escalate their overall environmental impact. The type of emissions, such as pollutants from combustion engines or waste materials from industrial processes, adds complexity to the environmental profile associated with the usage phase. Resource depletion is another critical aspect influenced by the usage phase. Products with high resource requirements, such as water-intensive processes or materials, can strain local resources, affecting ecosystems and communities. Additionally, the way products are designed for end-of-life considerations, including recyclability and disposal, is influenced by how they are used. Moreover, user behavior plays a pivotal role in determining the overall environmental impact during the usage phase. Inefficient use, improper maintenance, or misuse can significantly increase resource and energy demands, further intensifying the environmental footprint. In essence, the emphasis on energy use and dissipation during the usage phase, as highlighted in the initial passage, underscores the crucial importance of sustainable practices, energy efficiency improvements, and responsible user behavior to mitigate the overall life cycle impact of products on the environment. Addressing this critical aspect, particularly in terms of energy consumption and dissipation during the use phase, can be achieved through enhanced insulation performance of the element and precise definition of usage specifications, such as temperatures and operating hours. Importantly, the conclusion recognizes that the ultimate assessment of impacts is contingent on the energy supply/generation practices adopted by the end user. This underscores the need for a holistic approach to product life cycle assessments, taking into account not only material choices and design improvements but also the user's energy practices for a more sustainable and informed decision-making process.Utilizing network diagrams offers a valuable means to dissect and assess the impact of each stage within the life cycle of the products under scrutiny in this study [21]. It is evident that, in both scenarios examined, the usage phase of the product holds the greatest significance, notwithstanding the observation that stainless steel has an impact approximately 64% higher than iron. Through this methodology, the normalized results emphasize key categories, namely:

- Global warming (measured in kilograms of CO2 equivalent): where greenhouse gases are converted into CO2 equivalents using Global Warming Potential factors over a 100-year interval (GWP100).
- Freshwater ecotoxicity (measured in kilograms of 1,4-dichlorobenzene (DBC) per kilogram).
- Marine ecotoxicity (measured in kilograms of 1,4-dichlorobenzene (DBC) per kilogram).
- Human carcinogenic toxicity (measured in kilograms of 1,4-dichlorobenzene (DBC) per kilogram).

In conclusion, the network diagrams allow for a comprehensive analysis of product life cycle stages. Despite stainless steel exhibiting a notably higher impact than iron, it is evident that the utilization phase significantly influences environmental considerations. The normalized results highlight crucial impact categories, including global warming and various forms of ecotoxicity, underscoring the need for targeted interventions and sustainable practices, particularly during the product usage phase, to mitigate overall environmental effects.

Bibliography

[1] ISO 14040. Environmental management - Life cycle assessment - Principles and framework. 1996.

[2] Alfa Laval, CECO Environmental Corporation. Market Research Report, 2014.

[3] DI SCHINO, Andrea. Manufacturing and applications of stainless steels. Metals, 2020, 10.3: 327.

[4] LU, Xin, et al. Decarbonization options of the iron and steelmaking industry based on a three-dimensional analysis. International Journal of Minerals, Metallurgy and Materials, 2023, 30.2: 388-400.

[5] TAM, Vivian WY; LE, Khoa N.; SHEN, Liyin (ed.). Life Cycle Assessment on Green Building Implementation. MDPI AG-Multidisciplinary Digital Publishing Institute, 2016.

[6] VAN DER GIESSEN, Aart Antonie. Chemical and physical properties of iron (III)-oxide hydrate. 1968.

[7] CURRAN, Mary Ann. Overview of goal and scope definition in life cycle assessment. Springer Netherlands, 2017.

[8] SALA, Serenella; JUNGBLUTH, Niels. Normalization and weighting: the open challenge in LCA. 2020.

[9] Ashby, Michael F. Materials and the environment: eco-informed material choice. Elsevier, 2012.

[10] Li, Hanyong, Jiaqing Chen, Jiaqing Wang, Jing Gong, and Bo Yu. "An improved design method for compact vertical separator combined with the theoretical method and numerical simulation." Journal of Petroleum Science and Engineering 173 (2019): 758-769.

[11] Groen, Evelyne A., Reinout Heijungs, Eddie AM Bokkers, and Imke JM de Boer. "Sensitivity analysis in life cycle assessment." In Proceedings of the 9th international conference on life cycle assessment in the agri-food sector, pp. 8-10. Vashon, WA, USA: ACLCA, 2014.

[12] Guo, Miao, and R. J. Murphy. "LCA data quality: sensitivity and uncertainty analysis." Science of the total environment 435 (2012): 230-243.

[13] CROES, Pim R.; VERMEULEN, Walter JV. The assessment of positive impacts in LCA of products. The International Journal of Life Cycle Assessment, 2021, 26: 143-156.

[14] Uki, Tamagna, Subhash T. Sarda, and Thomas Mathew. "Design of gas-liquid separator for complete degasing." International Journal of Chemical Engineering and Applications 3, no. 6 (2012): 477-480.

[15] Bjørn, Anders, Mikołaj Owsianiak, Alexis Laurent, Christine Molin, Torbjørn Bochsen Westh, and Michael Zwicky Hauschild. "Mapping and characterization of LCA networks." The International Journal of Life Cycle Assessment 18 (2013): 812-827.

[16] Laurent, Alexis, Bo P. Weidema, Jane Bare, Xun Liao, Danielle Maia de Souza, Massimo Pizzol, Serenella Sala, Hanna Schreiber, Nils Thonemann, and Francesca Verones. "Methodological review and detailed guidance for the life cycle interpretation phase." Journal of Industrial Ecology 24, no. 5 (2020): 986-1003.

[17] Zeng, Xiaobo, Meng Wang, Guangming Fan, Jie Cheng, and Changqi Yan. "A theoretical model for calculating particle trajectory in a vane-type separator." Chemical Engineering Research and Design 194 (2023): 529-541.

[18] Rott, Nikolaus. "Note on the history of the Reynolds number." Annual review of fluid mechanics 22, no. 1 (1990): 1-12.

[19] Romero-Resendiz, L., M. El-Tahawy, T. Zhang, M. C. Rossi, D. M. Marulanda-Cardona, T. Yang, V. Amigó-Borrás et al. "Heterostructured stainless steel: Properties, current trends, and future perspectives." Materials Science and Engineering: R: Reports 150 (2022): 100691.

[20] Hammond, Elizabeth M., Dieter Robin Helm, and David J. Thompson. "British Gas: options for privatisation." Fiscal Studies 6, no. 4 (1985): 1-20.

[21] Harding, K. G. "A technique for reporting life cycle impact assessment (LCIA) results." Ecological indicators 34 (2013): 1-6.

[22] Haque, Nawshad. "Life cycle assessment of iron ore mining and processing." In Iron Ore, pp. 691-710. Woodhead Publishing, 2022.

[23] Faanes, Audun, and Sigurd Skogestad. "A systematic approach to the design of buffer tanks." Computers & Chemical Engineering 24, no. 2-7 (2000): 1395-1401.

[24] Guinée, Jeroen B. "Selection of impact categories and classification of LCI results to impact categories." Life Cycle Impact Assessment (2015): 17-37.

[25] Wang, Richard Y., Veda C. Storey, and Christopher P. Firth. "A framework for analysis of data quality research." IEEE transactions on knowledge and data engineering 7, no. 4 (1995): 623-640.

[26] Cherubini, Edivan, Davide Franco, Guilherme Marcelo Zanghelini, and Sebastião Roberto Soares. "Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods." The International Journal of Life Cycle Assessment 23 (2018): 2055-2070.

[27] Hélias, Arnaud, and Rémi Servien. "Normalization in LCA: how to ensure consistency?" The International Journal of Life Cycle Assessment 26, no. 6 (2021): 1117-1122.

[28] Guzović, Zvonimir, Predrag Rašković, and Zoran Blatarić. "The comparision of a basic and a dual-pressure ORC (Organic Rankine Cycle): Geothermal Power Plant Velika Ciglena case study." Energy 76 (2014): 175-186. [29] Singh, Prashant, and Srinath V. Ekkad. "Effects of spent

air removal scheme on internal-side heat transfer in an impingement-effusion system at low jet-to-target plate spacing." International Journal of Heat and Mass Transfer 108 (2017): 998-1010.

[30] Foken, Thomas, Ray Leuning, Steven R. Oncley, Matthias Mauder, and Marc Aubinet. "Corrections and data quality control." Eddy covariance: a practical guide to measurement and data analysis (2012): 85-131. [31] Babu, B. V. "Life Cycle Inventory Analysis (LCIA)." Life cycle Assessment & Life Cycle Management Methodologies (2006).

[32] Olmez, Gulnur Maden, et al. "The environmental impacts of iron and steel industry: a life cycle assessment study." Journal of Cleaner Production 130 (2016): 195-201.

[33] PIZZOL, Massimo, et al. Impacts of "metals" on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA). Journal of Cleaner Production, 2011, 19.6-7: 646-656.

[34] REBITZER, Gerald, et al. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment international, 2004, 30.5: 701-720.

[35] CUNAT, Pierre-Jean. Alloying elements in stainless steel and other chromium-containing alloys. Euro Inox, 2004, 2004: 1-24.

[36] SEADER, J. D.; HENLEY, Ernest J.; ROPER, D. Keith. Separation process principles: With applications using process simulators. John Wiley & Sons, 2016.

[37] AC10857684, Anonymus, ed. Water, air & soil pollution: an international journal of environmental pollution. Springer Science+ Business Media BV, 1971.

[38] Humbert, Sébastien, Manuele Margni, and Olivier Jolliet. "IMPACT 2002+: user guide." Draft for version Q 2 (2012).