Master's Degree in Engineering and Management

Master's Thesis

Optimization Models for the Agri-Food Manufacturing Industry:

Economic and Engineering Perspectives for Sustainability

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Abstract

The ecological transition and the challenge of sustainability are becoming increasingly central to corporate decision-making. This phenomenon is supported by the evolution of regulations in recent years, as demonstrated by the Green Deal 2019, which identified the agri-food sector as one of the most significant in terms of environmental impact. Corporate sustainability is based on balancing three fundamental dimensions: economic, environmental, and social.

The objective of this study is to develop models capable of optimizing business processes by integrating both environmental and economic analyses. The starting point is represented by two key methodologies: Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), essential tools for ensuring transparency towards customers and gaining competitive advantages in the market.

Through an in-depth literature review (Chapter 4), the most effective methodology for integrating these two approaches will be identified, addressing the research question of this study. The conducted analyses will enable the identification of the most impactful production process within our case study, which focuses on pesto production.

The most critical phase of the production process will serve as the basis for modelling a multi-objective optimization problem, where the studied functions will be related to water consumption and energy consumption of the machinery. To solve this problem and obtain a set of Pareto-optimal solutions, a genetic algorithm (NSGA-II) will be implemented using Python.

Subsequently, all obtained solutions will be incorporated into an evaluation matrix, which will be analyzed using the TOPSIS Method, allowing for the identification of the most efficient solution among the Pareto-optimal ones.

This approach will enable the development of a replicable model for businesses, yielding significant results applied to the case study. It will contribute to reducing the water and energy consumption of the machinery involved in the most impactful phase and lead to a decrease in environmental impacts and costs, as identified in the initial LCA and LCC analyses.

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Chapter 1
INTRODUCTION

This thesis aims to identify models that integrate environmental and economic analyses of corporate production processes, applying them to the case study under examination to optimize operations through sustainable indicators. The life cycle concept will play a key role, considering both the direct and indirect economic and environmental impact. Direct impacts pertain to factors within the company's direct control. In contrast, indirect impacts arise from services or processes not directly managed by the company but are still essential for the completion of the production process.

This study aims to contribute significantly to the industrial sector by identifying optimal solutions that enable companies to balance the various criteria they must meet. The research is structured into several phases: First, an overview of the agri-food supply chain will be presented, focusing on the secondary industry. Subsequently, the two primary tools used for conducting the environmental as well as economic analyses will be introduced. Finally, the methodology will be outlined to address the research question: How can these two tools be effectively integrated to optimize corporate processes?

1.1 Agri-food supply chain

The agri-food supply chain represents the set of all economic and political agents who, directly or indirectly, define the path an agricultural product must follow to move from the initial production stage to its final utilization stage. It is a fundamental sector as it helps meet the global food demand.

The supply chain incorporates several players who generate what is known as the value chain, which has various stages through the application of systems:

- Production stage: This pertains to the additive agri-food value chain. It is the primary sector of the agriculture supply chain, which includes all the processes performed for the growing, breeding, and harvesting of raw materials.
- Processing stage: refers to what one may call the secondary agri-food sector. It encompasses the efforts of converting synthetic and biological resources into something consumable by the ultimate consumers.
- Distribution and marketing stage: This encompasses the final step of selling the manufactured items to the consumers. Thus, it includes all logistical and organizational activities that aim to distribute the processed goods to the retail stores and residences of final consumers.

External actors can also be found in the agri-food supply chain. They do not operate at the level of production, processing, or distribution but support and influence the supply chain's operations. They are crucial to ensuring the system's efficiency, safety, and quality. In the figure below, we can identify the structure related to the agri-food industry.

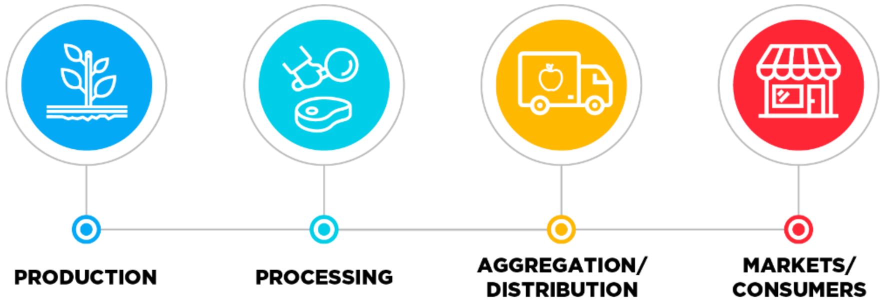

Figure 1: Agri-food supply chain

The agri-food sector plays a significant role in the Italian economy, contributing approximately 4% to the national GDP. Moreover, exports in this area are among the country's top-performing categories. According to the literature, its share in the food industry, compared to the national total, stands at 9.2%, with an overall growth of 56.3% from 2019 to 2024. Furthermore, Istat data from 2024 shows Italy's total production ranks third in the EU-27. However, the data regarding the added value generated is of particular importance. With 42.2 billion euros, Italy ranks first in this category (ISTAT, 2024)

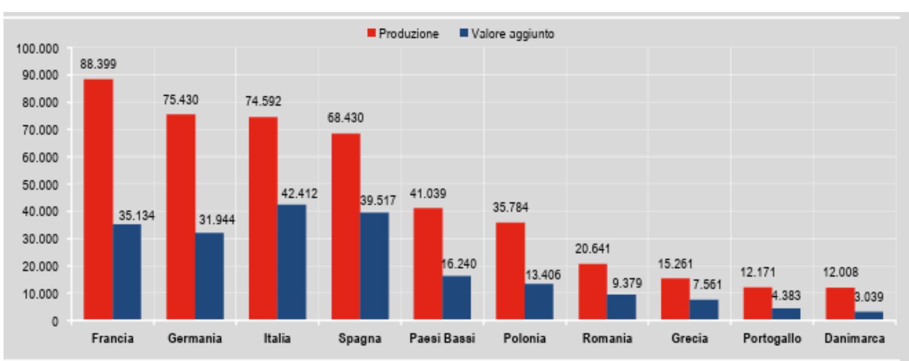

Figure 2: Production and added value of EU-27 countries (ISTAT, 2024)

These impressive figures translate into significant responsibilities, mainly due to the challenges posed by sustainability in recent years. This study will focus on analysing the second link in the supply chain related to transformation processes, specifically to identify supporting models to address these challenges. In the next paragraph, we will examine the concept of sustainability in manufacturing industries and how it influences the decisions made by companies in the secondary agri-food sector.

1.2 **Sustainability in food manufacturing**

Sustainability means fulfilling the needs of the present generation without compromising resources and opportunities for the future (United Nations, 1987). What backs this principle is the “Triple Bottom Line”, first coined in 1994 by John Elkington and later analyzed in more detail in his book “*Cannibals with Forks: The Triple Bottom Line of 21st Century Business*.”(John Elkington, 1997) The concept is based on three key components: environmental, economic, and social. To fully grasp this principle, however, one must first outline what defines it:

- Environmental: This principle looks at minimizing the global ecological footprint, including the amount of greenhouse gas emissions, freshwater consumption, resource depletion, waste generation, and biodiversity loss. These impacts can be mitigated with proper environmental management. A prime example would be the adoption of sustainable energy sources.
- Economic: The sustainability triad can never be complete without keen economic management. The ecological transition must first be economically feasible. For example, the construction of sustainable plants is expensive. However, sustainable plants pay themselves off in the

long run with reduced operational costs and increased revenue.

- Social: This principle rests on the tenet of social justice, fairness, and an equal opportunity society with equitable distribution of resources. One instance may be enhancing the conditions under which employees work within the scope of business. Below is an image that illustrates the concept described above:

Figure 3:Triple bottom line

The agri-food sector is one of the most impactful in global sustainability. According to FAO (Food and Agriculture Organization of the United Nations), this sector accounts for 29% of greenhouse gas (FAO, 2024). This study will focus on developing sustainable models within the secondary agri-food sector. While it is acknowledged that earlier stages related to extraction and primary processing have a more significant environmental impact, optimizing the production phase under the company's control remains of the utmost importance.

The Department of Commerce defines the concept of sustainability in the manufacturing sector as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound" (U.S. Department of Commerce, 2012).

Primary issues regarding sustainability within the secondary agri-food sector relate to accelerated demographic growth. In this regard, the industry is required to increase the resources needed for the conversion of raw materials and, simultaneously, observe the standards concerning the health and safety of the consumers. According to the WHO, 600 million people are said to suffer from at least one illness that is related to food contamination every year, with an estimated 420,000 fatalities (WHO, 2024). Thus, in recent years, a certification scheme has been designed to make marketable for companies with sustainable procedures and policies. As far as the main standards that cover this field are concerned, ISO 9001 (ISO, 2015a), is the first, which covers the quality of the processes within the organization. Moreover, ISO 14001 (ISO, 2015b) covers the organization's environmental management. At the production level, there is type 3 ISO and the impact of the life cycle of products on the processes and procedures of ISO 14025 (ISO, 2006a) and ISO 14040/14044 (ISO, 2006b) based on Life Cycle Assessment (LCA) analysis. The research by Murphy, McDonnell, and Colette (Murphy et al., 2014) reveals the several drivers pushing food-processing companies towards sustainable practices:

- Legislative Drivers: Policies such as the European Industrial Emissions Directive and the ETS aim to lower the emission of pollutants in food processing activities.
- Economic Drivers: Increased energy prices annually compel businesses to adopt more efficient and renewable energy consumption methods. In

addition, European policies impose higher taxes on companies that pollute by disposing of waste in landfills, thus gaining more economically friendly and effective solutions.

- Consumer Drivers: On the other hand, consumers are more conscious of their choices regarding a product and its packaging. As stated before, certified products are more marketable for niche consumers, and a majority of them are willing to purchase certified products, which shows how a sustainable approach is gaining traction.

The same study also determines the most significant inputs affecting secondary agri-food companies, such as the following:

- Energy Consumption: Heating systems for spaces and processes and heating and cooling processes consume an enormous quantity of energy. The combination of process improvement, energy recycling, recuperation systems, and high-quality production practices form the optimal solution to this issue.

- Water Consumption: Water is important in various activities in such firms, such as cooling and washing ingredients for further processing. One primary aspect to consider is the safety and health standards of the food as it is prepared for consumers.

- Generally, these inputs give rise to three different types of outputs in the production processes:

- Air Emissions: A case in point is the release of CO_2 emitted from the combustion of natural gas in the energy production process or gas emissions during the cooling and storage phases.

- Solid Waste: The industry is a major contributor to solid waste production, such as food leftovers and other packaging waste materials.
- Wastewater: During processing the water, its quality needs to be modified before it can be discharged into natural water bodies or recycled. Therefore, steps in the treatment of wastewater must be implemented.

As explained earlier, policy instruments regarding emissions, solid waste, and wastewater are critical for any sustainability efforts. Legislation and regulations provide the backbone for establishing systems that adhere to the defined limits for each sector and help advance the sustainability agenda. The following paragraph will focus on the most important legal frameworks of the broader agri-food industry.

1.3 **Regulations in food manufacturing**

Europe has moved quickly to create legislation that enables the adoption of sustainability-related proposals in the secondary agri-food industry. The European Green Deal (EC, 2019) was the first step in this direction. This strategy has many aims, such as making the region climate-neutral by 2050, decarbonizing the energy system, promoting the circular economy, safeguarding biodiversity, implementing public health risk mitigation policies, and encouraging sustainable transport, agriculture, and food systems within the EU.

Part of these goals is the Farm to Fork program (EC, 2020a), which encompasses the latter which seeks to establish an efficient and eco-friendly farming system. This system envisioned by the EU should:

- Have a neutral or positive environmental impact.

- Reverse biodiversity loss.
- Ensure food security, nutrition, and public health by guaranteeing access to sufficient, safe, nutritious, and sustainable food for all.
- Maintain the economic affordability of food.
- Generate fair economic returns, enhance the competitiveness of the EU's food supply sector, and promote fair trade. (EC, 2022)

The development of the European Green Deal coincided with the COVID-19 pandemic, which could have hindered European countries' achievement of sustainability goals. For this reason, the promotion of sustainability was supported by the NextGeneration EU economic recovery plan (EP, 2021a), whose primary goal, alongside post-pandemic recovery, was to encourage the ecological transition. According to this reform, Italy's plan was the PNRR, the National Recovery and Resilience Plan, which earmarked nearly €6.53 billion under the purview of the Ministry of Agriculture, Food and Forestry Policies, towards the agri-food industry.

These initiatives laid the groundwork for stronger strides toward sustainability efforts. In the succeeding years, various policies and legislations were made to promote ecological transition in the secondary agri-food industry.

In the same year Italy issued the PNRR, the European Union adopted a new regulation called the Common Agricultural Policy (EP, 2021b). Its main objectives are:

- Increasing the efficiency and effectiveness of support to small farms.
- Enhancing the environmental and climate action performance of the EU agriculture.
- Granting more discretion to member states to implement measures that better fit the local circumstances.

Another important directive (EU) is Directive 2024/825 (EP, 2024). It originates in the context of the reforms previously implemented to monitor the transparency of practices related to the sustainable transition of businesses. Among its main objectives, we can identify the protection against unfair commercial practices and the improvement of consumer information. The timeline below shows the evolution of relevant legislation with respect to the supporting frameworks of the secondary agri-food industry:

Figure 4: Sustainable Legislative Development. Elaborated by the author.

In the context of transparency for sustainable products, we can introduce an approach that enhances environmental communication with customers: Life Cycle Assessment (LCA), based on the analysis of impacts across a product's entire life cycle. This tool will be described in the following chapters, but for now, it will be considered how it can support companies in their ecological transition efforts. The LCA analysis regards all impacts, both indirect (not under the company's direct control) and direct (those generated by internal processes, such as transformation activities). This method enables the realization of these objectives:

- Decision support for product and process development: By understanding industrial processes using raw materials or optimizing processes.
- Support for marketing strategies: At times, environmental labels can be attained to highlight the contribution of the company towards the ecological transition.
- Development and selection of indicators to monitor product environmental performance: The environmental performance of a product can be tracked continuously with the help of indicators like carbon footprint, consumption of natural resources, and waste generation.
- Supplier selection: Suppliers who practice LCA can also consider satisfactory sustainable efforts, thus making the process of selection easier.
- Strategic planning: This gives a company ample choice regarding informed strategies to meet sustainability standards in line with the company’s long-term objectives.

From the perspective of transparent communication, two main tools can be obtained by companies through a proper LCA analysis:

- Environmental Product Declaration (EPD): The EPD is an environmental declaration based on ISO 14025 (ISO, 2006a) and LCA. It is a valuable tool for ecological communication with stakeholders, enabling product and service comparisons. The EPD is valid for five years (Envirodec, 2025).
- Product Environmental Footprint (PEF): This tool uses LCA as a methodological foundation but includes specific guidelines for certain product categories, making the study more standardized. The PEF helps

producers and consumers safeguard against misleading environmental claims or greenwashing (European Commission, 2021).

Therefore, the Life Cycle Assessment is a crucial tool for effective environmental communication. This thesis proposes an accurate description of the LCA methodology and its application together with an economic analysis. The Life Cycle Costing (LCC) approach has been recognized as particularly suitable in this context. Although not yet fully standardized, LCC can follow the same guidelines as the Life Cycle Assessment, which is also based on Life Cycle Thinking. This approach redefines traditional industrial concepts by accounting for impacts throughout the value chain and including direct and indirect effects.

The following section will analyse the thesis structure to ensure the correct achievement of the set objectives.

1.4 Thesis framework

After analysing the concept of sustainability within the secondary agri-food sector and introducing methods that can support a transparent ecological transition for companies, this study aims to examine a business process from both environmental and economic perspectives. The goal is to identify and apply a model that integrates Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) in order to pinpoint the most critical phase of the production process, analyse it in detail, and optimize it to achieve both environmental and economic improvements.

The thesis is structured as follows

1. Analysis of Life Cycle Assessment

This chapter will provide a historical and regulatory overview of the LCA model and an in-depth description of its application process.

2. Analysis of Life Cycle Costing

The second chapter will be like the first: After a historical and regulatory analysis of the LCC model, it will detail its application.

3. Integration models for LCA and LCC

This chapter will explore methodologies developed to integrate LCA and LCC to achieve a comprehensive environmental and economic analysis.

4. Case study description

This chapter will present the case study, focusing on a company that produces pesto packaged in glass bottles. A detailed analysis of the sterilization process will be carried out, as this is likely the most impactful phase regarding both environmental effects and costs.

5. Results

The results obtained from the application of the model will be presented, including analysis and proposed optimizations.

6. Conclusions

The final chapter will discuss the study's general conclusions, summarizing the main findings and their implications for the agri-food sector.

Chapter 2
LIFE CYCLE ASSESSMENT

This chapter will explore life cycle assessment, emphasizing its historical development, which has made it one of the most effective tools for analysing the environmental impacts associated with a product's life cycle. Additionally, it will examine the regulatory framework governing the methodology and its application in current European regulations and policies.

The final section of this chapter will provide detailed guidelines for conducting a life cycle assessment.

2.1 Historical development

The urgency of pursuing sustainability has grown year by year, compelling policymakers and businesses to confront unprecedented challenges. Global economic growth, population increases, and the escalating exploitation of natural resources have driven decision-makers to adopt innovative approaches, laying the foundation for what is now known as life cycle thinking (LCT).

LCT refers to evaluating the impacts associated with products, sectors, or projects from a holistic perspective—from raw material extraction to end-of-life management. The primary goal of LCT is to prevent the shifting of impacts across different environmental categories (e.g., reducing climate change at the expense of increased land use), different regions of the world (e.g., lowering local impacts while exacerbating indirect effects elsewhere), or other stages of the life cycle (e.g., decreasing production-phase impacts while increasing those associated with end-of-life management) (Sala, 2019). The conceptual framework of Life Cycle Thinking is illustrated in the figure below.

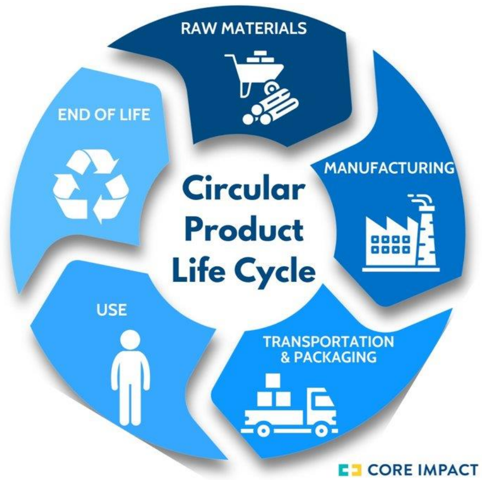

Figure 5: Life cycle thinking

The precursors of Life Cycle Thinking emerged between the late 1960s and early 1970s, initially appearing in 1963 as global models and energy audits known as Resource and Environmental Profile Analyses (REPA) and Net Energy Balance Analyses. In 1969, one of the earliest practical examples laid the groundwork for subsequent sustainable product analysis models: a study developed by Coca-Cola and commissioned to the Midwest Research Institute (MRI). This study aimed to compare the environmental impacts of glass and plastic bottles (EC,2010).

In 1990, during the SETAC (Society of Environmental Toxicology and Chemistry) conference held in Vermont, USA, the term Life Cycle Assessment (LCA) was used for the first time. On this occasion, a definition was introduced that remains widely recognized:

"The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases to assess the impact of those energy and material uses and releases on the environment and to evaluate and implement opportunities to effect environmental improvements. The assessment includes: The entire life cycle of the product, process, or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/reuse/maintenance; recycling; and final disposal." (SETAC, 1991)

The following year, the International Standardization Organization (ISO) standardized the Life Cycle Assessment (LCA) methodology for the first time, building on the framework proposed by SETAC. This document introduced a clear definition and guidelines for conducting LCA in a structured and systematic manner. Doing so, it provided a methodological foundation that transformed Life Cycle Thinking into an organized, actionable model.

In 2003, during the COM held in Brussels, the LCA tool was described as:

"The best framework for assessing the potential environmental impacts of available products. They are, therefore, an important support tool for IPP. However, there is an ongoing debate about good practices in LCA use and interpretation. Through a series of studies and workshops, the Commission will further this discussion and produce a handbook within two years on best practice based on the best possible consensus attainable among stakeholders." (EC, 2003)

2.2 **Development of European Regulation**

Life cycle assessment has become an essential tool for addressing sustainability challenges. However, initiatives to promote its dissemination, development, and practical application have been crucial to make it effective and universally applicable. According to a study conducted by the Life Cycle Initiative (UNEP/SETAC, 2016), LCA's primary role in recent years has been in environmental labelling and the formulation of product regulations (Sonnemann et al., 2017)

In 1992, following the European Council resolution of May 7, 1990, the first EU regulation based on the ecological quality label (EC, 1991) was introduced, placing the life cycle at the center of the evaluation system.

In 2001, the IPP identified LCA as the best available tool for assessing the environmental impacts of products (Sala, 2019). This communication was instrumental in paving the way for policies incorporating life cycle concepts, recognizing Life Cycle Thinking as a critical element in fostering sustainable development and supporting science-based decision-making (Sala et al., 2021). In December 2005, LCT gained a pivotal role as an indicator for assessing the decoupling of economic growth from environmental impacts, as highlighted in the Thematic Strategy on the Sustainable Use of Natural Resources (EC, 2005). Similarly, the Thematic Strategy on Waste Prevention and Recycling (EC, 2008b) introduced amendments to the 1975 Waste Framework Directive, integrating the life cycle approach into evaluations of environmental impacts related to waste management.

Over the years, the EU integrated LCT into many other important policies and regulations. The Eco-design Directive (EP, 2009) set forth requirements for the improvement of the environmental value of energy-related products, and in 2010, the regulation on the Ecolabel 2(EP, 2010) established a voluntary certification system to promote products with reduced environmental impacts. Both pieces of legislation expanded the use of tools such as Life Cycle Assessment. A significant step in promoting this tool was certainly the Bioeconomy Strategy (EC, 2012) and the Single Market for Green Products initiative ((EC, 2013a); (EC, 2013b)) which, by introducing the PEF and OEF tools, proposed a method that overcame a limitation of the tool—its standardization—allowing for a simplification in the comparison of products within the same sector.

The development of the method in recent years has been encouraged by the regulatory system described in Chapter 1, which, through the Green Deal (EC, 2019), has provided a solid foundation that led to the latest Directive 2024/825 (EP, 2024), supporting environmental claims for transparency towards the ecological transition.

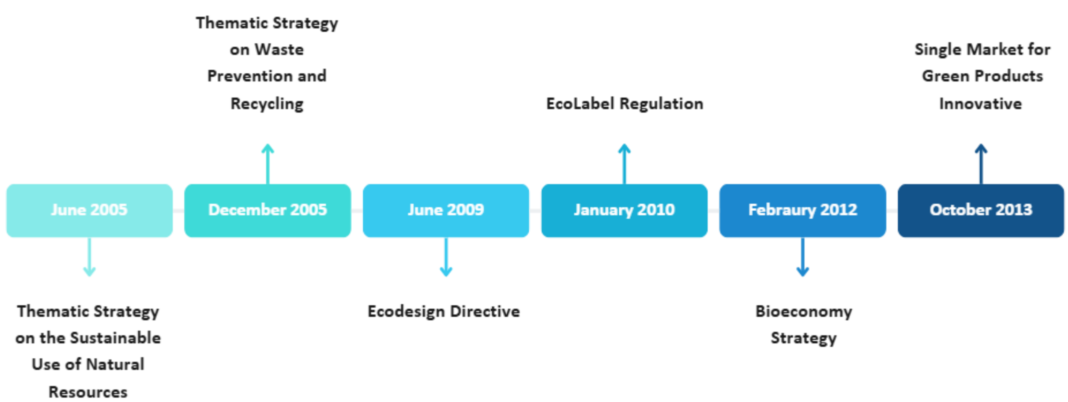

Figure 6: Development of LCT-LCA Regulations. Elaborated by the author.

2.3 **Regulatory references**

The primary regulatory references regarding the definitions and guidelines for conducting an LCA analysis are standardized by the International Organization for Standardization (ISO). The ISO is considered the world's leading organization for developing technical standards. It ensures that our daily products and services are safe, reliable, and high-quality. It is also a fundamental guide for adopting ethical and sustainable practices (ISO).

The ISO 14000 standards were developed based on the principles and objectives set by this organization. This family of standards provides practical tools for companies and organizations that wish to manage their environmental responsibilities.

The ISO 14040 (ISO, 2006b) and ISO 14044 (ISO, 2006c) regulations are within this series of standards, which represent the main guidelines for conducting a Life Cycle Assessment study. ISO 14040:2006 describes the principles and framework for LCA evaluation. ISO 14044:2006 specifies the requirements and provides guidelines for life cycle assessment, including:

- Defining the goal and scope of the LCA
- The Life Cycle Inventory Analysis (LCI) phase
- The Life Cycle Impact Assessment (LCIA) phase
- The Life Cycle Interpretation phase
- Reporting and critical review of the LCA
- The limitations of the LCA
- The relationships among the LCA phases
- Conditions for the use of value choices and optional elements

Supplementary resources also ensure a consistent and comprehensive analysis. Among the main technical reports, it should be paid attention to: ISO/TR 14049 (ISO/TR, 2012), which provides concrete case studies to illustrate examples of goal definition, scope, and inventory analysis, and ISO/TR 14048 (ISO/TR, 2002), which defines data fields and structures that must be used for LCA-related documentation.

2.4 **Conducting a Life cycle assessment**

The phases defined by the guidelines (ISO, 2006c) are illustrated in the figure below. They will be described in detail in the following paragraphs.

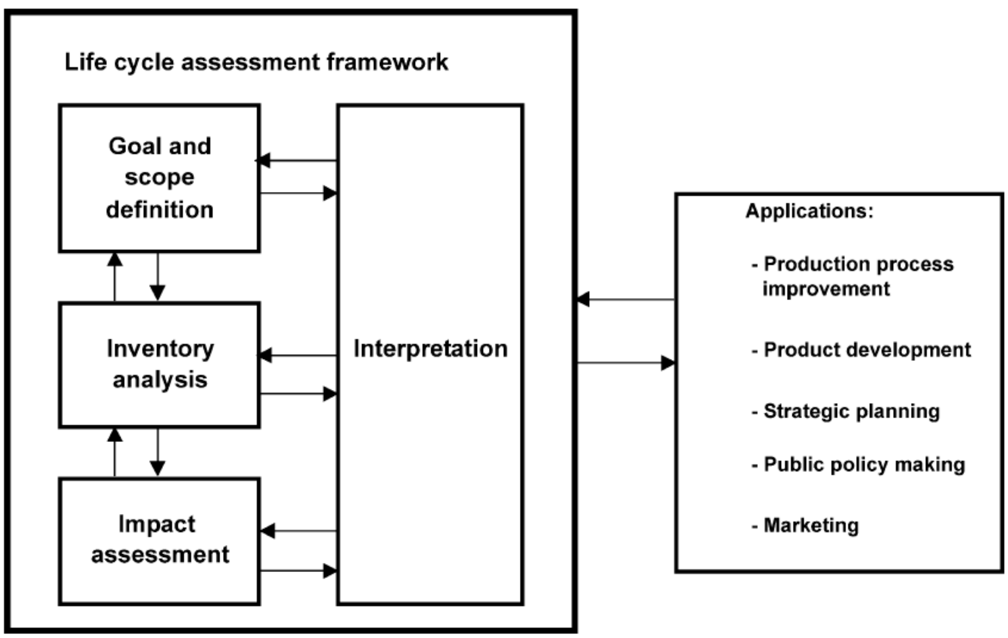

Figure 7: Life cycle assessment framework (G. Mercado, 2017)

From this image, it can be seen that there is always a correlation between the different phases of the LCA. This implies that, although there is an order, the information extracted during the study influences the phases conducted previously.

2.4.1 Definition of Objectives, System, and Functional Unit

The first phase of the life cycle assessment must clarify the study's objectives. Therefore, it is essential to define the reason for conducting the analysis, the target audience, and the intended scope. A life cycle assessment study within a company can be conducted for various reasons, such as comparing the environmental impacts of different products, identifying the parts of the production process with the greatest impact during an operation, evaluating potential changes in product design, or documenting the environmental performance of a specific production process.

The purpose of the study must include and clearly outline the specific functions of the product and the processes considered during the assessment. For this reason, it is necessary to address the following topics in detail:

- Definition of the functional unit
- Definition of the product system
- Definition of system boundaries
- Definition of cut-off rules

Functional unit

In an LCA, the product itself is not as important as its function or service. Therefore, determining and outlining the functional unit to be measured in the study is critical. As per ISO 14040:2006, a functional unit defines the scope of input and output information to be analysed. The unit must be quantifiable, and understanding its context must not be difficult.

Then, the reference flow will be established as the amount of products/scope of work that will be needed in the study to satisfy the defined need.
The reason of having a defined functional unit is the ability to compare measuring different products of the same service.

Product system

The product system is defined as the set of process units, connected in terms of matter and energy, that pursue one or more specified functions (ISO, 2006c)

Within the product system, two macro areas can be identified: the ecosphere, which refers to the environment for which the LCA study is designed to ensure its protection, and the technosphere, where all process units belonging to the model are found. These are the minor elements in a life cycle inventory model for which input and output data are quantified. Unit processes can, therefore, be considered the building blocks of a life cycle inventory model, linked to each other through input and output data (Hauschild et al., 2017). The process units are connected through flows, divided into product or waste and elementary flows. The latter is defined as:

"A single substance or energy entering the system under study and originating from the ecosphere without prior human transformation, or a single substance or energy leaving the system under study and being released into the ecosphere without further human transformation." (ILCD, 2010).

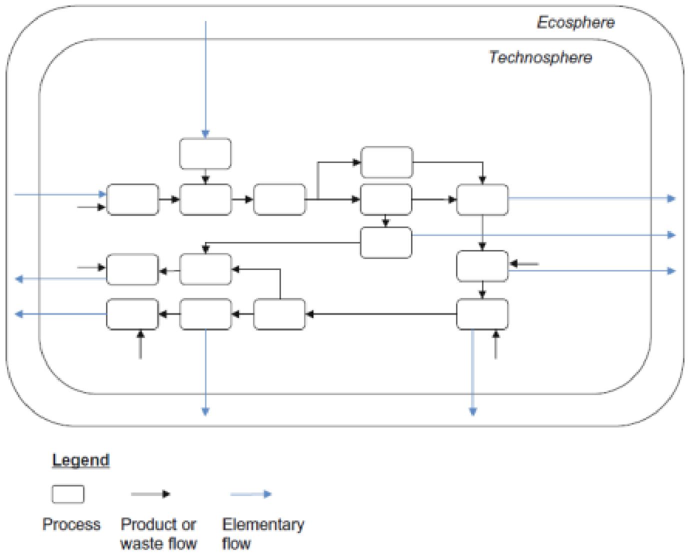

Figure 8: Life Cycle System process (Barbanera, 2020).

System boundaries

The system boundaries define the process units to be included in the LCA. It is necessary to establish which process units should be included in the analysis and their level of detail. The selection of the system boundaries must align with the study's objective. There are four types of boundaries to define: physical, geographical, temporal, and technological. Within the identified outer limits, we include the following:

- From gate to gate: This concentrates on a segment of the life cycle, usually a production stage like activities in a plant, such as a particular portion of the life cycle.
- From cradle to gate: This involves all steps from the collection of raw materials through to the point where the product exits the manufacturing firm, but not the use phase and end of life for the product.

- From cradle to grave: This allows one to have an all-encompassing view of the environmental consequences, covering all five stages in the life of a product: raw material exploitation, refinement, distribution, utilization, and disposal.

Cut off rules

The cut-off rule is essential for managing the inclusion of processes based on what to include or exclude in a study. The criteria for excluding certain phases of the process are established based on the significance of the impact, data availability, and complexity. This avoids including numerous time-consuming and insignificant phases in terms of their environmental impact.

2.4.2 **Inventory analysis**

The inventory analysis phase is undoubtedly the most resource-intensive part of the study due to the time required to collect and organize data associated with each life cycle phase. By identifying inputs and outputs at every stage of the process, the goal is to create a representative model of the system.

This analysis is divided into the following steps:

- Creating a flowchart
- Data collection and validation
- Allocation

Flowchart development

The first step is creating a flowchart that clarifies all the product's life cycle phases. As mentioned, the process unit is the individual phase for quantifying inputs and outputs. The detailed system diagram shows a specific method of determining the value chain by using the categorization of units at different levels in a hierarchal decomposition of what processes are accomplished in the chain.

- Level 0: Identifies the unit process of the elementary flow, which may be more than one if there are multiple reference flows.
- Level 1: These unit processes are considered upstream as they provide materials or components of the reference flow.
- Level 2: These processes support the product but do not constitute the physical product themselves and are supportive of Level 0.
- Level 3: These processes service the Level 0 process.
- Level 4: These are processes required for the production and upkeep of the infrastructure needed to support the Level 0 process.

The objective in this approach is to dissect each process unit and clarify the structures that enable the value chain to be componentized into simpler units conducive to easier establishing the qualitative and quantitative input and output entities.

Data collection and validation

In the following step, it is necessary to gather information about what the system has communicated externally. The inputs measure the amount and kind of energy and materials consumed during process phases, while the emissions released externally are measured by outputs.

The main categories of inventory data are:

- Raw material consumption
- Water consumption
- Energy consumption
- Water emissions

- Air emissions
- Waste

Depending on the source, it is possible to classify the data into two broad types.

- Primary data: Information that is obtained from the specific processes related to the area of concern. Primary data is the most accurate information, compared to secondary data, however, it is time-consuming to obtain and limited in space or time.
- Secondary data: Information that is available in databases, scientific literature, or from previously conducted studies. Though secondary data is simpler to obtain, it is often less precise than primary data.

The ISO prescribes that primary data collection should be prioritized, and secondary data obtained from databases or other sources should be used to fill in the gaps in primary data.

Aside from that, the accuracy of the data analysis should be considered, which determines whether the results of the analysis are valid and reliable. The levels of accuracy are measured in three ways, which are:

- Geographic accuracy: Determine the adequacy of the information concerning the area spatially because different parts of the world have different energy resources.
- Time accuracy: Determine the currency of the data related to the period of analysis.
- Technology accuracy: Looks at the data and details pertinent to the technology or technologies in the focus of the system under study.

Multi-functional process management

The final phase of inventory analysis involves managing multi-functional processes. This step is necessary when the system generates co-products, by-products, or multiple functions.

ISO provides guidelines for handling these situations, recommending an order of preference to address the challenge. The goal is to ensure that allocating inputs and outputs among the various products generated is as accurate as possible.

- Subdivision: The first recommended step is separating the multi-functional process into independent processes associated with a specific product or function. In this case, flows are modeled separately, ensuring accuracy in allocation. However, this method is not always feasible.
- System Expansion: The second step is expanding the system boundaries to include all functions the multi-functional process provides. Equivalent functions are added to the model, reflecting the system's entire benefit, though this approach is complex to implement.
- Allocation: The final step, used when the previous two are not feasible, involves allocation. There are three allocation methods:
    1. Physical relationship: A standard physical parameter is identified, based on which inputs and outputs are allocated to the various products generated.
    2. Economic value: Flows are distributed based on the relative monetary value of products and services.

2.4.3 **Impact assessment**

An impact is any environmental change, whether adverse or beneficial, wholly or partially resulting from an organization's activities, products, or services (ISO, 2015c). The Life Cycle Impact Assessment (LCIA) is the third phase of the LCA, aimed at evaluating the impacts associated with our study's inventory data. Once the inputs and outputs are collected, an efficient analysis requires translating these data to understand and estimate the environmental effects generated by the product system under examination.

As outlined by ISO 14044, the environmental impact assessment phase consists of the following five stages, the last two of which are optional:

- Selection of impact categories
- Classification of impacts
- Characterization
- Normalization
- Weighting

Selection of Impact Categories

Selecting impact categories is a delicate step as it entirely depends on the type of analysis model under study. That is, the impact categories chosen must align with the primary effects that the product system might generate. For example, if the system produces significant CO_2 emissions, climate change will likely be a critical impact category to select.

Once chosen, it is essential to note that each category will have its specific indicators and methods for calculating environmental effects. Major impact categories include:

- Global warming potential: Measures the greenhouse effect caused by released gases; the indicator is kg of CO_2 equivalent.
- Acidification: Assesses the impact of substances like SO_2 and NO_x that acidify soil and water bodies, damaging ecosystems and vegetation. The primary indicator is kg of SO_2 equivalent.
- Eutrophication: Measures the excessive enrichment of nutrients in water bodies, calculated using the indicator kg of PO_4 equivalent.
- Ozone depletion: Calculates the reduction of the atmospheric ozone layer caused by substances like CFC_s and halogens, measured in kg of CFC-11 equivalent.
- Human toxicity: Evaluates the negative impacts on human health caused by toxic substances like heavy metals or solvents.
- Land use: Analyzes impacts associated with changes in land use, such as deforestation, urbanization, or agriculture.
- Water consumption: Calculates the impact related to freshwater consumption, measured in cubic meters.

Classification

The aim of classification is to sort inventory data with respect to their potential impacts on the environment. Hence, every input and output is linked to one or more impact categories. For example, when a data point has CO_2 and SO_2 emissions, it will be linked to the climate change and acidification categories.

There are two methods to classify impacts:

- In parallel, A single substance can cause several impacts at the same time. Effects are simultaneous and interdependent; thus, for example, SO_2 could lead to both acidification and human toxicity.

- In series: A substance's impact is single and one after another causally related. For example, SO_2 leads to soil acidification, which causes the solubility of heavy metals and further impacts.

This classification step can be made less tedious using automated methods within certain software. ReCiPe, CML, and TRACI are the main ones.

Characterization

The characterization phase is crucial for quantifying impacts in a measurable way. As mentioned earlier, each impact category has different units of measurement and can be influenced by various substances differently. Characterization factors are used to convert the contribution of each substance into the unit of measurement for the impact category.

These factors allow the aggregation of the effects of different substances within the same category. For example, in the case of climate change, characterization factors enable the comparison and summation of greenhouse gas effects based on their equivalency to CO_2.

Gas Serra	**kg CO_2 equivalenti**
CO_2. (anidride carbonica)	1
CH_4. (metano)	21
N_2O. (biossido di azoto)	310
HFC_s. (idrofluorocarburi)	140-11700
PFC_s. (poliflorocarburi)	6500-9200
SF_6. (sulfurhexafluoryde)	23900

Figure 9: Characterization factors for kg CO_2.Elaborated by the author.

To calculate the impact ($ISc.$) related to an impact category, we multiply each substance (Ei) by its respective characterization factor (CFi). The total impact is the sum of these calculations:

$$ISc = \sum_{i=0}^{n} (CFi * Ei)$$

- c = impact category
- i = interventions

Normalization and weighting

Normalization is the procedure of dividing the value of a singular impact element by a reference value. This reference value typically reflects the total global impact within that specific area. Normalization helps in contextualizing the impact by giving a clear picture of its value in comparison to other global environmental impacts.

Weighting is done after normalization if there is a need to quantify and integrate the system's environmental impacts into a singular dimensionless value. At this stage, each impact score is assigned a weight that indicates its importance in relation to the environment and the other impacts. With these weights, instead of viewing the specific category scores separately, they are aggregated into one composite score, making the evaluation of the system performance at a particular period based on an aggregate score simple.

This procedure assists in ranking the categories in order of consideration, which is useful for developing policies on matters that need a lot of attention.

2.4.4 **Interpretation and analysis of results**

The interpretation and analysis of results phase is the final step of the study. It aims to transform raw data generated during the inventory analysis and assessment into actionable insights aligned with the study's objectives and scope. As noted earlier in this chapter, this phase can influence previous ones, as all LCA steps are interconnected, forming an iterative process.

After a thorough interpretation of the results, the following key questions can be addressed:

- What is the system's overall impact?
- Which materials are the most influential?
- Which processes contribute the most to the system's environmental effects?

The interpretation phase should include an analysis of completeness, consistency, and sensitivity (European Commission - Joint Research Centre Institute):

- Completeness: Ensures no essential elements are missing from the model.
- Consistency: Confirms that all methodologies, assumptions, and choices made during the analysis align with the study's objectives and scope.
- Sensitivity: Evaluates the robustness of results in response to variations in data or assumptions.

Moreover, this concluding phase should highlight the study’s limitations and offer recommendations for environmental improvement.

Chapter 3
LIFE CYCLE COSTING

Life cycle costing consists of recording the costs of physical assets throughout their life cycle. This approach is beneficial for making decisions regarding asset acquisition, use, and disposal, ensuring cost optimization. This paragraph will analyze this method, from its historical development to its regulatory framework, emphasizing how this tool has become essential in recent years. The concluding part will provide a detailed analysis of the cost elements to be considered in conducting a life cycle costing analysis.

3.1 Historical development

Based on global demographic development and increasing demand for resources, in line with the evolution of the life cycle thinking concept, the need arises for a tool that ensures economically sustainable management of business processes and operations. The history of life cycle costing is quite different from that of life cycle assessment, as the latter was developed to create a model accounting for sustainability in business processes. On the other hand, life cycle costing was originally not designed as a sustainability accounting tool but as a model aimed at reducing business costs alone.

The first documented use of life cycle costing dates back to 1960, introduced by the U.S. Department of Defense (Sherif & Kolarik, 1981). During the Cold War, the United States needed to procure high-cost military equipment, whose value was determined by the purchase price and usage, maintenance, and disposal costs. During the same period, this tool, not yet formally named as it is today, began to be increasingly used in the private sector due to rising costs during the 1973 energy crisis, particularly in civil engineering, construction, and manufacturing, with a primary focus on infrastructure (Cole & Sterner, 2000). In subsequent years, the model was introduced into the public sector in Europe. In 1992, the concept of LCC was officially accepted as a British Standard (Heralova, 2017). It was only after the first ISO standard (ISO, 1997) on life cycle assessment that life cycle costing began to be conceived as the economic counterpart of LCA, creating a complementary and coherent model. In this context, the first standardization occurred in the early 2000s with the formal definition of life cycle costing as: "*a technique which enables comparative cost assessments to be made over a specified period, taking into account all relevant economic factors both in terms of initial costs and future operational costs*" (ISO, 2000).

The conceptual model related to LCC can be observed in the figure below:

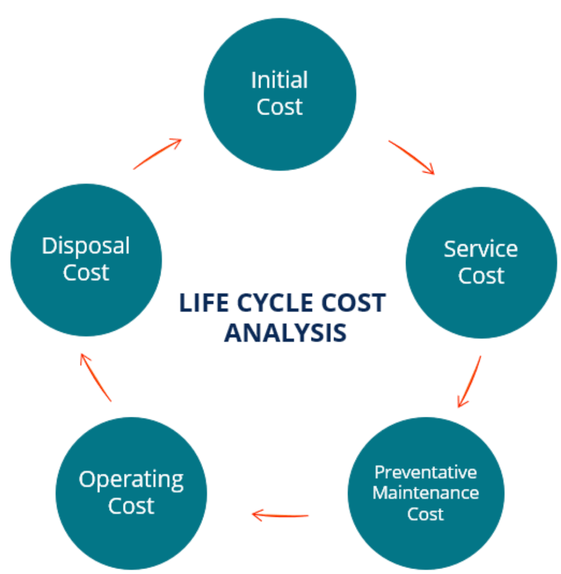

Figure 10: Life cycle cost analysis. (Timothy O. Iyendo et al., 2024)

Based on the concept of life cycle management, a business approach that considers economic and environmental aspects during a product's life cycle, SETAC Europe identified the strength of using both approaches together. Consequently, in 2002, a dedicated working group was created to promote the use of LCC, develop increasingly standardized guidelines, and define clear and shared methods. This process contributed to establishing the state of the art of the technology and the definition of a Code of Practice (G. Rebitzer & S. Seuring, 2003).

3.2 **Development and Regulatory References**

Life Cycle Costing has become an increasingly important and widely used tool over time, so much so that it has been integrated into European policies promoting sustainability, resource efficiency, and the circular economy in recent years.

In the context of public administrations, Green Public Procurement emerged as an approach in which public authorities seek to procure goods and services and work with a reduced environmental impact throughout their entire life cycle compared to conventional alternatives (EC, 2008a). From this, the Public Procurement Directive of the European Parliament (EP, 2014) and the concept of Minimum Environmental Criteria were introduced. Life cycle costing was formalized as a criterion for evaluating bids in this context, encouraging authorities to consider all costs throughout the entire life cycle of a good so that public procurement could contribute to ensuring both environmental and economic sustainability.

In the context of the circular economy, the European Commission's 2020 action plan introduced measures to optimize the life cycle of products and reduce waste, thus promoting the concept of life cycle thinking and its applications. This plan encourages companies to use both LCA and LCC to analyze phases related to product recycling and sustainable packaging (EC, 2020b).

Regarding energy efficiency, the European Commission promotes using the LCC model to assess the economic feasibility of energy efficiency measures, making this tool essential in this sector (EP, 2012).

Life Cycle Costing is the oldest tool within the life cycle thinking framework. However, there are only two regulatory references that standardize this model:

- L'ISO 15686: Regulates LCC for buildings and constructed assets (ISO, 2017)
- L'ISO 15663: Regulates LCC for the petroleum, petrochemical, and natural gas industries (ISO, 2021)

While the LCA methodology is standardized and applicable to all types of products, no international standard concerning the LCC methodology is available for all sectors. Nevertheless, several studies use ISO standards 14040 and 14044, which regulate life cycle assessment, to conduct an LCC study.

3.3 **Conducting a Life Cycle Costing**

The Society of Environmental Toxicology and Chemistry (SETAC) defines three types of LCC studies: Conventional LCC, Environmental LCC, and Societal LCC (D.Hunkeler et al., 2008).

Conventional life cycle costing is the most widely used type by companies and can be defined as the simplest of the three. It mainly focuses on direct and monetizable costs incurred by a single actor or entity during the life cycle of a product or service. This type of study excludes economic externalities resulting from ecological and social effects.

Environmental life cycle costing expands on the previous approach by including costs associated with environmental impacts throughout the product's life cycle. It considers costs incurred by multiple actors during various phases while also accounting for externalities that may be internalized in the future based on the costs generated by ecological impacts.

The third type of study is societal life cycle costing, which assesses all costs associated with a product's life cycle, taking into account externalities from environmental and social impacts. It is described as the most comprehensive model among the three, though a key limitation is the difficulty in monetizing these effects and the lack of a consolidated standard.

Below is a diagram highlighting the boundaries the three models use to generate costs.

Figure 11: Types of life cycle costing

From the previous figure, the following can be identified:

- Internal costs: These are costs that can be directly linked to a business expense and are directly monetizable.
- External costs: These are not directly charged to the company, existing outside the economic system, and are definable as externalities.

Hunkeler (Hunkeler & Rebitzer, 2003) defines the conceptual system of life cycle costing, in which the boundaries of economic and natural systems can be identified, and the contributions of both types of costs can be observed for each phase of the process.

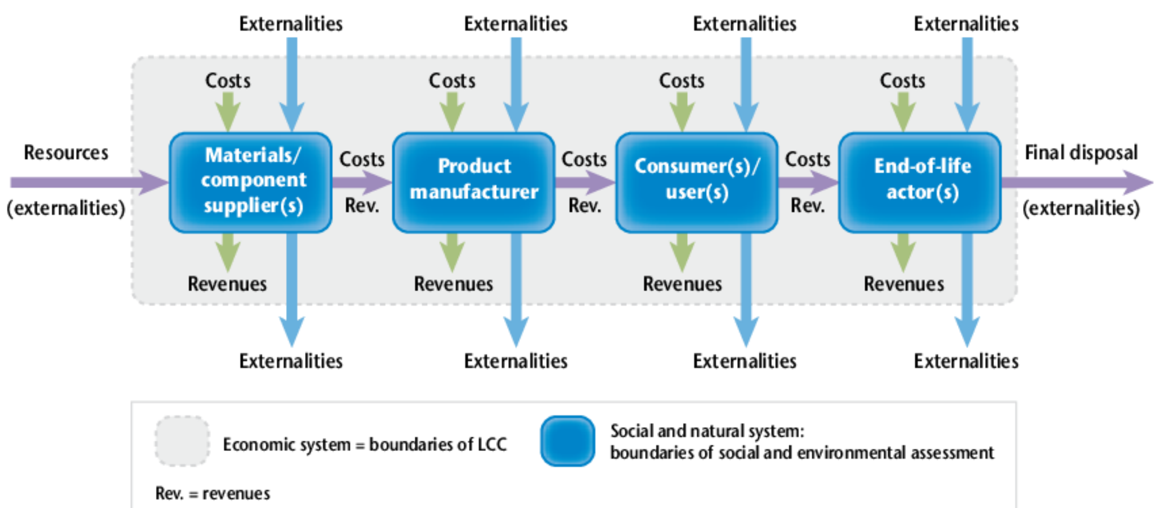

Figure 12: Conceptual model of life cycle costing (H. Estevan, 2018)

The model aligns and remains consistent with the framework established for life cycle assessment, as it follows the four main phases of a study:

- Material suppliers
- Product manufacturer
- Consumer use
- End of life

As defined by standard 14044, which formalizes the guidelines for conducting an LCA study, LCC also consists of four main phases:

- Definition of objectives and scope: In this phase, the study's scope and system boundaries are established. It is recommended to determine a discount rate based on the time horizon, which can be derived from the ECB inflation rate or the company's r_{wacc}.
- Inventory analysis: During this phase, all cost items necessary for the study are collected.
- Cost assessment: Costs are categorized and divided across the various phases of the life cycle.
- Interpretation of results: At this stage, cost categories or life cycle phases with the highest impact on the analysis can be identified, providing insights for future system improvements.

First, the reference time horizon and the discount rate must be defined to effectively conduct this type of analysis.

Reference Time Horizon

This factor, if not critically assessed, can dictate the validity as well as the scope of a project's economic evaluation analysis throughout its life cycle. For example, unexpected changes in future cost burdens may not be accurately captured. A classic case is when the analysis is performed over 5 years for a machine with a useful life of 20 years. Such analysis would miss out a few cost elements like maintenance.

Discount Rate

The discount rate is a fundamental component of life cycle costing. It allows the present value of future costs to be calculated, enabling a fair comparison with current expenses. It is based on concepts such as the time value of money, which is influenced by factors like risk, investment opportunities, and inflation.

The discount rate can be calculated using the inflation rate provided by the European Central Bank or the company r_{wacc}.

The present value costs can, therefore, be calculated using the following formula:

$$C_0 = \frac{C_f}{(1+r)^n}$$

Where $C_0$is the discounted cost, C_f is the future cost, r is the annual discount rate, and n is the number of years between the future cost occurrence and the present.

3.4 **Cost Elements in Life Cycle Costing**

After defining the objectives and scope of a life cycle costing analysis, which, if conducted alongside a life cycle assessment, must be consistent with the latter to ensure reliability in results and analysis, it is necessary to identify the cost elements included in the study.

The cost breakdown structure is crucial for properly categorizing costs. It also enhances estimation accuracy by systematically breaking down costs into smaller components until a level of detail is reached where they can be easily assessed.

Among the main cost elements, we can identify:

- Acquisition Cost
- Operating Cost

- Maintenance Cost
- Disposal Cost

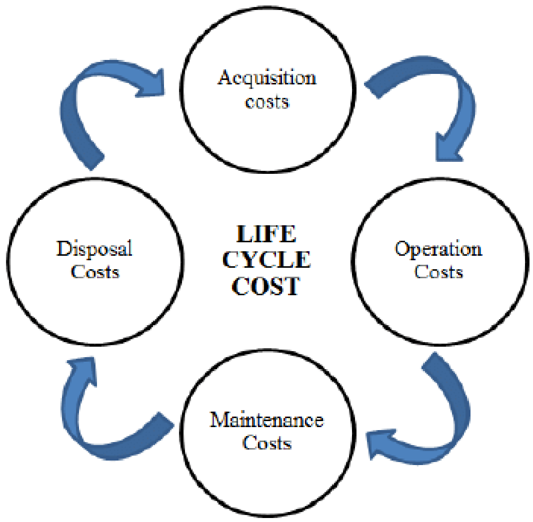

Figure 13: Life cycle cost breakdown (Jurnal Teknologi, 2015).

These costs can be defined as internal, meaning those directly monetizable within the company.

Acquisition cost

Acquisition costs represent the initial investment required to obtain and operationalize an asset or system. These are all the expenses incurred to make a project operational. They are the first elements included in the analysis as they mark the initial stage of the product life cycle. Among them, we can identify:

- Purchase cost of machinery or raw materials
- Installation costs
- Training costs
- Transportation costs

Operating cost

Operating costs are expenses that arise from the functioning and maintenance of a system. Unlike acquisition costs which are single payments, these costs, usually incurred during a system's operational phases, are recurring in nature.

Some of the primary operating expenses are:

- Direct labor costs
- Utility costs
- Consumable material costs
- Routine maintenance costs
- Administrative and management costs

Maintenance cost

Maintenance costs are the expenses incurred to keep a system in operational condition throughout its useful life. These costs are necessary to preserve an asset's functionality, safety, and efficiency. They are variable costs, as they depend on the type of asset, and they are also recurring and continuous.

The following types can be identified:

- Preventive maintenance: Planned intervention costs aimed at preventing failures and maintaining efficiency.
- Corrective maintenance: Unplanned costs resulting from failures or malfunctions

Disposal cost

Disposal costs represent the expenses incurred during the final stages of a system's life cycle. They occur when an asset is no longer functional or cost-effective to maintain and needs to be eliminated or decommissioned.

After analyzing the two main tools that will guide our study, we will now examine how the research was structured to identify models that integrate LCA and LCC, ensuring a proper balance between their contributions.

Chapter 4
METHODOLOGY

In the following chapter, we will present the methodology used to identify the methods that integrate the two analyses and select the most appropriate one for our case study. Initially, we will use the PRISMA method to analyze the selection process of the papers and identify the most suitable models for this thesis. Subsequently, the tools that will specifically support our case study will be described.

4.1 Prisma method

The methodology used to identify the best models applicable to our case study is based on a systematic literature review, a process aimed at collecting, evaluating, and synthesizing all relevant studies related to our research question. This review follows the guidelines of the PRISMA method (Preferred Reporting Items for Systematic Reviews). The PRISMA method is divided into several phases that must be followed systematically to achieve the intended goal of the methodology, as implemented in the study by B. Peixoto (Peixoto et al., 2021). We can identify these steps as follows:

- Decision on eligibility criteria.
- Search strategy.
- Study selection.
- Data collection process.

Initially, it is necessary to identify the eligibility criteria used for the inclusion and exclusion of articles. Among the inclusion criteria, we can identify:

- The article must include the following terms in the title, abstract, or keywords.
    - Life cycle assessment.
    - Life cycle costing.
    - Model.
    - Optimization.

To obtain an adequate query, all abbreviations and synonyms related to the above keywords were included.

- The article must be written in English.

Among the exclusion criteria, we identify:

- The article is not open access.
- The article is not written in English.
- The article does not include optimization models.
- The article does not integrate the two models.

We utilized the Scopus and Web of Science databases, and after analyzing the literature to identify potential methods, we conducted a more in-depth investigation. An example of a query that we entered into the databases is as follows:

(“life cycle assessment” OR” lca”)AND (“life cycle costing” OR “lcc” OR “economic”) AND (manufacturing) AND (model).

No specific restrictions were applied to the agri-food or manufacturing fields, as studies in these sectors were limited. Therefore, a broader research approach was chosen, with the aim of integrating the methods found in our case study.

Once we selected the relevant articles for this thesis, we adopted a data collection method using Mendeley to record key details, including the abstract, year of publication, title, and keywords. Additionally, we included summaries of the results and methodologies used in each study. By entering the first query into the two databases, we found a total of 1,654 papers (783 in Scopus and 871 in Web of Science). Then, we applied initial limitations based on language, accessibility (open access), and document type, including only articles and conference papers. As a result, 1164 papers were excluded due to the large number of papers without full-text availability, leaving 490 papers (215 from Scopus and 275 from Web of Science). Afterward, using databases such as Mendeley, an analysis was carried out to detect duplicates, resulting in the exclusion of another 37 papers. At the conclusion of this phase, the remaining papers amounted to 453.

This led to the screening phase, in which the titles, abstracts, and keywords were analyzed based on the inclusion and exclusion criteria mentioned above. This phase resulted in the exclusion of another 346 papers, leaving 89 papers on which a full-text analysis was conducted, mainly focusing on the methodology used in the study. After this screening phase, the papers that remained available amounted to 18. Below, we can visualize the framework of the PRISMA method.

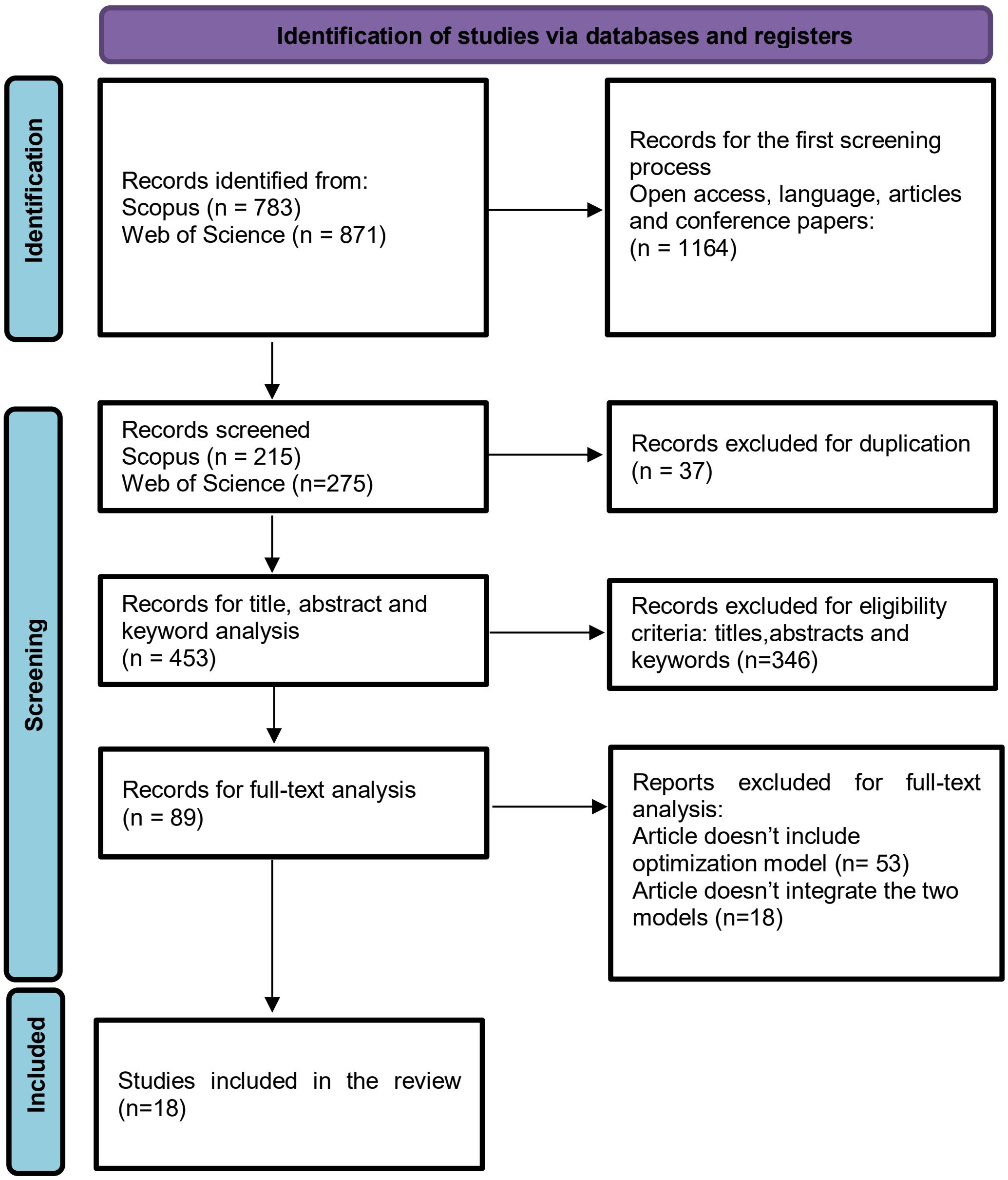

Figure 14: PRISMA flow diagram. Elaborated by the author

The literature review highlights two main types of models: those based on genetic algorithms, as seen in the works of R.Wang (Wang et al., 2020), D. Le Roux (Le Roux et al., 2023), D. Le Roux (Le Roux et al., 2022) e Z. Zhang (Zhang et al., 2022), and those employing linear programming such as the studies by C. Miret (Miret et al., 2016), M. Budzinski (Budzinski et al., 2019). The latter uses the MILP method, an optimization technique that combines continuous and integer variables. Genetic algorithms will be analyzed in detail in the section on the NSGA-II method, which, alongside TOPSIS, was chosen as the preferred solution. This is because genetic algorithms are particularly suited to managing multi-objective problems, effectively balancing different optimization criteria. From the study by J. Laso (Laso et al., 2018), it is observed that algorithms based on linear programming often require the creation of an aggregate function that combines environmental and economic costs. This involves assigning weights to normalize the different variables to the same unit of measurement. However, this process may carry the risk of introducing errors, as the choice of weights can significantly influence the results obtained. In many of the analyzed studies, the genetic algorithm is accompanied by analysis through the TOPSIS method, which allows for the selection of optimal solutions from the Pareto-efficient ones generated by the algorithm.

Furthermore, among the studies considered, three belong to the agri-food sector (Miret et al., 2016), (Zhang et al., 2022), (Bayram et al., 2024). In these works, the main impact categories used for conducting the life cycle assessment (LCA) are: global warming potential, acidification, eutrophication, and water usage.

A limitation of this research is the scarcity of studies integrating both models for optimizing manufacturing production. For this reason, we primarily referenced Z. Zhang (Zhang et al., 2022) as this study focused on optimization within the manufacturing process itself rather than on supply chain and logistics stages. Based on this, our analysis extended to the search for other works exploring similar studies, with an in-depth focus on genetic algorithms and the TOPSIS method. Thus, following the research analysis, it was decided to implement the model that will be described in the following sections.

4.2 **Inventory analysis and impact categories**

Chapter 2 has been detailing how to conduct a Life Cycle Assessment (LCA). Now, we will work on the choices made in the case study regarding the objective, definition of the functional unit, system boundaries, and the choice of inputs and outputs. The associated results will be further discussed in Chapter 6.

The study's objective is to identify the most impactful process within an agri-food manufacturing company, particularly in the production of pesto, which will be described in the next chapter. The system boundaries follow a gate-to-gate approach, covering the process from raw material reception to storage. Therefore, the study does not consider the preceding phases related to raw material extraction, transformation, and transport, nor the subsequent phases related to product distribution, use, and disposal.

This choice aims to optimize internal processes, even though literature indicates that the most impactful agri-food sector processes are typically linked to primary production. However, analyzing the earlier phases would have been more appropriate for a study focusing on resource procurement. The results will refer to the production of a single jar, defined as the functional unit of the study.

Regarding inputs and outputs, the analysis is based on the study by Murphy, McDonnell, and Colette (Murphy et al., 2014) described in Chapter 1. The main inputs are:

- Electricity: The Italian public grid supplies electricity. Therefore, impacts will be calculated using the national energy mix available in the database.
- Thermal energy: Heat is primarily used during the cooking and sterilization phases, with steam generated by boilers powered by natural gas.
- Water resources: The water used undergoes a reverse osmosis process to meet the required standards for company operations.

The main outputs are:

- Solid waste: Ingredient waste will be quantified, and the associated impacts of its management will be evaluated.
- Wastewater: Similarly, liquid waste and the impacts of its management for discharge into natural bodies of water will be accounted for.
- Air emissions: In addition to indirect emissions related to electricity supply, direct emissions such as natural gas combustion will be included.

The study will not include impacts related to packaging waste and jar breakage, as the company considers them negligible.

A mix of primary and secondary sources ensures the data's representativeness. The company provides estimates related to energy use, waste generation, and air emissions, which are considered primary data. Indirect emissions, such as those related to water supply and waste management, are calculated using the ELCD database. This database meets geographic, temporal, and technological representativeness criteria by providing up-to-date data on innovative waste management processes and the Italian energy mix.

The next chapter will describe the process flowchart, highlighting the contributions associated with inputs and outputs in each stage. The subsequent step is the analysis of environmental impact categories, which were introduced in the LCA methodology chapter. These categories are selected based on studies identified through the PRISMA method, particularly those related to companies in the same sector. The categories analyzed are:

- Global warming potential.
- Water consumption.
- Eutrophication.
- Acidification.

Impact calculations will be performed using OpenLCA, which will also assist in data management and result analysis.

4.3 **OpenLCA**

OpenLCA is an open-source database developed by GreenDelta, a company specializing in environmental analysis services. The development of an LCA is well supported by the information contained in the database. It is regularly employed by companies in this area because it enhances the handling of sophisticated data and impact analysis with standard procedures. The software does not come with functioning internal databases but allows for connections to certified ones:

- ELCD: Created by the Institute for Environment and Sustainability (IES) of the Joint Research Center (JRC) of the European Commission, which contains approximately 503 processes in version 3.2 from different sectors.
- Ecoinvent: Created by the IES of JRC of the European Commission. Over 5,000 organizations are using it now.
- Agrybalise: Created ADEME, the French Environmental and Energy Management Agency, it is primarily used for modeling processes in the food industry.

These are just a few of the main databases used by the software. ELCD was selected for this study because it is completely free and provides a lot of information.

OpenLCA has important key functions:

- Integration of both primary and secondary sources: The software enables the combination and analysis of both primary and secondary data, ensuring comprehensive coverage in data analysis.

- Process modeling: OpenLCA provides the possibility for the development of process models using diagrams that link the process's various inputs and outputs.
- Impact assessment methods: Several methods are available for evaluating and comparing impact categories. These include:
    - CLM 2001: Evaluates various impact categories at the midpoint level and is widely used for its scientific robustness and precise impact categorization.
    - CED: The Cumulative Energy Demand method calculates the total energy demand of a system by categorizing energy consumption based on its sources.
    - Eco-indicator 99: This method evaluates impacts using three perspectives (individualistic, hierarchical, and egalitarian). The main damage categories include human health, ecosystem quality, and resource consumption.
    - Ecological Scarcity Method 2006: This method assesses impacts based on ecological scarcity by assigning scores according to the gap between current emissions and policy targets.
    - ILCD 2011: Developed to provide harmonized guidelines for life cycle assessments within the European Union. It includes various midpoint impact categories, such as climate change, acidification, eutrophication, and human toxicity.
    - Recipe 2008: This model integrates both midpoint and endpoint approaches, offering a comprehensive view of environmental impacts. Midpoint categories include climate change, acidification,

  - and fine particulate matter, while endpoint categories include human health, ecosystem quality, and resource availability.
  - TRACI 2.1: Commonly used in North America, it includes midpoint impact categories.
  - USEtox: A scientific model for characterizing human and ecotoxicity impacts in life cycle assessment.

For consistency with studies identified through PRISMA analysis, the ReCiPe 2008 method (midpoint approach) will be used to select the impact categories mentioned earlier.

- Sensitivity and scenario analysis: The software includes tools to analyze the sensitivity of results by varying key parameters and simulating different scenarios.
- Output and reporting: OpenLCA can generate tables, charts, and reports to facilitate the interpretation of results.

OpenLCA could conduct an LCC analysis but given the available data and the calculation of the indicator described in the next chapter, it is preferred to use the software exclusively for LCA calculations.

4.4 Cost analysis and LCOP

As discussed in the previous chapters, the Life Cycle Costing (LCC) analysis follows a similar approach to the Life Cycle Assessment (LCA). This section will examine the costs related to the case study. It is essential to clarify that the objectives, functional unit, and system boundaries must be aligned between the two analyses to ensure consistency and completeness.

One of the main challenges encountered is related to the temporal definition. The LCC analysis must cover a long time, corresponding to the product's useful life.

However, in our case, the LCA analysis adopts a gate-to-gate approach, which does not consider the entire life cycle but only the activities between the input of raw materials and the output of the finished product.

Inspired by the literature, we adjusted the perspective by defining the functional unit as the entire production process over a 20-year time frame to overcome this difficulty. Subsequently, to convert the costs back to the functional unit used in the LCA analysis (a single jar of product), we adopted a normalization index called LCOP (Life Cycle Operating Cost), as defined by Pereira (Pereira et al., 2024). This index allows us to express the economic results in a manner that is comparable to the environmental results.

Below is the formula for the previously defined index.

$$LCOP = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + E_t}{(1 + r_{wacc})^t}}{\sum_{t=1}^{n} \frac{P_t}{(1 + r_{wacc})^t}}$$

I_t represents the machinery investment costs, M_t maintenance expenses, and E_t other costs associated with the company's operational expenditures (OPEX). In our case, the denominator P_t represents the annual production of jars. r_{wacc} allows us to discount future costs and sum them with present expenses. LCOP will thus provide a result expressed in units equivalent to euro per jar.

The cost definition is based on a combination of company data and assumptions from studies that have estimated costs for similar business processes.

Below, we outline the methodology used to obtain these data and the limitations associated with the study:

- CAPEX: Investment costs were obtained from the book “Food Plant Economics” (Maroulis & Saravacos, 2008), which provides estimates for key equipment used in food manufacturing processes.
- Personnel costs: The company provided data on the number of employees and working hours. Hourly wage rates were based on ISTAT data on gross remuneration (13.74 $\frac{€}{h}$), with additional costs for employer contributions and severance pay (TFR) equivalent to 35% and 7% of gross remuneration, following estimates from Randstad (Randstad, 2025).
- Depreciation and maintenance costs: Depreciation was calculated based on the investment cost and the machinery's useful life, assuming a zero residual value at the end of the 20-year lifespan. Maintenance costs were estimated using the study (Carolina et al., 2021), which assumes an amount equivalent to 2-5% of the Replacement Asset Value (RAV), considered equal to the initial investment.
- Raw materials and components costs: These costs were obtained from company data equivalent to 1.049 $\frac{€}{jar}$.
- Electric energy costs: Hourly electricity cost equivalent to 0.289 $\frac{€}{kWh}$ were obtained from the ARERA report (ARERA, 2023). The company provided the amount of kWh consumed by the machinery. Lighting costs were estimated as follows: First, a 150W LED lamp producing an average of 26,500 lumens, available on the market, was used as a reference. Based on the UNI EN 12464-1 (UNI, 2021) standard, the required lux level to illuminate the facility was determined (300 lux), and the number of lamps needed was calculated using the following formula in which the area of the factory is equal to 26,000 m^2:

$$n_{lamps} = \frac{area \cdot lux}{lumen}$$

It is possible to calculate hourly energy consumption based on the number of lamps, their power, and the working hours (assumed to be 10 hours).

- Natural gas costs: The cost of natural gas equivalent to 0.509 $\frac{€}{m^3}$ was obtained from the ARERA report (ARERA, 2023). Consumption was estimated based on the thermal energy required for processes such as cooking and sterilization, divided by the calorific value of natural gas, which is equal to 34.8 $\frac{MJ}{m^3}$.
- Water supply, wastewater disposal, and solid waste disposal costs: The tariffs set by the integrated water system (SII, 2024) provided the costs for water supply and disposal (5.188$\frac{€}{m^3}$ and 0.8749 $\frac{€}{m^3}$). The cost of waste disposal is provided by the company and is equivalent to 120 $\frac{€}{ton}$. As for the quantities, they will be analyzed in the results chapter.

Machinery disposal costs were not included in this study due to the difficulty in obtaining data and because these costs have minimal impact on the result.
Once both LCA and LCC analyses are aligned to the same functional unit, the next step will focus on impact assessment and identifying the most critical process. This process will then be optimized through two functions, which will be examined in the following section.

4.5 **Multi-objective problem**

Multi-objective problems are of particular importance because, in real-world case studies, they often depend on multiple parameters that influence the objective functions in different ways. As historically analyzed in the study of De Weck (De Weck, 2004), multi-objective optimization has its roots in economic thought, where the concept of the "best decision" is tied to the need to balance different criteria. One of the first studies to formalize these trade-offs was conducted by Edgeworth in 1881 (F.Y. Edgeworth, 1881). He proposed a criterion for optimal choice between two utility criteria, showing that improving one necessarily leads to the deterioration of the other. At the same time, Vilfredo Pareto (V. Pareto, 1906) developed the concept of Pareto optimality, which states that resource distribution is considered optimal if it is impossible to improve the condition of one individual without worsening that of another. Following these studies, the analysis and application of multi-objective problems have increasingly been extended to engineering, leading to the development of various solution techniques, including linear programming and genetic algorithms, described in the previous sections.

A multi-objective problem can be formally defined as follows:

$$min/\max \quad f_1(x), f_2(x) \dots, f_k(x)$$

Subject to:

$$x \in X$$

Where:

- $f_1(x), f_2(x) \dots, f_k(x)$ are the objective functions to be minimized or maximized, often conflicting with each other.
- X represents the space of feasible solutions defined by constraints and restrictions.

A concrete application of multi-objective optimization can be found in the industrial process of our case study, where multi-objective functions aim to represent key elements that directly impact consumption and costs. Specifically, this study focuses on accurately modelling two fundamental functions related to Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), as they serve as critical inputs in almost every phase of the process. Optimizing these functions will, in turn, optimize the impact categories and costs established for the study. Both functions are influenced by a single process parameter: the sterilization temperature, which will be discussed in detail in the next chapter. However, each function reaches its minimum value at a different temperature, generating a set of Pareto-optimal solutions within the range defined by both minimum values. While it may seem intuitive to select the temperature that minimizes a single function, in many cases, the impact of costs and emissions per unit can be unpredictable. Therefore, the methodologies described in the following sections will demonstrate how to identify the process optimum without relying solely on intuition, which can be misleading when balancing costs and emissions.

4.5.1 **Nsga-II**

The NSGA-II (Non-dominated Sorting Genetic Algorithm II) is an evolutionary algorithm for multi-objective optimization problems. As previously mentioned, these problems do not have a single optimal outcome but rather a set of results referred to as the Pareto front. The solutions on this front are optimal, as it is impossible to improve one objective without negatively impacting another. NSGA-II aims to identify the optimal outcomes along the Pareto front.

This method belongs to the class of genetic algorithms derived from evolutionary algorithms inspired by Charles Darwin's theory of natural selection. According to this theory, organisms adapt to their environment through the following mechanisms:

- Natural selection: Only the most suitable individuals have a higher chance of survival.
- Mutation and crossover: Genetic variations and the combination of genetic material create new generations with potential improvements.
- Adaptation and improvement: Over time, organisms with advantageous traits become more prevalent.

These principles were applied to optimization methods, leading to the development of genetic algorithms, first introduced by J.H. Holland (John H.Holland, 1992).

In the case of the NSGA-II algorithm, the key steps are as follows:

- Population initialization: A random initial population of candidate solutions is generated.
- Objective evaluation: Each solution is evaluated based on the established criteria, i.e., the objective functions.
- Non-dominated sorting: The algorithm ranks solutions based on dominance. A solution A is said to dominate a solution B if A is equal to or better than B in all criteria. Solutions are classified into levels:
    - Level 1: Solutions not dominated by any other solution.
    - Level 2: Solutions dominated only by those in Level 1, and so on.

- Crowding distance calculation: To maintain a good distribution of solutions on the Pareto front, the algorithm calculates the crowding distance, which helps prioritize solutions farther apart to promote diversity.

- Parent selection: Based on dominance ranking and crowding distance, solutions from lower levels are prioritized, and if they are on the same level, those with a higher crowding distance are preferred.
- Crossover and mutation: Selected parents undergo crossover, combining to produce new solutions, and mutation, where small changes are applied to generate diversity.
- Population merging and survival: The current population is merged with the newly generated one to form a temporary population. Non-dominated sorting is applied again, and the population is reduced to its original size.
- Repetition: The process is repeated until a termination criterion, such as a maximum number of generations, is met.

The first version of the NSGA algorithm was introduced by Kalyanmoy Deb (Siinivas & Deb, 1994). However, it had limitations related to high computational complexity, lack of diversity control, and the failure to preserve the best solutions across generations. These issues were addressed in 2002 when Deb refined the algorithm, introducing improvements such as the crowding distance and non-dominated sorting, which resolved these earlier shortcomings. Today, a more advanced version, NSGA-III, is used for highly complex problems. In our case, the second version of the algorithm is sufficient for exploring the best solutions on the Pareto front.

The following figure illustrates the described model (M. Dendaluce et al., 2014):

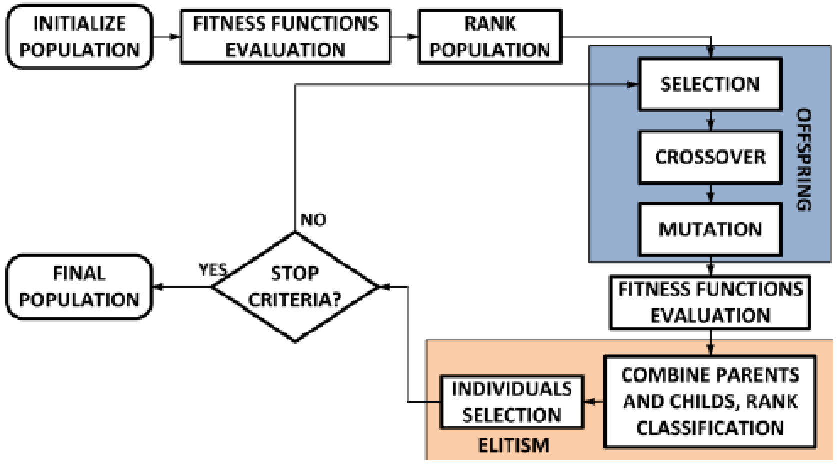

Figure 15: Nsga_II framework. (M. Dendaluce, 2014).

In practice, this algorithm will be implemented using Python. The programming language allows for solving the described problem through brief and straightforward steps. In addition to writing the functions, importing specialized libraries for solving genetic algorithms will be necessary, enabling us to address the problem with just a few lines of code. In our case, the library used will be *pymoo*, designed explicitly for evolutionary optimization problems. More precisely, the NSGA-II algorithm will be imported along with functions to define the problem (*ElementWiseProblem*) and optimize it (*minimize*).

```
from pymoo.algorithms.moo.nsga2 import NSGA2
from pymoo.optimize import minimize as nsga2_minimize
from pymoo.core.problem import ElementwiseProblem
```

Figure 16: Libraries for Nsga-II algorithm. Elaborated by the author from python code.

Once the libraries have been imported, the next step is to define the functions and represent them in Python code. After completing this, we can set the process parameters and develop the algorithm. The steps are outlined below:

```python
class MultiObjectiveProblem(ElementwiseProblem):
    def __init__(self):
        super().__init__(n_var=1, n_obj=2, xl=114.03, xu=116.14)

    def _evaluate(self, x, out):
        out["F"] = [Qs(x[0]), m(x[0])]

problem = MultiObjectiveProblem()
algorithm = NSGA2(pop_size=100)
result = nsga2_minimize(problem, algorithm, termination=('n_gen', 100))
```

Figure 17: Implementation of Nsga-II. Elaborated by the author from pyhton code.

The first function initializes the problem by defining four parameters. The first corresponds to the independent variable of the problem, while the second represents the objectives (in this case, two functions to be optimized). The third and fourth set the lower and upper bounds, with temperature limits ranging from 104°C to 130°C. Regarding the other parameters, *self* refers to the current instance of the class and allows access to its attributes; *x* represents the independent variable and, therefore, a candidate solution; and *out* is a dictionary that communicates the values of the objectives. This setup is necessary to define the problem. Subsequently, the algorithm will be implemented, and the results will be presented. In our case, the population size is set to 100, and the algorithm will stop after exploring 100 generations.

Once the 100 Pareto-optimal solutions have been identified, the study's objective shifts to finding the best solution. To achieve this, the *TOPSIS* method, which will be described in the next section, will support us.

4.6 **Topsis method**

The *Topsis* (Technique for Order of Preference by Similarity to Ideal Solution) is a multi-criteria decision-making (MCDM) approach developed by C.L. Hwang and K.

Yoon (C. Hwang & K. Yoon, 1981). This method allows us to rank and identify the best solution among various alternatives based on weighted criteria.

Widely adopted by companies, particularly in supplier selection, the TOPSIS method follows these key steps:

- Definition of alternatives: In our case, these correspond to the Pareto-optimal solutions previously identified using the NSGA-II method.
- Definition of criteria: In this context, the criteria correspond to the impact categories previously defined in the LCA study, namely: Global Warming Potential, Eutrophication, Acidification, Fine Particulate Matter, and Water Consumption. Additionally, we include an economic criterion represented by the LCOP index, described in the section dedicated to life cycle costing.
- Definition of criteria weights: In this case, we will use the entropy method defined in the study by Zaho (Zhao & Wang, 2019), which will be explained later.
- Evaluation of alternatives with respect to the criteria: This step involves ranking the alternatives and identifying the best solutions.

The practical calculation involves the following phases, detailed further:

- Create an evaluation matrix.
- Normalize the matrix.
- Calculate the weighted normalized matrix.
- Identify the worst and best solutions.
- Calculate the closeness coefficient and rank the alternatives.

Create an evaluation matrix

The creation of the evaluation matrix is based on the previously defined alternatives and criteria. Each row represents an alternative, and each column represents a criterion.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1J} \\ x_{21} & x_{22} & \dots & x_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ x_{I1} & x_{I2} & \dots & x_{IJ} \end{bmatrix}$$

Figure 18: Evaluation matrix. Elaborated by the author

$A_i = (i = 1,2 \ldots .,I)$

$C_j = (j = 1,2 \ldots .,J)$

For each criterion, we can define a weight:

$W_j = (j = 1,2 \ldots .,J)$

As mentioned earlier, the calculation is performed using the entropy method, which involves the following steps:

1. Standardization of the matrix:

$$Y_{ij} = \frac{Xij - max(Xj)}{max(Xj) - min(Xj)}$$

Here, X_{ij}represents a single element within the matrix, i.e., the value of criterion j for alternative i. Max(X_j) and min(X_j) denote the maximum and minimum values of the corresponding criterion in the j-th column.

2. Calculation of the proportion for each standardized value:

$$Z_{ij} = \frac{Yij}{\sum_{i=1}^{I} Yij}$$

Here, Y_{ij} are the previously standardized values, and the denominator is the sum of all standardized values for criterion j.

3. Calculation of the criterion's entropy:

$$E_j = -\frac{\sum_{i=1}^{I} Zij \cdot lnZij}{ln\, I}$$

Here, I is the total number of alternatives, Zij is the proportion calculated in the previous step, $lnZij$ evaluates how much each proportion contributes to the overall information of criterion j, and $ln\, I$ is a normalization factor that ensures the entropy is between 0 and 1.

4. Calculation of the weight of each criterion:

$$w_j = \frac{1 - Ej}{\sum_{j=1}^{J}(1 - Ej)}$$

Here, $1 - Ej$ represents the degree of divergence, indicating the extent to which criterion j contributes to differentiating between alternatives.
Once the criteria, alternatives, and their respective weights are defined, we can proceed to the next phase.

Normalise the matrix

The second step involves the normalization of the previously presented matrix to achieve dimensionless units. This step is essential to enable comparison between criteria that have different units and scales.

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1J} \\ y_{21} & y_{22} & \cdots & y_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ y_{I1} & y_{I2} & \cdots & y_{IJ} \end{bmatrix}$$

Figure 19: Normalized Evaluation Matrix. Elaborated by the author.

We can obtain the matrix shown in the figure through this step:

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{I} x_{ij}^2}}$$

Here, x_{ij} represents the value of criterion j for alternative i, while the denominator is the normalization term, defined by the square root of the sum of the squares of x_{ij} for the j-th criterion.

Calculate the weighted normalised matrix

Once all elements of the matrix have been normalized, the next step is to weight them according to the previously calculated weights. The final result will be the following matrix:

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1J} \\ v_{21} & v_{22} & \cdots & v_{2J} \\ \vdots & \vdots & \ddots & \vdots \\ v_{I1} & v_{I2} & \cdots & v_{IJ} \end{bmatrix}$$

Figure 20: Weighted normalized evaluation matrix. Elaborated by the author

Here, v_{ij} is given by the following formula:

$$v_{ij} = w_j \cdot y_{ij}$$

Where w_j is the weight of criterion j, and y_{ij} is the normalized value of the criterion for alternative i.

Determinate the worst and the best solution

The next step is to determine the best and worst solutions for each criterion. If the criterion is a "benefit," the best solution will correspond to the maximum value and the worst to the minimum value. However, since we are dealing with environmental and economic costs, the interpretation is reversed: the best solution corresponds to the minimum value, while the worst corresponds to the maximum value.

This process is repeated for each criterion, resulting in two vectors—one containing the best solutions and the other containing the worst solutions:

$A^* = [\, v_1^*, v_2^*, \ldots, v_j^*]$ $\quad v_j^* = min(vij)\ for\ the\ j - th\ criterion$

$A^- = [\, v_1^-, v_2^-, \ldots, v_j^-]$ $\quad v_j^- = max(vij)\ for\ the\ j - th\ criterion$

Calculate the closeness coefficient and rank criteria

The final step to find the optimal solution is based on calculating the **closeness coefficient**. To do this, we need to introduce and calculate two parameters, defined as the distances of each alternative from the best and worst solutions, respectively. The formulas for these distances are provided below:

$$d_i^* = \sqrt{\sum_{j=1}^{J} (v_{ij} - v_j^*)^2}$$

$$d_i^- = \sqrt{\sum_{j=1}^{J} (v_{ij} - v_j^-)^2}$$

Once the maximum and minimum distances have been calculated, we can finally obtain the **closeness coefficient** using the following formula:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}$$

As we can see from the formula, the alternative with the highest closeness coefficient will be preferred, as the numerator represents the distance from the worst solution. Once this coefficient has been calculated for each alternative, the next step is to rank them and identify the optimal solution.

This chapter has provided all the necessary guidelines to fully understand the methods that will be implemented to achieve the results presented later. The next step is to provide a detailed description of the case study examined in this thesis.

Chapter 5
CASE STUDY

In the following chapter, the production process analyzed in this thesis will be described. Specifically, it involves the production of jarred pesto in glass containers, carried out by a company based in Piedmont. The main ingredients that make up the product include water, cream, butter, pesto base, egg yolk, cashew nuts, starches, and sifted powders. The company has a production capacity of about 30,000 jars per day, and in the first section, the functioning of the production line will be analyzed. Subsequently, we will focus on modelling the sterilization process, as it has been identified as a critical phase in terms of both energy consumption and costs. This hypothesis will be confirmed and reinforced by the results presented in Chapter 6.

5.1 **Process' description**

The process consists of several phases, each of which is crucial to achieving the daily production goals. In particular, we can identify two main lines: one dedicated to the reception and preparation of raw materials and another focused on handling and preparing jars. These two lines eventually merge to complete the production process.

Reception, preparation, and cooking of ingredients

The raw materials arriving at the company are collected and transported to the laboratory, where an operator analyzes key parameters, such as the food safety of the ingredients. Once this analysis is completed, another operator records the data in an Excel file, which is then archived and named according to the specific raw material. After this phase, the ingredients are stored based on production needs and their specific storage requirements. For example, raw materials containing milk are kept in large refrigerators that use ammonia as the refrigerant. Since ammonia is a hazardous substance, according to company controls and specifications, there is absolutely no gas leakage.

Certain fresh ingredients, such as basil, undergo a high-water-consumption washing phase. Once the materials are properly stored and washed, the process moves on to the cooking phase. Butter, stored in refrigerators, is thawed and mixed with water and cheese by a specialized machine. The resulting mixture is then transferred through vacuum suction into one of the three bowls that make up the "kitchen" section, where the liquids are maintained at a temperature of 65°C. A temperature sensor is located under the bowl to continuously monitor the pressure and steam temperature.

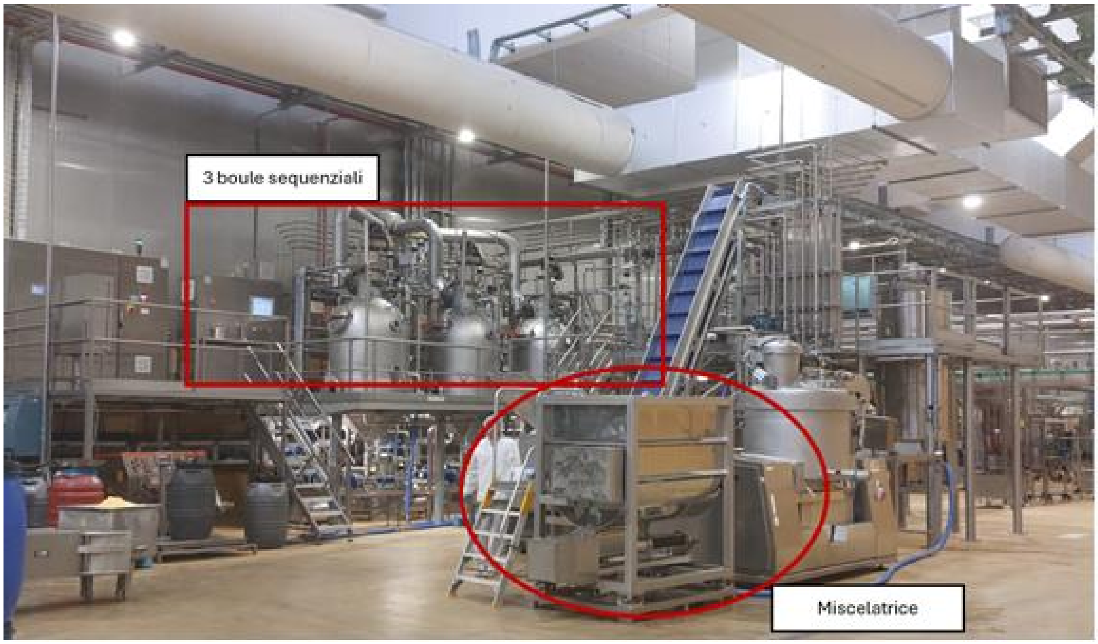

Figure 21: Cooking and mixing machines. Provided by the company.

Once this phase is completed, the mixture is transferred from bowl 1 to bowl 2, where powders and the pesto base are added through vacuum suction.

The mixture moves on to the next cooking phase in bowl 3, where it is heated to a temperature of 90°C. This is done specifically to ensure an optimal temperature of 85°C at the time of bottling to meet food safety requirements.

During this process, an operator collects a sample directly from bowl 3 to chemically verify all key parameters, such as pH, Bostwick consistency, viscosity, color, and salt content.

Reception, depalletization, and jar blowing

Once the jars are received, they are specifically stored and organized on pallets with nine levels. The process then moves on to placing the jars on the production line, where the pallets are positioned on a depalletizer. This machine, using mechanical arms with a suction system, lifts each level of jars.

Figure 22: De-palletizer process. Provided by the company

Afterward, the jars are transferred onto a metal conveyor belt via a plate, which transports them to the production lines. Before reaching the filling phase, the jars are turned upside down and cleaned by a blower using a high-pressure air jet.

Filling, capping, and coding

The two previously described phases occur in parallel to ensure that, once the ingredients are cooked and the pesto preparation is complete, the jars can be filled with the sauce at a temperature of 85°C.

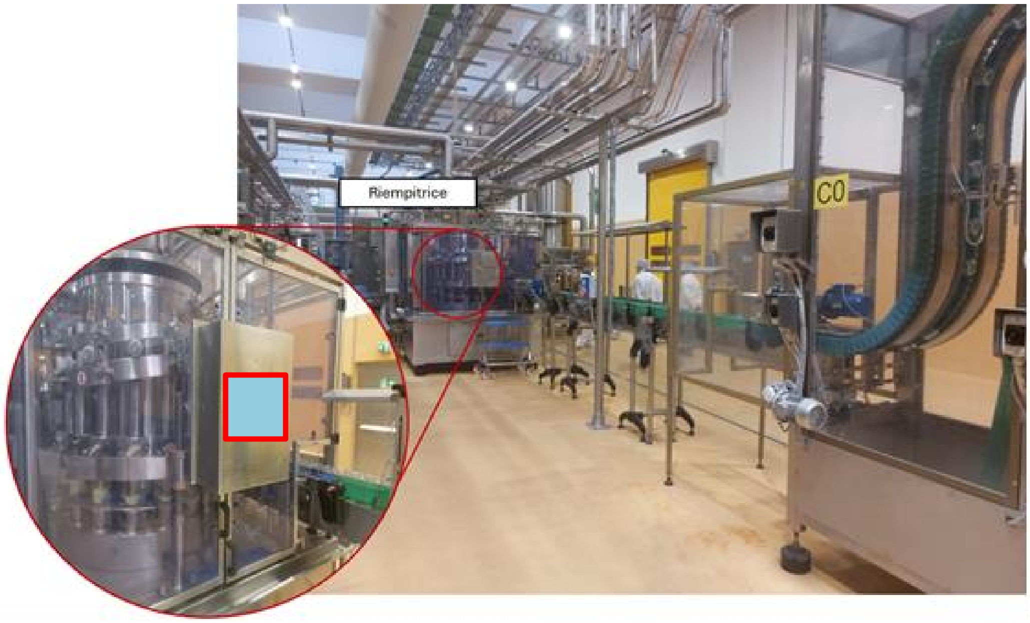

Figure 23: Filling process. Provided by the company

At this stage, a control is carried out to ensure that jars with sauce below 80°C are discarded.

Figure 24: Filling phase. Provided by the company.

Afterward, the jars are sealed with caps using a belt system that screws the lid onto the jar.

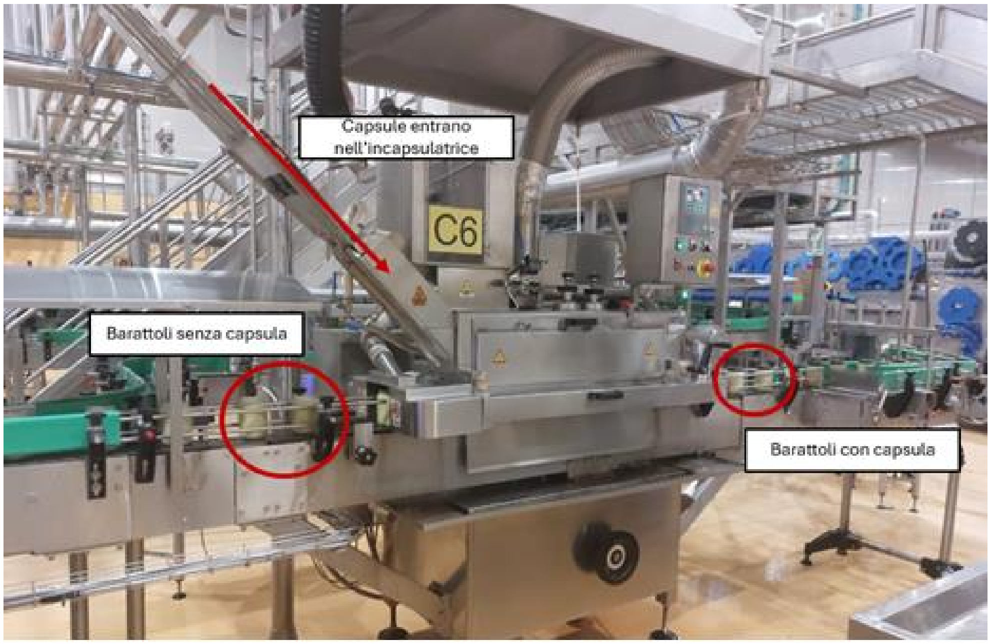

Figure 25: Capping phase. Provided by the company

Sample closure checks are carried out (screw tightening of 4-8mm) along with a vacuum integrity check (100-700 mbar) performed by the operator. Non-compliant jars are temporarily set aside and later reintroduced into the production line after intervention by an operator.

Following this, a code is applied to the jar lids, which includes information such as the plant, the production line, the year of production, the day of the year, the product code, and the production time.

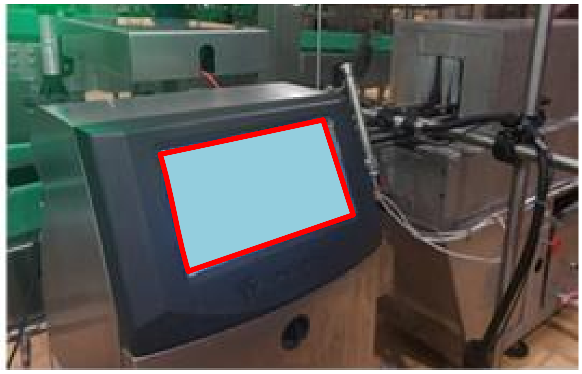

Figure 26: Coding phase. Provided by the company

Sterilization in autoclave

Once the jars have been filled, sealed, and coded, they are accumulated and automatically loaded into multi-level baskets. The autoclave can hold up to 4,000 jars, organized across 6 stacked levels. These baskets are then inserted into the autoclave for the sterilization process. Inside the autoclave, sensors monitor both pressure and temperature. The process parameters and their modelling will be described in detail in the following section, as this is a highly energy-intensive phase.

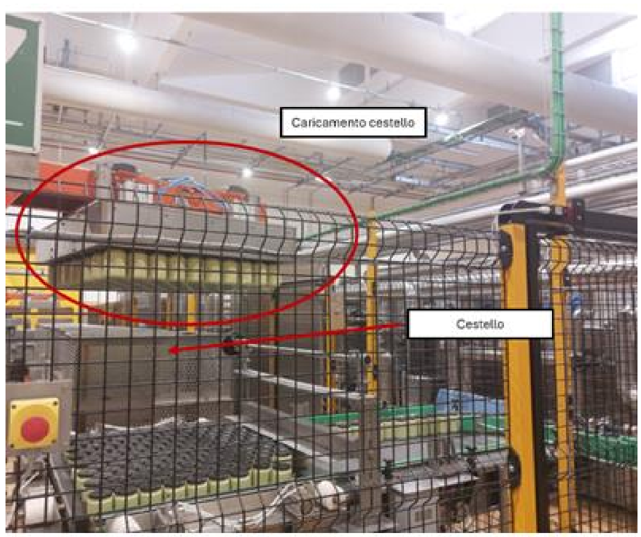

Figure 27: Autoclave basket loading process. Provided by the company

There are 10 cycles per day carried out by 4 autoclaves in parallel, each of which lasts about two and a half hours, during which the autoclave operates within a pressure range of 300 to 1600 mbar and a temperature range of 30°C to 120°C. This cycle is essential for eliminating pathogenic microorganisms and ensuring the preservation of the product. During the cycle, monitoring probes are used to continuously measure the temperature inside the jars.

Figure 28: Sterilization phase. Provided by the company

The probe is placed in the most unfavourable position, which is the presumed coldest and most central area. Through this probe, the sterilization factor (F) is determined, indicating the reduction of the microorganism population, measured in terms of the time and temperature required to eliminate a specific quantity of microorganisms. This parameter thus represents the effectiveness of the process. In the event of a malfunction or failure to reach the desired F factor, analyses are carried out to assess the integrity of the process.

Figure 29: Temperature detection sensors. Provided by the company.

Labeling and final packaging

At the conclusion of the sterilization process, a control check is repeated on the jars regarding screw tightening (4-8mm) and vacuum (100-700 mbar). The next phase involves labelling through an automated line that applies labels to the jars. This process can also take place several months after production and the initial storage of unlabelled jars. During this phase, the jars are stored in a controlled chamber at 4°C. It is noteworthy that the energy contribution associated with this phase is minimal, as storage is shared with other company production lines. Since the labelling line is relatively small, its contribution to refrigeration storage is negligible.

After labelling, the jars are grouped together, and a cardboard tray is built around them directly on the line. The jars and tray are then wrapped in a durable nylon film and subjected to heat shrinking. The finished products are palletized and stored in warehouses.

Figure 30: Secondary Packaging. Provided by the company.

5.2 **Sterilization Process Parameters**

The sterilization process is a fundamental phase in pesto production due to its high energy and water consumption. As we will later observe from the results derived from the LCA and LCC, it will be the key process that we need to optimize in our study.

The following paragraph will present energy and water consumption, since it forms the basis of the multi-objective problem to be solved using the NSGA-II algorithm. The analysis will focus on the phase of maintaining temperature and pressure required for sterilization, including an estimate of the time needed to reach these conditions. The cooling phase will not be considered, as it operates in a closed-loop cycle with low electricity consumption and nearly zero water loss.

The model used to describe the sterilization process is based on the study by Barreiro (Barreiro et al., 1984), which has been referenced in other more recent analyses (Giraldo Gil et al., 2020), (Simpson et al., 2006). To calculate the mass of steam and the energy associated with it, we can identify several contributions, assuming a steady-state system, meaning that all the energy entering the system through the steam is equivalent to the energy exiting the system. Among these contributions, we have:

- Thermal energy leaving the bleeds (Q_b)
- Thermal energy leaving with the condensate (Q_w)
- Thermal energy required to heat the retort shell (Q_{rt})
- Thermal energy required to heat the jars (Q_j)
- Thermal energy required to heat the containers (Q_e)
- Thermal energy lost by convection and radiation (Q_c and Q_r)

The formula for the thermal energy transported by the steam, based on the identified contributions, can be expressed as:

$$Q_s = Q_j + Q_w + Q_b + Q_{rt} + Q_e + Q_c + Q_r$$

Each parameter in the formula will be detailed to clarify its components and dependence on the model's independent variable, the sterilization temperature (T_s). The only parameter excluded from the model is the thermal energy required to heat the containers (Q_e).

Thermal energy leaving the bleeds

During the process, a portion of the steam exits the system to maintain stable temperature and pressure conditions. In Barreiro's model (Barreiro et al., 1984) the assumption is that the venting is continuous, and the valve is always open. In our case, considering a more innovative and efficient system, it is hypothesized, according to company data, that the valve remains open for one-tenth of the process time. Therefore, the formula to calculate this energy is equivalent to:

$$Q_b = \dot{m}_b \cdot H_s \cdot \frac{P_t}{15}$$

H_s is the enthalpy associated with the steam, calculated using the tables available in the study conducted by Beaton (C.F. Beaton, 1986). This value depends on the temperature reached during the sterilization phase. By plotting the values using Python, we can find the following function.

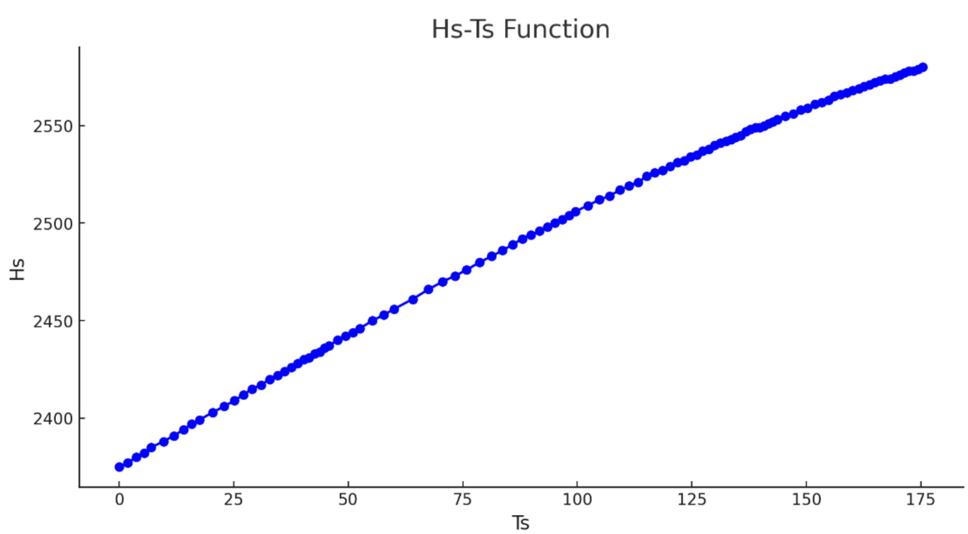

Figure 31: Enthalpy of saturated steam. Elaborated by the author.

P_t is the sterilization time, and like the previous parameter, it is closely related to the sterilization temperature. Intuitively, the higher the temperature, the shorter the time required to achieve the sterilization value F, mentioned in the previous section. We can find this index using the following formula:

$$F = \int_0^{P_t} 10^{\frac{T_s - T_{ref}}{z}}$$

Where P_t is the total process time, T_s is the process temperature, T_{ref} and z are the reference temperature and the temperature increment required to reduce the sterilization time by a factor of 10, respectively. In the case of the company, these values are set to 121.1°C and 10°C. Regarding the value of F, the company achieves a value of 9 for each process. This has been fundamental in finding the time-temperature relationships associated with different processes. In fact, the study "Experimental validation of models for predicting optimal surface quality sterilization temperatures" (C.L.M Silva et al., 1994) provides a series of relationships between the two variables for achieving different F factors. In our case, we can, therefore, find the relationship described by the following graph between P_t (given in minutes) and T_s:

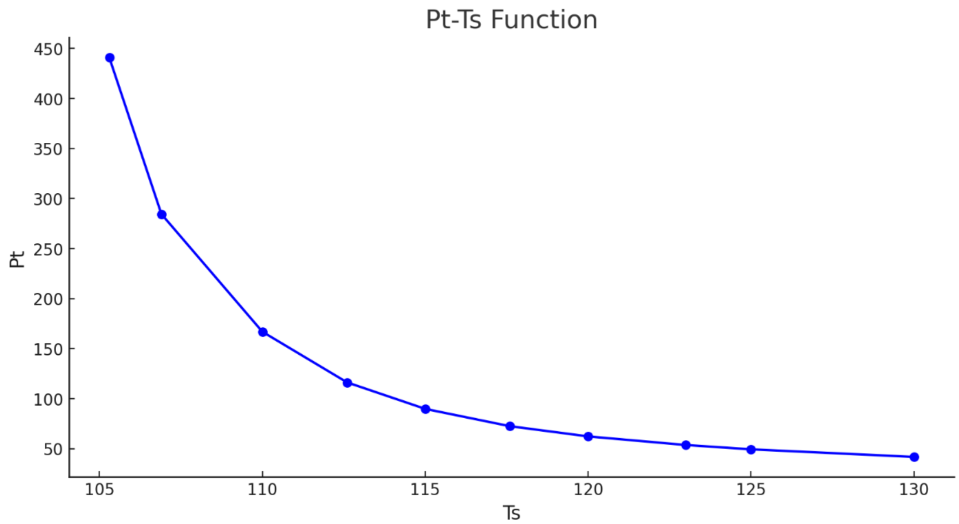

Figure 32: Process time. Elaborated by the author.

Even with limited data, the coefficient of determination R^2 is equivalent to 0.98. $\dot{m}_b$ represents the mass value that exits the system per unit of time when the valve is open. To find this value, we can use the formula presented in the model used as an example:

$$\frac{\dot{m}_b}{P_s \cdot A_0} \cdot \sqrt{\frac{R \cdot T_s}{\gamma}} = \left(\frac{P_a}{P_s}\right) \cdot \sqrt{\left(\frac{2}{\gamma - 1}\right) \cdot \left[1 - \left(\frac{P_a}{P_s}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

If:

$$\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \leq \left(\frac{P_a}{P_s}\right) \leq 1$$

$$\frac{\dot{m}_b}{P_s \cdot A_0} \cdot \sqrt{\frac{R \cdot T_s}{\gamma}} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2 \cdot (\gamma-1)}}$$

If:

$$\frac{P_a}{P_s} \leq \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{(\gamma - 1)}}$$

The mass per second of the exiting steam ($\dot{m}_b$) depends on the area of the vent valve (A_0) in our case, equivalent to $4.91 \cdot 10^{-6}\ m^2$, the atmospheric pressure (101,325 Pa), the ideal gas constant R equals to 8.314$\frac{J}{mol \cdot K}$, and the process pressure, which in our case, like the enthalpy, depends on the process temperature and was calculated using the tables mentioned earlier, resulting in the following graph:

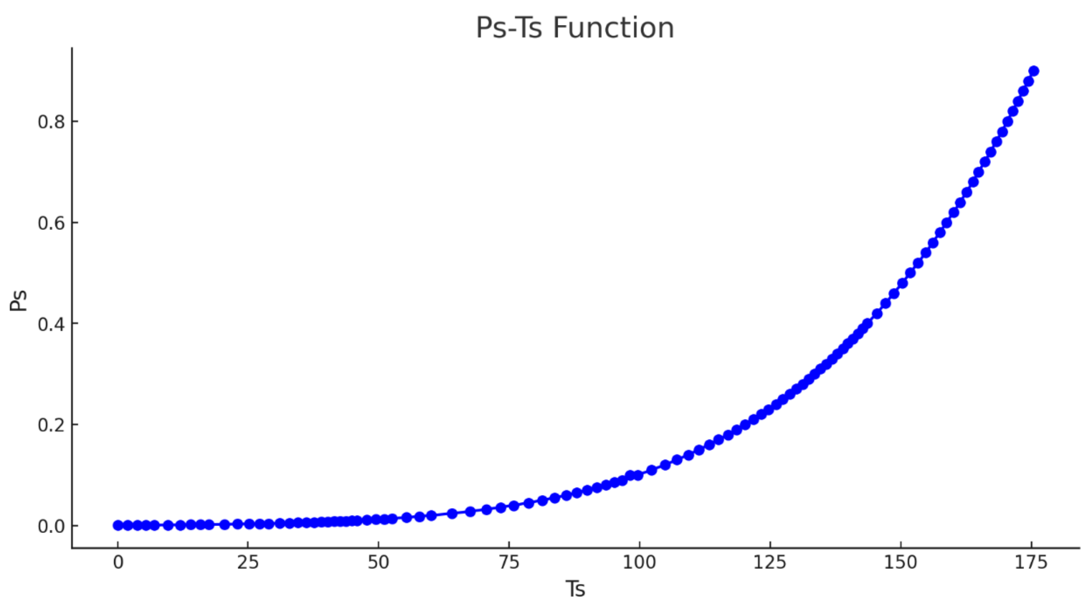

Figure 33: Pressure process. Elaborated by the author.

The last element is γ (gamma), obtained from the ratio of specific heat at constant pressure (c_p) to specific heat at constant volume (c_v). This value, calculated using the results from Beaton's book (C.F. Beaton, 1986), is equivalent to 1.3.

We now have all the necessary elements to calculate both the mass that will leave the process and the energy associated with it. Some of the data just presented will be reused in the formulas that will be presented next.

Thermal energy required to heat the jars

To calculate the energy required to heat the jars, we need to consider three contributions:

- The energy required to heat the sauce
- The energy required to heat the glass
- The energy required to heat the lids

For the first term, the associated formula is as follows:

$$Qp = m_p c_p (T_s - T_0)$$

Where m_p represents the mass of the sauce to be heated. In our case study, as we will see later, 3,000 jars are heated in one cycle. The net weight of the sauce is equivalent to 411 grams, so the total mass is 1,233 kg. The specific heat capacity (c_p) is equivalent to that of water, i.e., 4.186 $\frac{kJ}{kg \cdot K}$. The final temperature reached by the product can be assumed to be the sterilization temperature, as the difference between the two is negligible in relation to the final results of the problem. T_0 is the initial temperature of the sauce, which, by assumption, is equivalent to the glass and the lids (60°C).

The second term can be represented by the following formula:

$$Qg = m_g c_g (T_s - T_0)$$

Where m_g is the total number of jars multiplied by the mass of the empty jar, which is 205 grams. Therefore, the total mass is 615 kg. c_g is the specific heat capacity of the glass, which in our case is 0.84 $\frac{kJ}{kg \cdot K}$.

The last contribution is given by the following formula:

$$Ql = m_l c_l (T_s - T_0)$$

The mass of a single lid is 9 grams, and multiplying this by the 3,000 jars gives a total mass (m_l) of 27 kg. The specific heat capacity of aluminum, the material used for the lid, is equivalent to 0.9$\frac{kJ}{kg \cdot K}$.

By summing the three contributions, we can thus obtain the energy required to heat the jars during a sterilization cycle:

$$Q_j = Q_l + Q_g + Q_p$$

Thermal energy required to heat retort, and lost by convection and radiation

To calculate the energy required to heat the walls of the autoclave and the energy lost through convection and radiation, the guidelines of the model were not followed, because the process under consideration uses an autoclave that is insulated both internally and externally. According to the estimates provided by the company in the case study, the total energy for these three contributions is equivalent to 10% of the energy required for the jars:

$$Q_{rt} + Q_c + Q_r = 0.1 \cdot (Q_l + Q_g + Q_p)$$

Thermal energy leaving with the condensate

During the sterilization process, a portion of the energy is released due to the condensation of the steam in contact with the elements inside the autoclave. To calculate this contribution, we can use the following formula:

$$Q_w = \dot{m}_w \cdot H_w \cdot P_t$$

H_w represents the enthalpy of saturated water, a parameter that depends on the process temperature (T_s). To obtain its value, the same method is used for calculating the enthalpy of dry steam (H_s). has been applied. The final result is described by the following function:

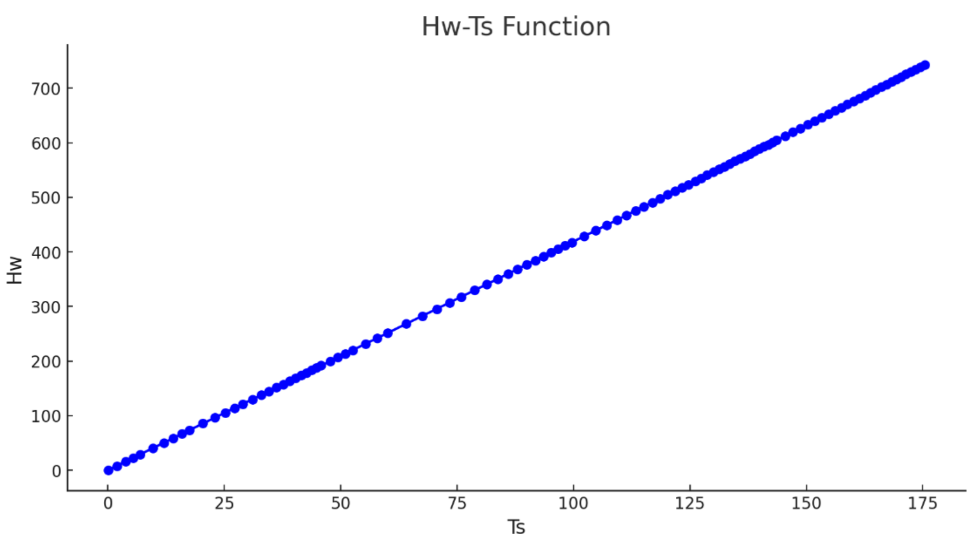

Figure 34: Enthalpy of saturated water. Elaborated by the author.

To obtain the mass of water that condenses per second ($\dot{m}_w$) we can use the following formula:

$$\dot{m}_w = \frac{Q_j + Q_{rt} + Q_c + Q_r}{(H_s - H_w) \cdot P_t}$$

Once the mass is obtained, we would be able to calculate the total energy associated with the process, as well as the mass per second associated with the entering steam, given by:

$$\dot{m}_s = \dot{m}_w + \dot{m}_b$$

Chapter 6
RESULTS

After analyzing the methodology and the case study, we now have all the necessary elements to optimize the process under examination. This chapter will present the results of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis, followed by data interpretation and the identification of the critical process. The latter will allow us to define the functions to be included in the multi-objective problem. The process optimization will be achieved by applying the rules of the NSGA-II algorithm and the TOPSIS method. Furthermore, this chapter will revisit some concepts from previous sections to ensure the clearest possible interpretation of the results.

6.1 Life cycle assessment

In section 5.2, the elements analyzed in the process were defined, along with the impact categories that quantify the environmental effects assessed in the study. The objective now is to present the actual data provided by the company under examination. Subsequently, the results obtained by entering this information into OpenLCA software will be illustrated, allowing us to evaluate the main contributions and the most significant effects within the production process.

For better understanding, the data will first be presented on a daily basis. Then, thanks to the functionalities of the software and the creation of our product system, we will be able to report all results related to the impact categories with

respect to the functional unit considered, which corresponds to a single jar of pesto, knowing that the daily production amounts to 30,000 jars.
To ensure greater clarity, we will follow the steps described in Chapter 2, which explains how to conduct a Life Cycle Assessment. The first step has been covered in previous chapters, particularly in section 5.2, where the functional unit, system boundaries, and study objective were established. The only missing element to complete this phase is the graphical representation of the production process, which will help us understand the contributions of each phase. The diagram below provides this visual representation:

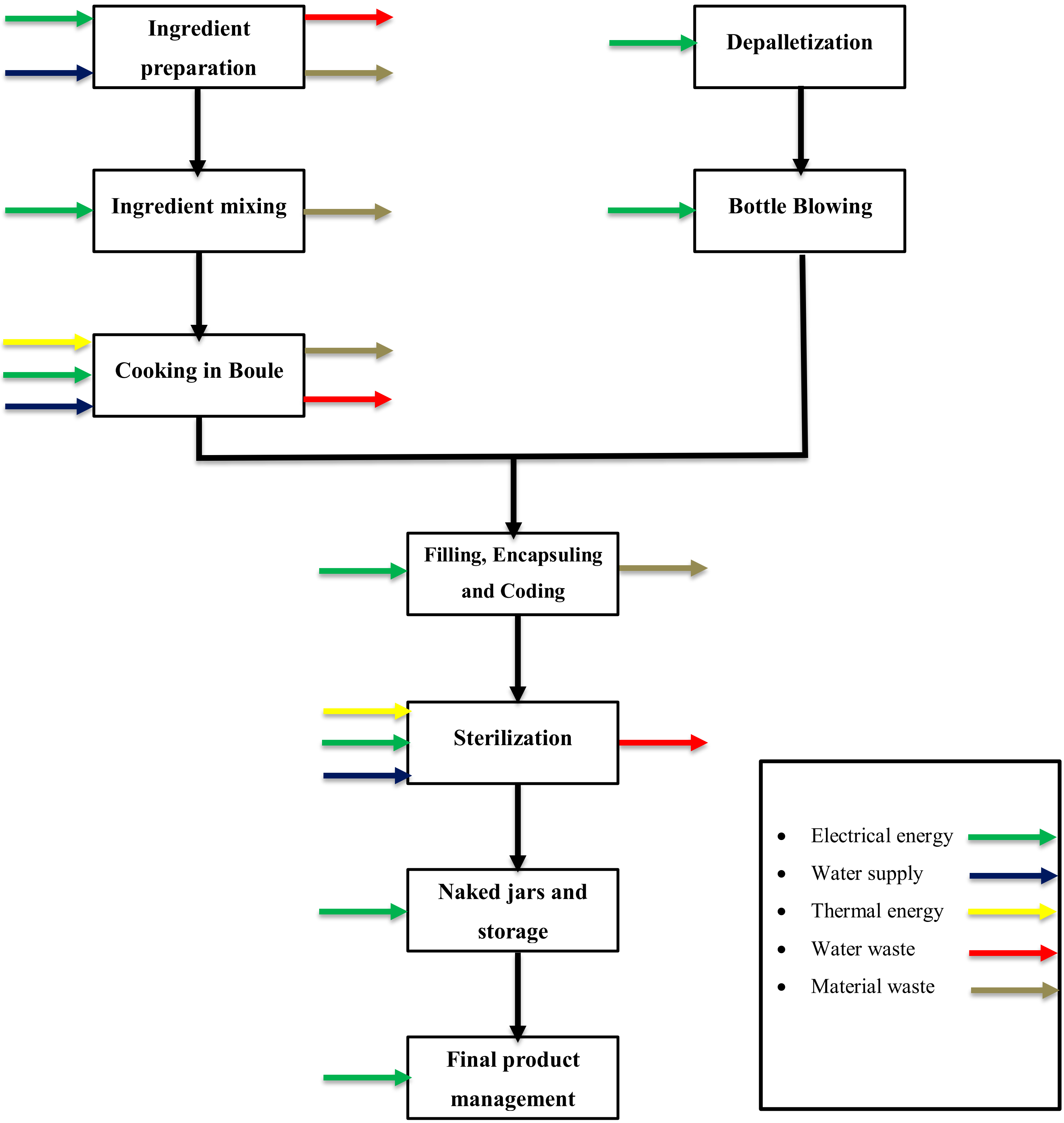

Figure 35: Product process. Elaborated by the author.

As shown in the image below, our case study takes into account not only the direct impacts generated within the company's internal processes, but also all indirect impacts, such as the supply of thermal energy through natural gas and electricity from the public grid. At the same time, once the company produces solid waste and wastewater, the environmental impact related to their subsequent management outside the company boundaries is also considered.

Following the scheme in section 2.4, the second step concerns data analysis. These data have already been identified in section 5.2 and in the previous diagram, but their values can be displayed in the following table, always referring to daily production:

Machines	Eletric Energy (kWh)	Thermal Energy (MJ)	Water Supply (m^3)	Water Waste (m^3)	Material Waste (kg)	Emission to air
Depalletization and Bottle Blowing	21.05					
Ingredient Preparation	52.65		26.00	26.00	96.67	
Ingredient Mixing	10.53				96.67	
Cooking in Boule	263.24	5161.24	26.00	26.00	96.67	283.2 kg CO_2
Filling, Encapsulation, and Coding	21.05				193.33	
Sterilization (3 Machines)	1250.00	8378.52	3.65	2.10		460 kg CO_2
Conveyor Belt	20.00					
Storage	2.00					
Naked Jars	21.05					
Final Product	64.81					

Figure 36: Data collection analysis. Elaborated by the author

Following the scheme in section 2.4, the second step concerns data analysis. These data have already been identified in section 5.2 and in the previous diagram, but their values can be displayed in the following table, always referring to daily production.

For better clarity regarding the second step of the LCA, no flowchart diagram has been developed, as our processes can be easily categorized as follows:

Level 0: Production process phases.

Level 1: Raw material extraction and processing (not included in this study).

Level 2: Electricity supply, natural gas, and water procurement.

Level 3: Waste management.

Level 4: Infrastructure processes (not considered as they are negligible for a single jar produced).

Additionally, no allocation step is required since our production line is dedicated to a single product and does not generate by-products. The only shared contribution concerns the storage phase, but the data reported in the previous table has already been calculated based on the specific production line analyzed. Once the first two phases are completed, we can proceed with the impact category analysis. These have been defined in section 5.2, but their contribution, in relation to the collected data, is calculated using the software. The results are presented in the following tables:

	Measurement Units/ Phase	Depalletization and Bottle Blowing	Ingredient Preparation	Ingredient Mixing	Cooking	Filling, Encapsulation, and Coding
GWP100	Kg CO2 eq.	4.856E-04	1.457E-03	4.047E-04	2.048E-02	8.093E-04
Water consumption	M3	7.930E-07	8.788E-06	8.788E-06	2.021E-05	1.758E-05
Eutrophication	Kg P eq	1.905E-10	2.462E-09	1.640E-10	1.081E-08	3.279E-10
Acidifaction	Kg SO2 eq	2.112E-06	2.007E-06	2.152E-06	3.982E-05	4.304E-06

Figure 37: Impact analysis 1. Elaborated by the author.

	Measurement Units/ Phase	Sterilization	Conveyor belt	Storage	Naked jars	Final Product
GWP100	Kg CO2 eq.	5.184E-02	4.613E-04	4.613E-05	4.856E-04	5.184E-02
Water consumption	M3	4.982E-05	7.533E-07	7.533E-08	7.930E-07	4.982E-05
Eutrophication	Kg P eq	2.487E-08	2.906E-12	1.810E-11	1.905E-10	2.487E-08
Acidifaction	Kg SO2 eq	1.452E-04	2.007E-06	2.007E-07	2.112E-06	1.452E-04

Figure 38: Impact analysis 2. Elaborated by the author.

The previous diagrams are somewhat complex to interpret; a more useful representation is provided in the tables, where the contributions of each process to the impact categories are presented as percentages:

	Depalletization and Bottle Blowing	Ingredient Preparation	Ingredient Mixing	Cooking	Filling, Encapsulation, and Coding
GWP100	0.62%	1.87%	0.52%	26.27%	1.04%
Water consumption	0.72%	7.99%	7.99%	18.37%	15.97%
Eutrophication	0.48%	6.21%	0.41%	27.29%	0.83%
Acidifaction	1.02%	0.97%	1.04%	19.29%	2.09%

Figure 39: Impact percentage 1. Elaborated by the author.

	Sterilization	Conveyor belt	Storage	Naked jars	Final Product
GWP100	66.49%	0.59%	0.06%	0.62%	1.92%
Water consumption	45.28%	0.68%	0.07%	0.72%	2.22%
Eutrophication	62.76%	0.01%	0.05%	0.48%	1.48%
Acidifaction	70.34%	0.97%	0.10%	1.02%	3.15%

Figure 40: Impact percentage 2. Elaborated by the author.

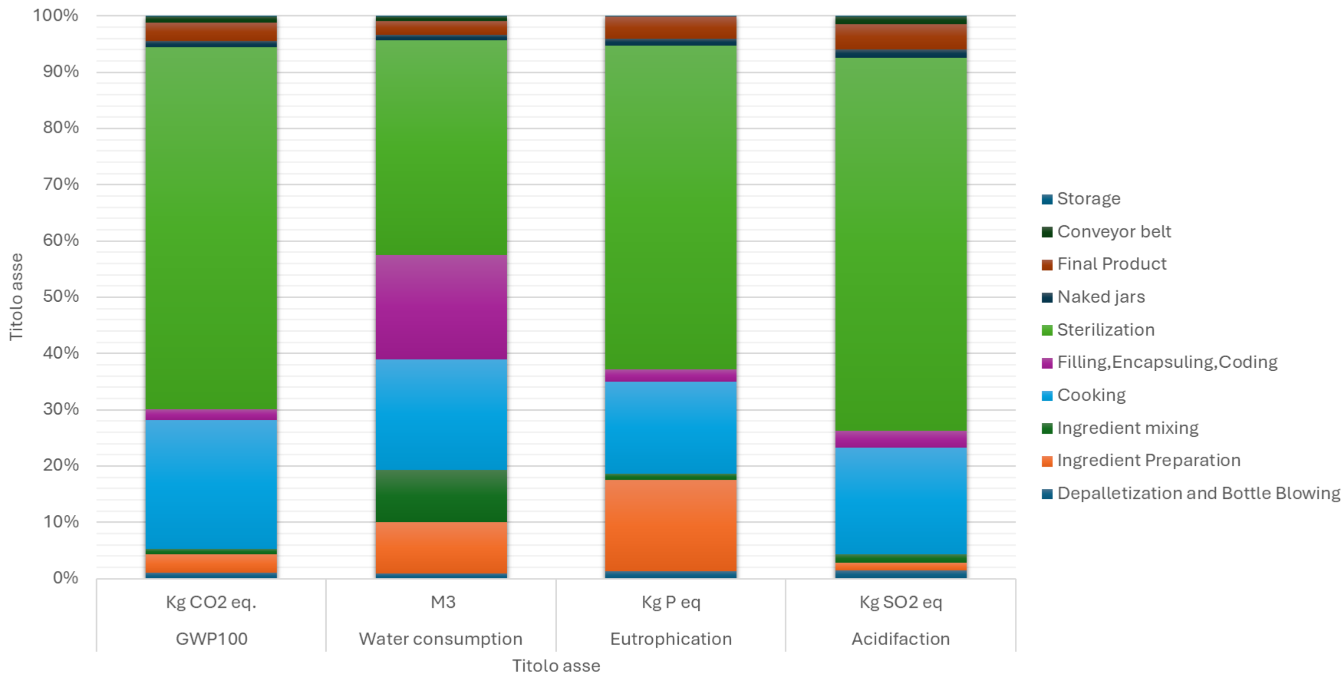

Figure 41: Impact percentage graph. Elaborated by the author.

We can observe, as initially hypothesized, that the sterilization process is the dominant contributor to environmental impact across all categories, with percentages close to 65%. The only exception is water consumption, where this value drops to 45.28%, as it is significantly influenced by waste management. In the case of sterilization, waste generation is nearly negligible.

The cooking phase is the second most impactful, contributing approximately 20% in each category. This is due to its high energy and water consumption, as well as the considerable amount of waste it generates.

Two particularly noteworthy aspects emerge from the analysis: the filling, encapsulation, and coding process in the water consumption category and the ingredient preparation phase in the eutrophication category. The former is heavily influenced by high waste generation, while the latter is characterized by significant water consumption.

6.2 **Life cycle costing**

As previously defined in the earlier chapters, we will aim to revisit key concepts without unnecessary repetition, ensuring maximum clarity at every step. It is important to recall that, to maintain consistency with the tool in use, the analysis must be conducted over a long-term period. For this reason, the calculation considers all costs incurred over 20 years within the production process. Subsequently, the will allow us to allocate the result to the functional unit, which corresponds to a single jar of pesto. All estimates for the single unit were provided in Chapter 5.4. In the figure below, however, after performing the necessary calculations, all cost elements are presented:

Cost's type	€
Machine investment cost	15,000,000.00
Machine energy cost	214,217.84
Electricity factory cost	71,341.71
Personnel cost	45,177.12
Deprecation cost	750,000.00
Raw material and component cost	9,441,000.00
Water supply cost	84,495.47
Water disposal cost	14,101.53
Waste disposal cost	17,400.00
Machine maintenance cost	300,000.00

Figure 42: Cost analysis. Elaborated by the author

Using these costs, we can calculate the LCOP index, which, as explained in section 4.4, normalizes the costs associated with the 20-year operation of the plant to a single jar. In our case, the resulting value is 1.35 €/jar.

The graph below highlights the percentage impact of each cost on OPEX. This value is approximately equivalent to the percentage by which costs influence the LCOP.

Cost's type	Percentage
Machine energy cost	1.96%
Electricity factory cost	0.65%
Personnel cost	0.41%
Deprecation cost	6.86%
Raw material and component cost	86.32%
Water supply cost	0.77%
Water disposal cost	0.13%
Waste disposal cost	0.16%
Machine maintenance cost	2.74%

Figure 43: OPEX contribution. Elaborated by the author.

We observe that raw materials are the most influential factor on the analyzed index. However, in our case study, which is primarily focused on the management of processes directly controlled by the company, these are not taken into account. We can calculate the total cost of the elements we can directly influence. The table below shows the sum of the costs associated with each phase of the process, including electrical and thermal energy consumption, water supply and disposal, and waste management.

Cost's type	€
Depalletization and Bottle Blowing	1,825.26
Ingredient Preparation	54,740.78
Ingredient Mixing	4,392.90
Cooking in Boule	95,646.46
Filling, Encapsulation, and Coding	8,785.26
Sterilization (3 Machines)	155,472.05
Conveyor Belt	1,734.00
Storage	173.40
Naked Jars	1,825.26
Final Product	5,619.44

Figure 44: Production process cost. Elaborated by the author.

Phase	Percentage
Depalletization and Bottle Blowing	0.55%
Ingredient Preparation	16.58%
Ingredient Mixing	1.33%
Cooking in Boule	28.96%
Filling, Encapsulation, and Coding	0.53%
Sterilization (3 Machines)	0.05%
Conveyor Belt	2.66%
Storage	47.08%
Naked Jars	0.55%
Final Product	1.70%

Figure 45: Contribution in production process cost. Elaborated by the author.

We can observe that the sterilization process has the greatest impact. We can calculate its contribution to the LCOP, which amounts to 0.017 €/jar.

As we will see in the following sections, this value will be used as an evaluation criterion, alongside the impact categories calculated in the LCA for sterilization, within the TOPSIS method.

6.3 **Sterilization and multi-objective**

In paragraph 5.2, all the necessary elements to calculate the required energy and the mass of steam related to a sterilization process are provided, based on the temperature considered. In our case study, consistent with the analysis conducted by Barreiro, the process will be analyzed by setting a temperature between 104°C and 130°C. Two functions will be defined from the sterilization process: one related to energy consumption and one related to water consumption (supply and waste). These two functions represent the inputs and outputs of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC); therefore, optimizing them corresponds to improving environmental and economic impacts. The functions are thus related to Q_s and the sum of m_s and m_w. In the graphs below, we can observe which temperature optimizes them:

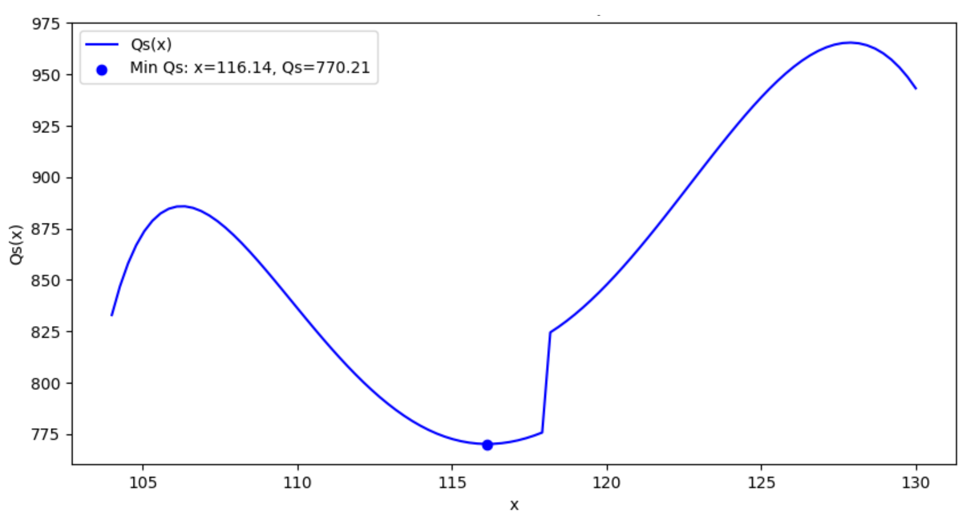

Figure 46: Energy minimization in the sterilization process. Elaborated by the author.

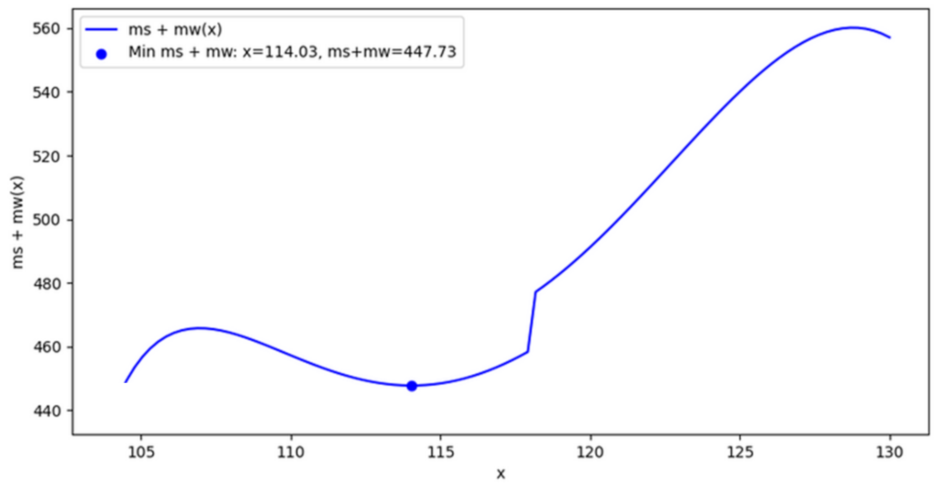

Figure 47: Water consumption minimization in the sterilization process. Elaborated by the author.

The minimum equivalent to Q_s is 770.21 MJ, while the minimum equivalent to water consumption is 447.73 kg, with temperatures of 116.14°C and 114.03°C, respectively. These values will define the range within which the Pareto optimal solutions will be identified.

6.4 Nsga-II and TOPSIS

The NSGA-II method helps us calculate the optimal solutions along the Pareto front. This algorithm allows us to explore the 100 optimal solutions on the Pareto front, which is bounded by the solutions that minimize energy consumption and water consumption, as previously determined. In the graph below, we have the 100 solutions on the x-axis and their respective values of water and energy consumption on the y-axis. We can observe that within this range, as the temperature increases, energy consumption worsens while water consumption improves:

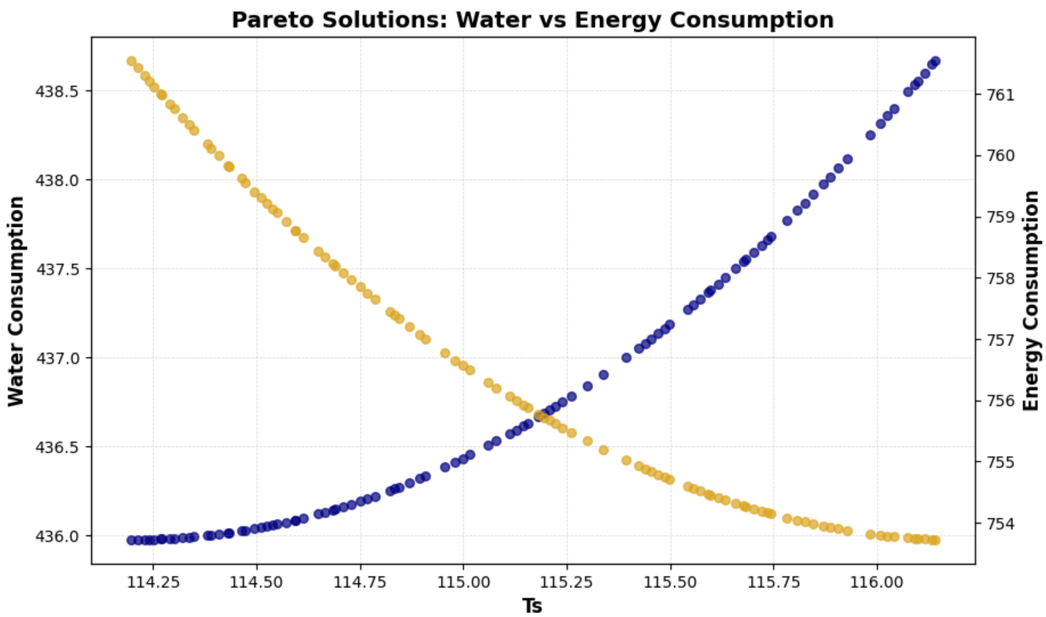

Figure 48: Nsga-II solutions. Elaborated by the author.

However, we cannot conclude that the intersection represents the optimal solution, since the two types of consumption have different values according to the criteria defined in the TOPSIS method. The next step is to insert the following 100 solutions into a matrix, where they will be rows, and the columns will represent the criteria. In our case, these criteria are the impact categories: Global Warming Potential, Acidification, Eutrophication, Water Consumption, and LCOP, calculated for the sterilization process. An example of 10 solutions is as follows:

	Ts	GWP100	Water consumption	Eutrophication	Acidification	LCOP
sol.1	115.31	5.051×10^{-2}	1.438×10^{-4}	2.391×10^{-8}	4.963×10^{-5}	1.637×10^{-2}
sol.2	114.93	4.998×10^{-2}	1.436×10^{-4}	2.377×10^{-8}	4.960×10^{-5}	1.632×10^{-2}
sol.3	116.11	5.010×10^{-2}	1.437×10^{-4}	2.384×10^{-8}	4.962×10^{-5}	1.635×10^{-2}
sol.4	115.69	5.011×10^{-2}	1.437×10^{-4}	2.385×10^{-8}	4.962×10^{-5}	1.635×10^{-2}
sol.5	114.06	5.000×10^{-2}	1.436×10^{-4}	2.379×10^{-8}	4.960×10^{-5}	1.633×10^{-2}
sol.6	114.14	4.998×10^{-2}	1.436×10^{-4}	2.378×10^{-8}	4.960×10^{-5}	1.632×10^{-2}
sol.7	115.06	4.998×10^{-2}	1.436×10^{-4}	2.378×10^{-8}	4.960×10^{-5}	1.632×10^{-2}
sol.8	115.27	4.998×10^{-2}	1.436×10^{-4}	2.378×10^{-8}	4.960×10^{-5}	1.632×10^{-2}
sol.9	114.35	4.998×10^{-2}	1.436×10^{-4}	2.378×10^{-8}	4.960×10^{-5}	1.632×10^{-2}
sol.10	115.29	4.998×10^{-2}	1.436×10^{-4}	2.377×10^{-8}	4.960×10^{-5}	1.632×10^{-2}

Figure 49: Example of TOPSIS matrix solution 1-10. Elaborated by the author.

After first applying the entropy rule for weight calculation and then using the TOPSIS method as described in the methodology section, we can determine the optimal solution, which is equivalent to the third among the Pareto optimal ones. This solution has a temperature of 115.33 °C, an energy consumption of 755.23 MJ, and a water consumption of 436.89 liters.

6.5 **Final results**

Once the optimal value for balancing the impact categories and the cost analysis previously conducted has been identified, it is possible to set the sterilization temperature at 115.33°C and observe the results as percentages relative to the previously established reference value.

From the perspective of energy and water consumption, optimization allows for a savings of 826.17 MJ, equivalent to a 9.86% reduction in energy consumption, and 455.65 liters of water, corresponding to a 9.44% reduction in water consumption.

Converting these results into environmental impact categories, the following benefits are obtained:

- Reduction of Global Warming Potential: 4.38%
- Reduction of Eutrophication: 5.38%
- Reduction of Acidification: 1.34%
- Reduction of Water Consumption: 0.54%

This decrease is also justified by the choice of these specific impact categories, as they are strongly related to energy and water consumption.

Regarding the economic impact associated with the sterilization phase, setting the temperature at 115.33°C enables a 2.98% cost reduction, resulting in annual savings of €4,628.98.

Therefore, conducting both analyses in an integrated manner allows for significant environmental and economic benefits, which are crucial for addressing corporate sustainability challenges.

CONCLUSION

This study began with an in-depth analysis of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies, aiming to integrate them into a unified model capable of balancing two fundamental pillars of sustainability: economic and environmental aspects. The growing need for companies to optimize their production processes while simultaneously reducing their environmental footprint has highlighted the importance of adopting structured, data-driven approaches in decision-making. This study contributes to the discussion on the integration of economic and environmental considerations in industrial processes, offering a perspective focused on sustainability and efficiency. The main outcome of this research is the design of an optimization framework that combines a genetic algorithm (NSGA-II) with the TOPSIS multi-criteria decision-making method. This approach was successfully applied to a case study in the agri-food industry, specifically focusing on pesto production. The analysis allowed for the identification of the most critical phase of the production process, enabling the development of targeted improvement strategies. The practical application of the model led to a significant reduction in both environmental impacts related to the sterilization phase and the associated economic costs. Beyond its practical implications, the study also offers a significant theoretical contribution. It represents one of the first applications of a pre-existing optimization model to a real case in the agri-food sector. The fact that a methodology already present in the literature has been successfully adapted to an industrial challenge demonstrates the flexibility and robustness of the proposed approach. Moreover, this research confirms the value of multi-objective optimization techniques in supporting data-driven decision-making in manufacturing environments. One of the main strengths of the developed model lies in its adaptability to different production contexts and industrial sectors. By modifying input parameters and specific constraints, the framework can be applied to a wide range of production processes. However, a specific limitation of our case study is that the analysis and optimization focused on a single phase of the process, whereas more significant results could be achieved by extending the application to the entire production system. A holistic approach would maximize the benefits, improving the overall efficiency of the entire production chain. However, to implement large-scale optimization, the availability of accurate and comprehensive data becomes crucial. The lack of detailed datasets for parameterizing the entire production process has emerged as one of the main challenges. In particular, in the secondary agri-food sector, this data scarcity represents a significant obstacle to a complete and thorough evaluation. For studies of this nature, close collaboration with companies is essential to collect precise information, enhance the quality of analysis, and ensure a more effective application of optimization models. In conclusion, this research lays the groundwork for a scalable and adaptable optimization framework, capable of supporting the analysis and reduction of environmental impacts without compromising economic efficiency. Further exploration and expansion of these methodologies will enhance the sustainability of industrial processes, fostering a vision where economic efficiency and environmental responsibility are not conflicting objectives but synergistic components of an integrated production strategy.

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