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Final Dissertation

Development and Application of an Integrated Life Cycle Assessment and Multi-Criteria Decision-Making Model to Support Sustainable Solutions in the Fashion Industry: The Case of Fashion Art

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Un’antica favola africana racconta del giorno in cui scoppiò un grande incendio nella foresta. Tutti gli animali abbandonarono le loro tane e scapparono spaventati. Mentre fuggiva veloce come un lampo, il leone vide un colibrì che stava volando nella direzione opposta. “Dove credi di andare? - chiese il Re della Foresta. - C’è un incendio, dobbiamo scappare! “Il colibrì rispose: “Vado al lago, per raccogliere acqua nel becco da buttare sull’incendio”. Il leone sbottò: “Sei impazzito? Non crederai di poter spegnere un incendio gigantesco con quattro gocce d’acqua!?”. Al che, il colibrì concluse: “Io faccio la mia parte”.

Chandra Livia Candiani, *Il silenzio è cosa viva*

Abstract

The urgent problem of climate change has gained widespread attention, leading to a critical analysis of its far-reaching effects. The fashion industry has come under scrutiny for its environmental, as well as social impacts. Consequently, the need to assess sustainability is becoming more and more important, not only as an ethical consideration but also as a strategic opportunity for competitive advantage. Indeed, this paradigm shift toward sustainable practices is not only a response to environmental imperatives but also a transformative pathway for the fashion industry to thrive in a changing world.

In this context, Life Cycle Assessment (LCA) emerges as a pivotal tool, offering a systematic approach to evaluate the environmental footprint of products or services across their lifecycle. However, interpreting LCA outcomes poses challenges due to result complexities and trade-off situations. To address this, integrating decision analysis tools with LCA can provide a comprehensive indicator that synthesizes product environmental performance with company objectives.

In this study, Life Cycle Assessment and Multi Criteria Decision Analysis were integrated to attempt the formulation of a single score that provides a clear and easily interpretable indication of the environmental performance of the alternatives evaluated. The model adopted in this study is the hybrid method: AHP TOPSIS applied to the case of Fashion Art, a luxury fashion company specialized in the design and production of clothing, particularly in the denim manufacturing. The results demonstrate the efficacy of this approach in summarizing LCA outcomes and enhancing decision-making processes, along with highlighting some critical aspects, mainly related to how to prioritize impact categories, which open the way for future developments.

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1. Context analysis

1.1. Fashion industry and its impacts

Before discussing the social and environmental impacts of the textile industry, it is important to clearly define the industry. The textile industry, also referred to as the "Textile and Clothing (TAC) industry," encompasses research, design, development, manufacturing, and distribution of textiles, fabrics, and clothing (Textileapex). A whole range of textile products are therefore part of the textile industry, although the main sector is clothing.

It seems that people have been using clothes to protect and cover themselves since the beginning of human history. But it wasn't until much later in the economic growth that the idea of fashion became recognized. It's hard to pinpoint the exact time when fashion first emerged. Some historians contend that there is a *sense of fashion* in every historical era, which implies that there are various fashion forms. However, it can be said that modern fashion emerged during the Industrial Revolution in the mid-eighteenth century when small-scale textile production shifted to a mass production industry (FashInnovation, 2022).

Today, the fashion industry is one of the most influential manufacturing industries in the global economy (WTO, 2017): the revenue of the apparel market worldwide in 2022 was 1.53 trillion USD and is estimated to reach 1.94 trillion USD in 2029 (Statista, 2022).

This sector predominantly adheres to a conventional linear economic model, utilizing virgin raw materials to generate new textile products, subsequently leading to their disposal. According to the Ellen MacArthur Foundation, 73% of textiles end up in landfills or incinerated, 12% represent production losses, 14% are collected for recycling into lower-value applications, and less than 1% is repurposed for producing new textiles, as shown in **Figure 1** (Figure source: *Circular Fibers Initiative Analysis, Ellen MacArthur Foundation*).

Impacts are evident across the entire value chain of textile production, encompassing fiber production, textile manufacturing, distribution and retail, utilization of textile products, and waste management. These impacts extend across various environmental spheres, including material resource usage, intensive water and land utilization, pollution from chemical treatments, and greenhouse gas emissions. In terms of greenhouse gas (GHG) emissions, for instance, Berg et al. (2020) in the Fashion on Climate report by McKinsey & Company state that the global fashion industry emitted approximately 2.1 billion tonnes of GHG emissions in

2018, constituting 4% of the global total. This equates to the annual GHG emissions of France, Germany, and the UK combined.

Because of all of this, the textile sector is among industries having the largest effects on the environment (Pal, Gander 2018).

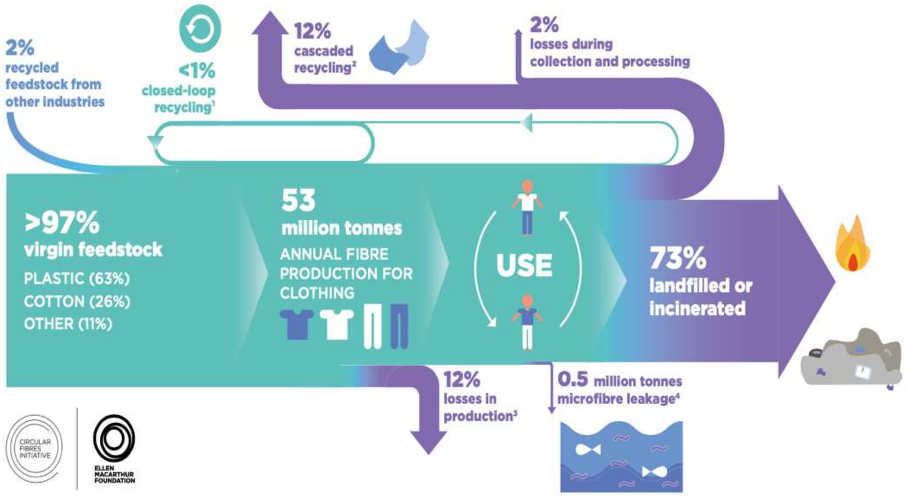

Figure 1 *Global material flows for clothing in 2015*

Furthermore, this has been and continues to be exacerbated by the introduction of the Fast Fashion model. Indeed, until the mid-twentieth century, fashion was primarily intended for the upper classes. However, since 1975, certain brands such as Zara have been offering fashion items inspired by haute couture at more affordable prices for lower social classes.

Fast Fashion can be delineated as a sector of the clothing industry that produces garments, inspired by high fashion, but retailed at lower prices and refreshed at a quicker pace. Thus, a business model that amalgamates three elements: quick response, frequent assortment changes, and fashionable designs at affordable prices (Carlo, F., and Martìnez-De-Albèniz, 2015). This has led and continues to lead to countless changes in the way clothes are produced, purchased, and perceived.

A transition from a paradigm where each clothing purchase was regarded as an investment due to the higher prices of items, to one where individuals are purchasing more clothing items than ever before. On average, individuals acquire 70 items per year, resulting in nearly 20 billion garments being sold annually (Thomas, 2019). Indeed, Fast Fashion has spurred consumers to purchase numerous garments that are used only a few times before being discarded. This consumption pattern amplifies resource and material utilization, as well as waste generation.

For instance, in Europe, the fashion industry generates approximately 11 kg of textile waste per person per year, amounting to 5.8 million tonnes that require management (EC, 2023).

In conclusion, the textile industry—which includes fast fashion and fashion—has a significant impact on society and the environment and without substantial changes, the situation will worsen. Concerted efforts towards sustainability, are incredibly important in this sector.

1.2. Government, business, and consumer responses

Government, business, and consumers have all responded in different ways to the massive impacts of the fashion industry.

On one hand, customers are becoming more conscious of environmental issues and the effects that the manufacture of apparel and textiles has on the environment. In addition, they are interested in the products' impact on the environment, the working conditions of those employed in the production process, and the source of the materials utilized. This growing interest translates into an increasing demand for more sustainable products and brand preference based on this factor as well. Companies, on the other hand also have an interest in moving towards more responsible production models, for several reasons. To start with, they may be driven by an honest concern for the environment, and they also understand that, to remain competitive, businesses must prioritize sustainability among their customers. Furthermore, businesses operating in the textile industry must comply with increasingly stringent regulations. Indeed, businesses which disregard the constantly evolving regulatory framework run a risk of facing penalties and losing their competitive edge in the market.

In this chapter, the European framework concerning the textile industry will be briefly explored, with particular attention to future developments, specifically focusing on eco-design regulation and digital passport initiatives. This is aimed at defining the context in which the examined company, Fashion Art, operates, and highlighting the imperative nature of transitioning towards a more sustainable production model within the textile industry.

1.2.1. Eu legal framework

The European legal framework governing the textile industry is complex and comprises a range of regulations, directives, and action plans aimed at addressing environmental, social, and economic concerns. This chapter aims at summarizing, this chapter aims at summarizing a few key elements of this complex and evolving landscape.

One significant regulation is the Textile Regulation (EU) No 1007/2011, also known as the "Textile and Labeling Regulation," which mandates the labeling of textile products with comprehensive information regarding fiber composition, ensuring transparency and facilitating trade. This regulation seeks to enhance consumer protection, promote fair trade practices, and facilitate the functioning of the internal textile market within the European Union.

Other important components of the European legislative framework is the REACH regulation (EC Regulation No 1907/2006), which attempts to lessen harmful chemicals in products and industrial processes in order to preserve human health and the environment. The Waste Framework Directive, which was updated in 2018, is, as well, very important since it sets forth policies to encourage recycling, waste prevention, and ecologically responsible disposal waste.

In terms of the European labeling of textile products, there are several rules enabling consumers to make informed choices. The most important of them is EU Reg. 1007/2011, which lays down the conditions for labeling and marking of textile products, as well as rules on textile fiber names.

Additionally, the European Union is committed to promoting highly sustainable production and consumption models through action plans, such as the Green Deal. Within the textile sector, the Green Deal encompasses several ongoing legislative initiatives aimed at fostering sustainable development across the entire textile supply chain, with notably ambitious standards.

Among these initiatives is the eco-design regulation and digital passport, which will be further discussed here, because of their relevance and the extent of the changes they will induce in the textile sector.

1.2.2. European eco-design regulation and digital passport

The information reported here is intended to present the contents of a conference held on 25 March 2024, on the Ecodesign Regulation and Digital Passport, proposed by Fashion Art. The event, sponsored by the Municipality of Limena, Confindustria Veneto Est, Sistema Moda Italia, was participated by Hon. Alessandra Moretti, MEP, and rapporteur in the European Parliament for the proposed regulation on eco-design, Mauro Scalia, as Business Sustainability Director at Euratex, Barbara Cimmino, Head of CSR and Innovation at Yamamay, Mauro Chezzi, Deputy Director Sistema Moda Italia, Andrea Rambaldi, CEO of Fashion Art.

The European eco-design regulation is a comprehensive framework aimed at reducing waste production, which will have impacts on both businesses and consumers. The regulation will govern a wide range of products, including textiles. The regulation focuses on eco-design, thus designing to minimize waste, with the goal of reducing overconsumption and creating more durable products, thereby assisting companies in producing less and better. This regulation will significantly affect the operations of the industry, indicating the path to managing the entire product lifecycle, including end-of-life considerations.

The innovative aspect of the regulation concerns the introduction of the digital passport. All products available on the European market will only be allowed for sale if accompanied by the digital passport, containing a plethora of information related to that product, from its environmental impact to the substances used and its circularity, enabling consumers to make informed choices. The digital passport represents a decisive tool to incentivize circularity and production transparency and enable the consumer himself to make informed and better choices. Consequently, this will have substantial impacts on consumers, but particularly on businesses. Indeed, they will need to adapt to designing and redesigning products to extend their lifespan and ensure minimal environmental requirements. This regulation aims at removing companies that do not meet the minimum quality and environmental standards from the market and increasing the competitiveness of companies that meet the required standards. Moreover, the digital passport will play a fundamental role in data exchange between companies and market regulators, as well as in imports.

The eco-design regulation represents an extremely significant regulation as it mandates the sale of products of a certain quality for the first time. In terms of timing, this regulation, the result of two years of work and collaboration between the European Commission, the European Parliament, and the European Council, will be approved on April 25. Being a regulation, once published, it will come into effect immediately. The regulation serves as a legislative framework, defining general elements from which other legislative acts will stem. A gradual transition is envisaged to allow companies to adapt, with specific phases of implementation, assistance, exemptions, and delegated acts. Similarly, the development of the digital passport is complex and will require time.

In conclusion, it emerges that, companies are called upon to take concrete actions to embrace and comply with the requirements of these regulations.

1.3. Sustainable solutions

A shift towards sustainable solutions and circular economy models appears necessary. This is especially true in manufacturing, where the concept of sustainability has fitted well with the objective of industrial applications to manage limited resources and produce with minimal damage to the environment (Acar E. et al., 2015).

In the textile sector, this transition becomes even more central, as companies find themselves operating in one of the most environmentally impacted sectors and subject to increasingly stringent regulations, as outlined previously. Companies are increasingly inclined to embrace the concept of sustainability not only to address growing environmental concerns, but also to optimize resource utilization, survive in a competitive market, comply with regulations, and ensure financial success (Acar E. et al., 2015).

There is therefore a need to move towards more sustainable production patterns. But how? The transition requires a well-structured methodological approach.

Above all, it is essential to measure sustainability itself. According to Peter Drucker's “what gets measured gets done” principle, measuring impacts and monitoring activities are fundamental prerequisites for pursuing more sustainable paths.

It is therefore necessary to develop indicators to measure sustainability, and to monitor and evaluate the environmental impacts of manufacturing activities. Furthermore, it is necessary to assess that the solutions adopted are effective in supporting sustainable development and that they do so in a resource-efficient manner.

In addition, since sustainability is a concept that includes conflicting criteria and decision points, this challenge is even more complex. Indeed, when talking about sustainability, all its three dimensions have to be taken into account: the economic, social and environmental dimension. It follows that he objective of sustainable development is quite clear; it aims to balance ecological equilibrium, ensure good living conditions for present and future generations, and balance economic growth, social progress, and sustainable resource usage (Zanghelini G.M., et al., 2017). Therefore, the ideal environmental decision-making process has to consider the concept of "triple bottom line" (TBL), which makes the management of trade-offs very complex (Zanghelini G.M., et al., 2017).

But even if only the environmental dimension is considered, as in the case of this thesis project, decision-making is never simple. Businesses contribute to a variety of interrelated environmental problems. When performing any type of impact assessment, many authors recognize this interrelated-dynamic behavior—that is, the trade-off between environmental burdens—as the central component of choice complexity (Zanghelini G.M., et al., 2017).

Therefore, in addition to the tools and indicators that measure sustainability in terms of impact assessments, methods are also needed to support decision-making in dealing with all these conflicting factors and components. This kind of support, to help decision-makers make better choices in such complex situations, can be achieved through decision analysis methods (Zanghelini G.M., et al., 2017). Regarding the tools that help this process, perhaps the most important and popular are those that form the Multicriteria Decision Analysis (MCDA) group (Zanghelini G.M., et al., 2017).

But these tools cannot be applied alone, as they require input data related to the assessment of environmental impacts themselves. An overview of how to make decisions to achieve sustainable solutions is presented in **Figure 2** (Figure dapted from Zanghelini G.M., et al. 2017).

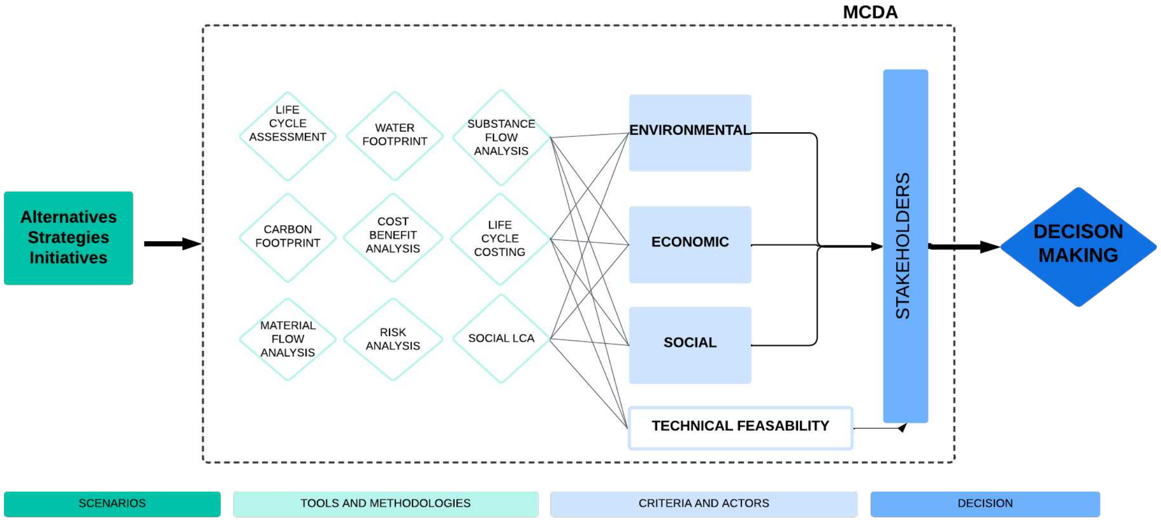

Figure 2 *General flowchart for sustainability decision making*

The work presented in this thesis project was developed precisely in the search for answers to these needs. What has been done, follows the framework illustrated in the figure, focusing however only on the environmental dimension. Starting with a specific company: Fashion Art, and evaluating the context of the textile sector, tools and methodologies were analyzed to direct the company towards more sustainable practices. In the following chapters, the company, the methodologies adopted, and the specific objectives will be presented in detail.

1.4. Fashion art

In the context defined above, i.e. on the one hand the massive impacts of the fashion world, on the other the increasingly stringent governmental and consumer demands and the consequent attempt to move towards more sustainable models, stands Fashion Art, a textile company that is the subject of the case study of this thesis project.

- **Corporate overview**

Fashion Art is a leading company in the field of design and production of haute couture garments, founded by Andrea Rambaldi in 2008. The company is engaged in the luxury sector of fashion design and specializes in denim manufacturing.

The company currently employs 38 people and collaborates with highly skilled suppliers to manage the production of clothing items. Meanwhile, it internally ensures the entire development cycle, including pattern preparation, classification, and sewing of prototypes, at its operational headquarters in Limena, near Padua, Italy.

The company was established from the desire of Andrea Rambaldi to overcome the difficulties he faced as an independent professional in the textile industry. After having collaborated with multiple textile companies, working with them in all stages of the garment production process, Andrea Rambaldi acquired the knowledge base necessary for creating his own business, as a concrete response to the need for improvement and study of the fashion industry and Made in Italy.

Fashion Art's beginnings are strongly linked to its partnership with Chanel. Since first meeting Karl Lagerfeld, creative director of Chanel, in 2007, Andrea Rambaldi has built a strong creative and working relationship with the French Maison. The relationship between the two fashion companies began with a délavé piece in denim for the Métiers d'art 2007/08 Paris-London collection and developed over the years, with the aim of "*ennobling*" denim, as defined by Fashion Art. Indeed, Fashion Art has been Chanel's major denim supplier for years, and in 2022 the latter acquired a 60 percent ownership in the business (Muret D., 2022). Along with Chanel, Fashion Art can count on a clientele that includes some of the leading luxury brands, such as Louis Vuitton, Burberry, and Off-White, to name a few, together with emerging designers, who all appreciate Fashion Art for its innovative approach and expertise in denim fabric.

Founded with the idea of bringing improvements to the fashion sector and above all to the made-in-Italy sector, Fashion Art's mission is to "serve as an intermediary between the designer's idea and the end consumer" finding solutions that have the person at the center and designed to achieve quality garments with total respect for the raw material, the fabric (Fashion Art, 2024). This goal is pursued with constant innovation, attention to detail and quality, Made in Italy experience, and commitment to sustainability.

Indeed, Fashion Art makes sustainability one of its cornerstones. Founded on the principles of innovation and continuous research, the company stands at the cutting edge of the transition to a circular economy. The focus on more sustainable production has declined in all aspects of the company's reality. From its headquarters, entirely designed using wood in adherence to the principles of bio-architecture, to the implementation of a Strategic Sustainability Plan and Sustainability Reports. To the pursuit of innovative technological solutions, such as The Eco Fog/E-Flow Technology, as well as The Ozone Technology and Laser Technology. The adoption of certifications, such as the Global Organic Textile Standard (GOTS), for a wide range of materials. And finally, the implementation of an eco-design tool, based on data from an LCA study, developed to facilitate a clear identification of the environmental impacts associated with the production of specific garments.

- **Collaboration with this thesis project**

This thesis work is part of the research project that Fashion Art has with CESQA, the Centre for Environmental Quality Studies at the University of Padua, and UniSMART University of Padua's foundation established to promote Technology Transfer.

Part of the collaboration aimed at creating the eco-design tool described above and part at conducting all the activities to achieve the objective of this research project.

The Life Cycle Assessment and Multi-Criteria Decision-Making integration model developed in this thesis was born as a future development of the eco-design tool and marks another step in the pursuit of sustainable solutions in the textile industry. More information on the objective of the model and the participation of Fashion Art in the model construction will be provided in the following chapters.

2. Objectives of the study

As highlighted in the context analysis, there is a growing need to steer production towards more sustainable patterns, especially in the manufacturing sector, where sustainability has become crucial in managing limited resources. Given the increasing pressure of legislative regulations and consumer demands, companies, particularly in the fashion industry, see sustainable production models as the only plausible solution.

The purpose of this thesis emerged from this need to make fashion production more sustainable, and focuses particularly on the case study of Fashion Art, a manufacturing company engaged in the luxury sector of fashion design and specialized in the production of denim.

The guiding principle of this project is therefore found in the research on how to make Fashion Art's production more sustainable. The path towards more sustainable production begins with measuring sustainability itself, which translates into assessing the impacts related to the production. Nevertheless, when carrying out any kind of impact assessment, making choices is always very complex, partly due to the nature of the results and partly due to the trade-offs that almost always characterize the results. Therefore, together with the need of assessing the impacts, the need to obtain results that can be easily interpreted by the company and provide a tool to support the decision-making phase arises as well.

This translates into the following objectives of the thesis:

- Identification of effective methodologies to assess the environmental impacts of production.
- Evaluation of how results can be presented in a clear and easily interpretable manner to support business decisions regarding sustainability.
- Assessment the feasibility of a single score that summarizes environmental impact data, making it easier to interpret results and manage trade-offs.
- Evaluation of how impact assessment and decision-making tools can be integrated to facilitate corporate sustainability decision-making.

Once the research phase is completed and a possible solution is identified, the final objective is to apply this solution to the specific context of Fashion Art and evaluate its effectiveness and feasibility. This involves adapting the methodology identified during the theoretical analysis to the needs and peculiarities of the company and evaluating its strengths and weaknesses.

3. Materials and methods

3.1 Life Cycle Assessment (LCA)

The pressures arising from expanding human populations and growing economies are becoming increasingly evident and severe. The effects of human activity have far-reaching consequences on the environment. These consequences can be observed in various environmental compartments, including global climate patterns, land and water usage, and the depletion of nonrenewable resources. Moreover, the emission of potentially harmful chemicals poses a threat to both humans and ecosystems, along with local environmental challenges like acidification and photochemical air pollution.

In response, enterprises, political leaders, as well as individuals, are compelled to confront this pressing reality, necessitating significant changes in their interactions with the environment through consumption habits and service utilization.

Although communication about sustainability is widespread and many claims are made about environmental sustainability, few are substantiated. The field suffers from a lack of factual knowledge about the effects of using products and services, as well as about what is important and what is not, and many decisions are made on a poorly informed basis. It is an old observation that ‘what gets measured gets managed’, and that what is not measured or measurable runs the risk of being neglected. Indeed, there is a need to put numbers on environmental sustainability to encourage a more robust debate about which alternative solutions are the most sustainable (Jolliet, O. *et al.*; 2016)

In addition, to ensure a sustainable future, there is not only the need to measure the impacts but also to prioritize the most meaningful actions to take. Indeed, for an action to be efficient, three conditions must be satisfied:

- Technology-based solutions need to be available.
- Solutions must be prioritized, and best practices chosen, by taking into consideration costs consequent economic restrictions, and environmental efficiency.
- Optimizing actions is necessary to minimize further impacts.

Life cycle assessment (LCA) is a decision-making tool that specifically addresses this need of selecting and optimizing available technological solutions (Jolliet, O. *et al.*; 2016). It can be said that LCA is a complement to technological developments since it highlights which processes should be improved in priority order. LCA is a tool that not only helps prioritize solutions, but it is at the same time a comprehensive and robust tool to help decision-making identify all relevant (direct and indirect) potential impacts caused by the solution, throughout its entire life cycle.

Its relevance as an assessment tool is demonstrated by the central role that it has been given in environmental regulations in many parts of the world, and the strong increase in its use over the last decades by companies from all trades.

3.1.1 LCA definition and main characteristics

As defined by the ILCD Handbook, “Life Cycle Assessment (LCA) is a structured, comprehensive, and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (“products”).”

The assessment considers a product’s full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste, with a broad range of environmental impacts considered.

These environmental impacts are linked to the system’s function by LCA methodology, making the comparison between alternatives easier. These characteristics make LCA one of the most powerful tools for evaluating how products or services affect the environment and allow it to address questions that no other assessment tool can successfully.

In the following paragraphs, the main LCA characteristics will be described in detail.

1. **LCA takes a life cycle perspective**

Similarly, to what happens in biology, a man-made object has a life cycle, as it begins with the collection and extraction of resources, then moves on to manufacture, usage, and, at the end of the process, its disposal as waste. Eventually, recycling or reuse can be seen as a new life for the objects. All these stages have to be taken into account when evaluating the environmental performance of a product, as impacts can occur at all stages and not solely in one as conventionally assumed for a long time.

The adoption of a life cycle perspective is crucial even because it enables revealing and avoiding problem-shifting, also the bias of resolving one environmental problem while unintentionally creating others somewhere else in the system.

Indeed, as LCA often focuses on physical products, the term "product system" highlights that all the processes required to deliver the function of the product are considered. This means that not only all the stages of the life cycle of the object under study are considered, but the object itself is analyzed together within its context.

Note that the life cycle concept is not limited to environmental impacts; the results of an environmental LCA can be combined with those of an economic analysis: life cycle costing (LCC), a technical analysis: life cycle engineering (Lundquist et al. 2000), or a social analysis: social LCA, thereby integrating the different aspects of sustainability.

2. LCA covers a broad range of environmental issues

Together with a comprehensive coverage of all the life cycle stages, the LCA analysis accounts for a comprehensive coverage of environmental issues. Rather than focusing on just one environmental aspect, such as climate change, which generally receives the most attention nowadays, a wide range of environmental impacts are covered by LCA, including freshwater use, land occupation and transformation, aquatic eutrophication, toxic impacts on human health, depletion of non-renewable resources, and eco-toxic effects.

In this case, just like in adopting a life cycle perspective, the comprehensive nature of LCA is designed to avoid the burden-shifting problem. In this instance, considering multiple environmental aspects is done to ensure that efforts to reduce the impacts of a product in one environmental compartment do not unintentionally increase other types of environmental impacts.

3. LCA links environmental impacts to the system function

The assessment conducted by the LCA is grounded in the function of the product or service under study, with the resulting environmental impacts directly linked to this function. The function of a product or service defines the purpose or role it serves within its intended use, encompassing the primary reason for its existence and the benefits it offers to users or consumers. Establishing a clear definition of the function is fundamental to the study, as it significantly influences the way LCA is performed, its outcomes, and its interpretation. This importance arises from the functional unit serving as a reference point. Understanding functions becomes especially crucial in comparative analysis as fair and meaningful comparison hinges on whether the compared systems provide (roughly) the same function(s) to the user.

In addition, while conducting an LCA, understanding the function of the product or service is crucial because it allows analysts to assess how different stages of the product's life cycle contribute to fulfilling that function and, consequently, how they impact the environment. By linking environmental impacts directly to the function, LCAs provide valuable insights into the trade-offs and environmental consequences associated with various design choices, manufacturing processes, use patterns, and end-of-life disposal methods.

4. LCA is quantitative

LCA results address the question of "How much does a product system potentially impact the environment?' One aspect of the answer might be, for instance, "the impact on climate change is 87 kg of CO2 equivalents" representing a quantitative response in terms of environmental impact (Jolliet, O. *et al.*; 2016).

The quantitative nature of Life Cycle Assessment enables the comparison of environmental impacts across different processes and product systems. This facilitates the assessment of which products or systems are more environmentally friendly, as well as the identification of processes that contribute most significantly to overall impact, thereby targeting areas requiring attention.

LCA results are derived through a two-step process: first, by mapping all emissions, resource uses, and their geographical origins, and second, by calculating potential environmental impacts through mathematical cause-and-effect models. Seeking the "best estimate," quantification usually chooses average values for the parameters used in the modeling process.

5. LCA is based on science

The overall methodology is grounded in scientific methods and principles to provide reliable and robust assessments of environmental impacts.

The methodology involves rigorous data collection, analysis, and interpretation, often relying on scientific databases and models to estimate environmental impacts. Moreover, flows are generally based on measurements and the models between emissions (or resource consumptions) and impact are based on proven causalities.

Despite this, in the LCA study, there are also value judgments and assumptions, primarily in the two optional steps of the methodology: normalization and weighting. When dealing with these situations, LCA always seeks to manage value judgments most consistently and transparently as possible.

6. Iterative nature

LCA is an iterative technique (ISO, 14044). This iterative nature inside and between phases helps to ensure the study's comprehensiveness and consistency, as well as the stated results.

Each phase of an LCA relies on insights from the previous phases, encouraging a continuous refinement process. Indeed, insights from the impact assessment are utilized to refine the inventory analysis, and insights from both phases may feed back into the scope definition.

Jolliet O. et al., strongly recommended conducting an LCA study in two steps: (1) a preliminary evaluation, also known as screening phase, to understand the contribution of each life cycle stage and to identify by an early sensitivity assessment, critical processes, and impacts, minimizing time spent on features with negligible contributions. (2) A deeper analysis that involves repeating the goal and scope definition, inventory, and impact assessment steps in greater detail.

This division can be seen as the first major iteration, as data from the preliminary evaluation is used to identify emissions, processes, and stages with significant environmental implications. These are then prioritized for further investigation in the second step, along with a rigorous sensitivity analysis and uncertainty assessment, which are part of the final interpretation phase. The deeper analysis is characterized by continuous refinement and involves many feedback loops between the individual phases of the LCA.

7. Standardized structure

The need for agreement on common principles for how to perform an LCA dates back to the 1980s (Hauschild M.Z., 2018). By the 1990s, an international discussion concerning methodological issues began under the guidance of the Society of Environmental Toxicology and Chemistry (SETAC). This debate resulted in the publication of cutting-edge reports and codes of conduct throughout the 1990s, establishing an environment for simultaneous standardization initiatives.

While discussions and developments on some methodological aspects continue today, the underlying framework has remained largely stable since the birth of the first ISO 14040 standard in 1997. Standards related to Environmental Management and LCA have been developed to address the need to align diverse methodologies employed in LCAs on a global scale.

The ISO 14040 series (14040 to 14049) is devoted to LCA. These are international standards, not intended for contractual or regulatory purposes, nor for registration and certification.

Instead, they furnish requirements and guidelines essential for conducting life cycle assessments effectively.

In addition to the ISO LCA standards, the European Integrated Life Cycle Assessment guidelines (ILCD handbook), which are rooted in the framework and methodological requisites defined by the standards, offer detailed methodological guidance. These guidelines are the product of an extensive consultation process involving expert and stakeholder input and consequently, they are considered a valuable point of reference for discussing LCA methodology and delineating methodological approaches.

When it comes to standardization, an important consideration must be made. The potential environmental impacts resulting from Life Cycle Assessment (LCA) studies can be calculated for a product system, with reference standards being ISO 14040-44. Alternatively, impacts can be calculated for the activities of an organization, known as organization LCA, governed by the ISO/TS 14072:2014 standard. This Technical Specification provides additional requirements and specific guidelines for the proper application of ISO 14040 and ISO 14044 standards within organizational contexts. Despite internal differences, the structure of LCA remains the same in both cases. Regardless of whether the focus is on the product or the organization, these two types of studies are closely interconnected because each product is the result of various steps within an organization, and conversely, an organization's output is a product (or service).

This thesis chapter aims to provide an overview of LCA and its structure. Therefore, as previously defined, reference will be made to ISO 14040-44 standards and the ILCD handbook, without going into details about the specific differences between product and organizational LCAs.

3.1.2 LCA compared with other tool

The results of the LCA can be used by governments, businesses, and consumers when making decisions. But LCA is not the only tool available. As defined by Jolliet, O. et al., LCA is part of a series of environmental instruments and other more general approaches focused on sustainable development. Within this context, different quantitative assessment tools, procedural methods, aspects of sustainability, and technological development, are present and interconnected with each other, as shown in **Figure 3** (Figure source *Jolliet, O. et al; 2016)*

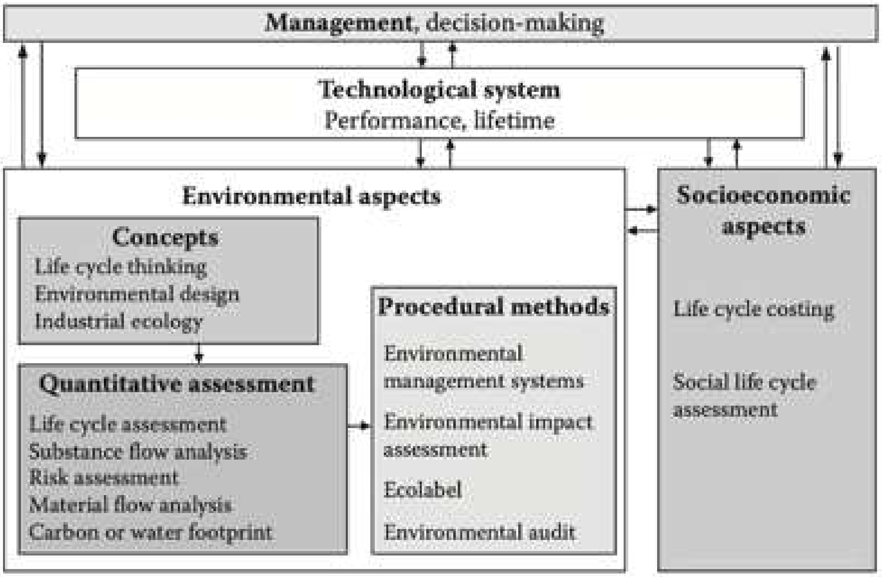

Figure 3 *Relationship between various tools to assess the sustainability*

LCA is thus just one of the quantitative assessments' methods available. Other commonly used methodologies are Substance flow analysis (SFA), Risk assessment (RA), Material flow analysis (MFA), Carbon footprint (CF), and Water footprint (WF).

These tools aim, although with different approaches, at calculating the impacts of a product or service. Some elements can be in common between different tools, while each has its structure and is suited to address particular environmental-related issues. The choice of approach depends on many factors, such as the object of the study, the scope of the decision problem, its definition in space and time, and the availability of data (Wrisberg et al. 2002) and every time a tailored analysis of which methods to adopt has to be made.

Here a more detailed comparison between LCA and the other quantitative assessment tools will be presented, highlighting the differences between methodologies:

1. **Comparison between Substance Flow Analysis and LCA**

   SFA quantifies the flows and environmental accumulation of either a single substance, such as mercury, or a group of substances. Both methods rely on mass balances to perform calculations and validate the emissions and extraction inventory. However, SFA focuses on the transfers among various environmental media (e.g., air, water, or soil) of a single substance associated with a given region or industry, whereas LCA considers the environmental fate of many substances associated with a product function, and then estimates impacts by accounting for the multiple effects of these substances.

2. Comparison between Risk Analysis and LCA

Risk analysis studies the risk or the probability of severe impacts occurring from an installation (such as a nuclear power plant) or the risks of using a chemical substance. Both approaches use dose-response models to assess the effects of human and ecosystem exposure to chemicals, and they consider the spread of contaminants among air, water, soil, and food. Different than LCA, RA is a regulatory-oriented methodology, with hazard-based indicators based on conservative assumptions, and incorporates safety measures to guarantee that exposure levels are much below the no-observable-effect levels. LCA on the other hand, aims to assess comparative risk and the average contribution of a product or service to defined environmental impacts (Pennington et al. 2006). Local maximum permissible concentrations or acute toxicity events are thus not usually addressed by an LCA.

3. Comparison between Material Flow Analysis and LCA

MFA has been defined as “a systematic assessment of the flows and stocks of materials within a system defined in space and time” (Brunner and Rechberger, 2003). Even though both methods use mass balance modeling, MFA is for the qualitative and quantitative assessment of material flows, while the LCA additionally performs the environmental assessment through the quantification of environmental impacts.

4. Comparison between Carbon Footprint and LCA

The term footprint can be defined as a metric used to report life cycle assessment results addressing a specific area of concern, which is an environmental aspect defined by the interest of society. The structure of a Footprint analysis is the same as the LCA but while LCA tries to be as comprehensive as possible by providing an eco-profile of the product under study, a footprint analysis focuses only on one area of concern, based on a specific need. In the case of Carbon Footprint, the area of concern is climate change, and it determines the direct and indirect emissions of greenhouse gases due to a product, a human activity, or a business, expressed as CO2 equivalents and based on a life cycle assessment using the single impact category of climate change (**Figure 4**).

5. Comparison between Water Footprint and LCA

The concept of a water footprint is similar to that of a carbon footprint but with a distinct focus on water-related impacts. The structure of a footprint analysis remains consistent with the one of LCA, yet the emphasis shifts solely to water concerns rather than providing a broader eco-profile. Unlike carbon footprint assessments, which measure only carbon emissions, water footprint evaluations encompass a range of categories all related to water, such as water availability, water scarcity, eutrophication, water acidification, and others. Indeed, the term water footprint is appropriately used without further qualification only when a comprehensive study specifically addressing water-related aspects has been conducted.

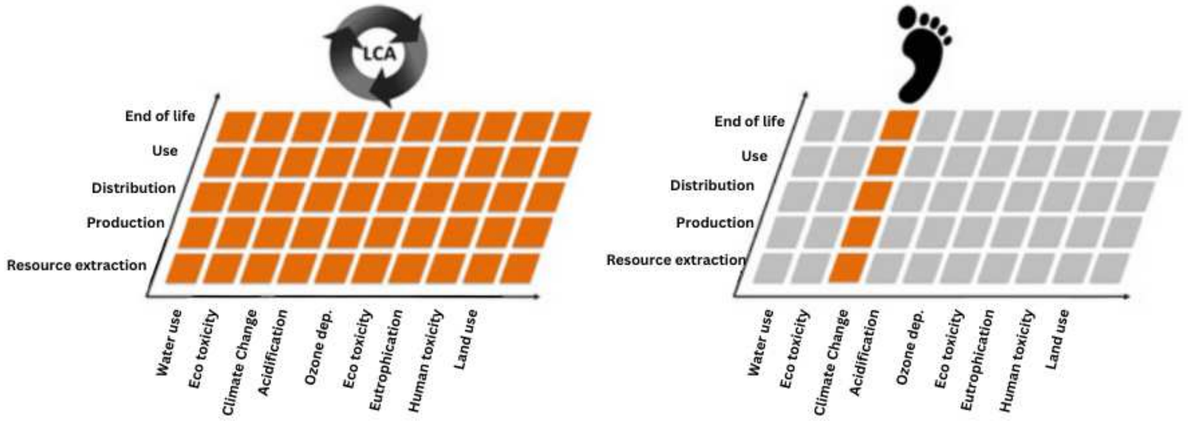

Figure 4 *Comparison between LCA and Carbon Footprint (Hauschild, M.Z, 2018)*

In essence, a Life Cycle Assessment (LCA) serves as a systematic tool to quantify the material flows involved throughout the entire life cycle of a product or service. By examining these flows, an LCA enables the estimation of environmental impacts across a broad variety of environmental categories. These impacts range from energy consumption and greenhouse gas emissions to water usage and toxicity, among others, thus providing a comprehensive eco-profile for the subject of study. One of the defining characteristics that sets LCA apart is its ability to link multiple environmental impacts directly to the function of the product or service. This feature is fundamental for conducting thorough comparative analyses. By adopting a life cycle thinking approach, LCA ensures a holistic perspective, considering not only the production and use phases but also disposal and any subsequent effects on the environment. This comprehensive approach, both in terms of life cycle perspective and environmental impact categories, ensures that all potentially relevant impacts are accounted for, thereby offering a more complete understanding of the environmental footprint associated with the product or service and allowing the avoidance of the burden-shifting problem. Furthermore, LCA considers the entire product system within its specific context, acknowledging the actual conditions under which the product is utilized and managed. This contextualization is crucial for accurately assessing the true environmental implications associated with its life cycle stages. When compared to alternative methodologies, LCA stands out as the sole approach capable of integrating this totality of considerations. Its ability to provide a detailed and contextually relevant analysis makes LCA an indispensable tool for making informed decisions aimed at reducing environmental impacts and promoting sustainability across various industries and sectors.

3.1.3 LCA methodology

As previously defined, LCA evaluates the potential environmental impacts of a product or service, the assessment is based on a particular function and considers all life cycle stages. It supports the design of new products and helps determine where in a product's life cycle environmental improvements can be made to make the product more sustainable in terms of environmental impacts.

The framework of Life Cycle Assessment (LCA) is defined by the International Organization for Standardization (ISO) standards and according to these standards, LCA comprises four distinct phases, which are defined as follows (ISO, 14044):

1. *Goal and scope definition:* the problem is described, together with the definition of objectives, and scope of the product under study. Some crucial elements are defined in this phase, such as the function of the product, the functional unit, and the system boundaries, and these influence the further structure of the LCA.
2. *Inventory analysis:* data collection is performed in this phase to quantify through mass and energy balances all the extractions of resources and emissions of polluting substances occurring throughout the life cycle of the product system.
3. *Impact analysis*: inventory flows are translated into potential environmental impacts
4. *Interpretation:* results are interpreted, assumptions and uncertainties evaluated, and conclusions are drawn.

Even though these stages have separate identities, they work together. Indeed, LCA is not a linear progression but rather involves numerous feedback loops between the various phases, highlighting the iterative nature of this methodology.
As shown in the figure below, ISO specified that the structured framework of LCA is the fundamental basis for performing this type of study and it is separated from its numerous and diverse applications.
These four phases of LCA will be here further examined, but it is important to note that they have not all reached the same level of maturity, yet great research on different aspects of LCA is ongoing.

The methodology chapter of this thesis is structured and based on the ISO standards and European ILCD guidelines. While the references to these sources may not be consistently provided throughout the chapter, unless otherwise mentioned, they are the basis of the presented methodology.

3.1.3.1 The four phases of LCA

The purpose of this chapter is to provide a broad outline of the four main stages of LCA as this methodology provides one of the fundamental tools used in the model of this thesis. The goal is to provide a basic understanding of these phases to lay the groundwork for discussing the methodology's challenges and limitations. However, it's important to note that the intention is not to delve deeply into the complexities of each phase, as it would exceed the scope of this paper.

- **Goal and scope definition**

The "*goal and scope definition*" is the first phase of the LCA and here the function of the system, the objectives of the study, and the boundaries of the analysis are defined. This phase is fundamental as it defines the structure of the whole LCA and influences all the future steps. The goal definition is the starting point of LCA, here the purpose of the study must be defined and described in the clearest way possible. Together with the object of the study, other elements must be defined that help to identify the context of the assessments, such as:

- Intended applications of the results

  The intended applications define what the study does, and which is the aimed application for which the LCA is performed, for example: comparing environmental impacts of products, documenting the environmental performances, developing policies, and evaluating improvements potentials….

- Limitations due to methodological choices

  These limitations are strictly related to limitations made in the goal and scope phase On the contrary, choices made during the inventory and impact assessment phases of an LCA relate to unforeseen constraints and assumptions (for example concerning data availability) and must be documented at a later point.

- Decision context and reasons for carrying out the study

  The reasons for carrying out the study may be similar to the intended application, although they answer two different questions, the first is why the study is made and the second one is about what a study does. For example, an LCA is conducted to perform a comparative assertion between two options (intended application) to support the government's decision (reason of the study).

- Target audience

  The target audience represents to whom the results of the study are intended to be communicated and this influences mainly the level of detail and the technical level of the LCA.

- Comparative studies to be disclosed to the public

  The goal definition should explicitly state whether the LCA study is of a comparative nature and if it is intended to be disclosed to the public.

- Commissioner of the study and other influential actors

Once the goal is determined, the scope of an LCA must consider and clearly describe the following elements: (1) the product system to be studied, (2) the function of the product and consequently the functional unit, and (3) the system boundaries.

As the LCA links the environmental impacts to the function of the product, its definition is crucial. Indeed, all the emissions, extractions, and impacts will be based on the functional unit which is considered as the reference unit of the analysis, as it quantifies the performance of the product system. The system boundaries include all the processes necessary to ensure the desired function and they identify what exactly the analysis will study (product system and system boundaries can differ).

In defining what to include in the study, three approaches can be followed:

- gate to gate: only production processes are considered.
- cradle to gate: the analysis starts from raw materials but stops at the output of a specific stage of the life cycle such as production.
- cradle to grave: encompasses all the life cycle stages of the products, from extraction of materials to end of life.

As LCA is an iterative process it is recommended to be the most comprehensive as possible at the beginning of the study and eventually exclude parts as they are assessed as negligible in terms of impacts.

Once these aspects are addressed other aspects must be defined in the scope definition phase, which according to the standard, are allocation procedures, Life cycle impact assessment (LCIA) methodology and types of impacts, Interpretation to be used, Data and data quality requirements, Assumptions, Value choices and optional elements and Limitations.

- **Inventory analysis**

Once the first part of a life cycle assessment (LCA) has specified the scenarios, the functions they serve, and the systems to be evaluated, inventory analysis will be performed, in accordance with the goals and definitions. Inventory analysis involves (i) data collection: all information required to characterize the product under study, are collected, and (ii) doing calculations to quantify the inputs and outputs of the product system. The process of conducting an inventory analysis is iterative. As data is accumulated and insights about the system are gained, new data requirements or limitations may emerge, necessitating adjustments to the data collection procedures to ensure the study's objectives are upheld. At times, issues may arise that call for revisions to the study's goals or scope, and practical constraints on data collection must be considered within the scope and documented in the study report.

Practically the inventory analysis identifies all the elementary flows, thus all the emissions of polluting substances to the environment, and the amounts of extracted resources from the environment (minerals, energy carriers, soil surface area, etc.) throughout the life cycle of the analyzed product system. The inventory of elementary flows or emissions and extractions is, by definition, the quantitative description of flows of matter, energy, and pollutants that cross the system boundary (Jolliet O. et al, 2016) and these flows are expressed in term of the functional unit.

When it comes to practical implementation, the ISO standard outlines the inventory analysis concept and provides a procedural framework, which includes (ISO, 14044):

1. Preparing for data collection: understand what information is required.
2. Data collection: gather information from databases, literature reviews, or company records.
3. Data validation: ensure the data's accuracy and quality. Validating data is crucial in LCI, and efforts should be made to use the highest quality data available. The iterative nature of LCA allows for data quality improvement over time, but any constraints on data collection should be clearly defined.
4. Allocation processes: many industrial processes generate multiple outputs or involve recycling intermediate or discarded products. Allocation procedures are necessary in such cases to allocate resources appropriately. Consideration should be given to allocation procedures, especially in systems with multiple products and recycling mechanisms. Several approaches exist to address the allocation issue, and ISO standards provide a guideline on how to proceed. Nevertheless, it remains one of the most challenging topics in LCA.
5. Ensure all data is related and expressed in terms of the functional unit.

While the principles of inventory calculation are relatively straightforward, data collection may necessitate substantial effort. Fortunately, databases now exist that integrate data for a wide range of processes, leaving only the processes specific to the considered application and industries to be modeled in detail. (Jolliet O. et al, 2016). One of the most used and accredited databases is Ecoinvent, which was developed to consolidate and improve existing inventory databases to create a unified, high-quality dataset. Initially focused on Switzerland and Western Europe, Ecoinvent has evolved to encompass global datasets and is widely regarded as one of the most reliable databases available.

In addition to Ecoinvent and the ELCD databases (European reference Life Cycle Database), Europe also offers country-specific databases, while other countries similarly maintain their localized datasets. As today numerous databases exist each LCA requires careful consideration of the specific data needed and where to source it to ensure the highest quality analysis.

- **Impact Assessment**

Impact assessment translates inventory flows into potential environmental impacts, making its primary focus the addressing and quantification of the consequences of the product system on the environment. The term “potential” is used to explain that impacts assessed during the LCIA phase represent possible impacts rather than actual impacts, thresholds, safety margins, or indicative of risk (Jolliet O. et al, 2016). LCIA process typically involves associating inventory data with specific environmental impact categories and indicators through an iterative process aligned with defined goals and scope. ISO standards define the elements of Life Cycle Impact Assessment (LCIA), categorizing them into mandatory and optional components as shown in **Figure 5**.

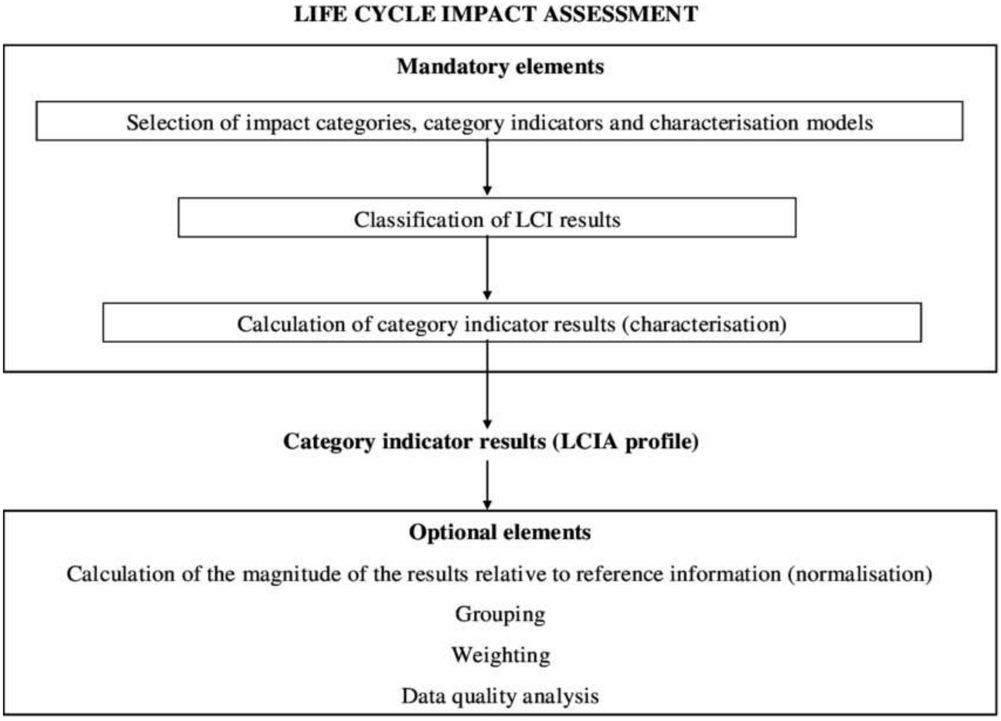

Figure 5 *Mandatory and optional elements of LCIA (BS EN ISO14044, 2006 + A2, 2020)*

The binding phases of LCIA encompass selection, classification, and characterization:

1. Selection: impact categories, category indicators, and characterization models are chosen. The selection of impact categories must be well-justified and aligned with the study's goals and scope (ISO, 14044). While striving for comprehensiveness, it is important to focus only on what is relevant to the study. To perform the impact assessment, it is

important to decide at which point to stop the LCA study, whereas at midpoint or endpoint level (BS EN ISO14044, 2006 + A1, 2020).

2. Classification: LCI results are allocated to the selected impact categories. Classification ensures that each input and output is appropriately attributed to a specific impact assessment category.

3. Characterization: impacts are calculated. Each input and output undergo evaluation using cause-effect models to derive metric values representing their impact. This phase comprises two main levels of analysis: midpoint characterization and endpoint (damage) characterization. Initially, each inventory flow is multiplied by a characterization factor to define its contribution to the midpoint category. Subsequently, in damage characterization, the contribution of each midpoint category to one or more damage categories is calculated and associated with broader areas of protection (Jolliet O. et al, 2016).

After these mandatory steps, an ECO-PROFILE is obtained, which is the result of the LCA. All the environmental impacts caused by the product system under study are identified, quantified, and reported in environmental categories.
Two additional steps may be carried out: normalization and weighting. According to the ISO 14044 standard, normalization is defined as *"the calculation of the magnitude of category indicator results relative to reference information"* and weighting as "*converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices*" (ISO, 2006b). Unlike selection, classification, and characterization, which are mandatory steps according to ISO standards, normalization and weighting are optional in Life Cycle Impact Assessment (LCIA) due to the potential biases and value choices that they are respectively associated with and for the increased uncertainty that these steps entail (Pizzol, M. et al., 2016).

- Normalization
  The scores of the various midpoint indicators are measured in different units across impact categories, making it impractical to directly compare them or determine their relative magnitudes. To facilitate such comparisons, it's essential to relate different impact potentials to a common scale and put them into perspective (Hauschild, M.Z et

al., 2018), and this is the purpose of normalization. Normalization relates the results obtained to reference systems like a country, the world, or an industrial sector and this helps to get an idea of the magnitude of the impacts. According to what is used as the reference system, different normalization techniques are defined. Given its applications, normalization could be seen as a step that helps interpret and communicate the results, rather than a part of the “impact assessment” in its strict sense, since normalization does not add to the quantification of potential environmental impacts (Pizzol, M. et al., 2016).

- Weighting

  Weighting is the process of assigning weights to each impact category while grouping aggregates several impact indicators into a group. Weights are applied to: (i) represent an evaluation of the relative importance of impacts according to specific value choices; and (ii) sum up results across impact categories to arrive at a single score indicator for an LCA. Therefore, weighting can help the decision-making process in situations where trade-offs between impact category results make it hard to choose one preferable solution among the alternatives or one improvement among possible others. There are several techniques for defining weights, yet each introduces a significant degree of subjectivity. Indeed, this is the main criticism directed at the weighting phase, namely that it is not "scientifically grounded," which is why ISO standards exclude it from mandatory steps and do not permit its application in comparative assertions disclosed to the public.

Pro and cons of each normalization and weighting approach, together with the challenges of their application will be further discussed in Chapter 3.2.

- **Interpretation**

Interpretation stands as a fundamental phase within the Life Cycle Assessment (LCA) framework. It operates as an iterative process, persistently present at each stage, yet deeply conduced at the end. Throughout interpretation, the primary focus revolves around assessing results, evaluating, assumptions, and exploring diverse ways for mitigating environmental impacts, all aimed at identifying prioritized actions. These activities conclude in producing analytical insights from the conducted assessment, providing clear and usable information for decision-making.

The interpretation phase also encompasses the execution of sensitivity and uncertainty analyses, crucial for evaluating the quality and robustness of the obtained results. Uncertainty analysis is an analytical procedure to determine how uncertainties in data and assumptions affect the calculations and the reliability of the results of the LCIA (BS EN ISO14044, 2006 + A1, 2020). While sensitivity analysis aim at showing how changes in data and methodological choices affect the results of the LCIA (BS EN ISO14044, 2006 + A1, 2020).

The comprehensive nature of LCA is well recognized again during this phase, as interpretation requires a holistic approach that examines different dimensions: from each stage of the LCA process to the product's life cycle stages and down to the individual components that make up the product system. Furthermore, it investigates the various categories that contribute to the total impact, all to provide full insights into the results obtained.

3.1.4 LCA application

Much effort has been made to facilitate the application of LCA and life cycle thinking in society, ranging from the regulatory and governmental level, through industry and production to the level of citizens and consumers (Hauschild, M.Z et al., 2018). Various initiatives have emerged to support and standardize the application of Life Cycle Assessment (LCA). Notable among these is the publication of ISO 14040 standards in 1997, subsequently updated as ISO 2006a, aimed at aligning the LCA framework and principles to enhance transparency. In 2001, the United Nations Environmental Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) collaborated to establish the Life Cycle Initiative (LCI). This global partnership aimed to promote widespread dissemination and utilization of LCA, to enable people all over the globe to implement life cycle thinking effectively. Another significant initiative emerged in 2005 with the launch of the European Platform of LCA. This platform was designed to promote life cycle thinking in both business practices and policymaking. In addition, various national initiatives have been launched to support and facilitate the application of LCA, and universities, research institutions, and private companies often collaborate closely on the development and application of LCA methodology.

These collective efforts have significantly contributed to improving the methodology, harmonizing the tool, and increasing its use and application. Here we will present some of the main areas of application of LCA, highlighting the motivation for adopting this tool:

- **Government perspective and policies:**

  LCA and lifecycle-based approaches are used by governments as supporting tools.

  For example, the European Commission has listed LCA as one of the reference models for the impact assessment of policies in the European Union (EU) within its "better regulation guidelines" document published in 2015 (European Commission 2015). This has the potential to increase the use of Life Cycle Assessment (LCA) in both retrospective evaluations of existing policy frameworks and prospective assessments of future policy options.

  The use of LCA can support policy formulation, implantation, and regulation imposed by policies (Hauschild, M.Z et al., 2018). As an example of LCA used for policy formulation, the European Commission has promoted Integrated Product Policy (IPP) to minimize the environmental impacts of products. This policy considers all stages of a product's life cycle, from the cradle to the grave (Mudgal 2008). The approach is not focused on manufacturing processes alone, but also on the use of products and their disposal (Wenzel et al. 1997; Azapagic and Perdan 2000). The directive is an excellent example of how life cycle thinking can guide policymaking within the EU. Governments often use Life Cycle Assessment (LCA) to make informed decisions about implementing new technologies in the market (such as the use of biofuels) or selecting waste management systems. For example, in Denmark, LCA was used in the 1990s to guide the development of the current Danish collection system for beverages and assess recycling strategies for various waste fractions (Hauschild, M.Z., et al. 2017). LCA has also been used in Sweden to evaluate the environmental impacts of introducing a waste incineration tax. Such examples of LCA being used for decision support can also be found outside of Europe (Hauschild, M.Z., et al. 2017).

- **Industry perspective:**

  With growing public concerns regarding environmental issues, coupled with an increasing consumer consciousness towards sustainability, and the strengthening of environmental regulations, businesses are placing great interest in quantifying their environmental footprint, using LCA as a tool to measure their environmental performance. The application of LCA within businesses can be categorized into five primary purposes (Hauschild, M.Z et al., 2018):

  - Enhancing the environmental performance of products and services.
  - Supporting decision-making in product design and process development.

- Serving marketing objectives, as in the case of eco-labeling.
- Informing choices regarding suppliers, subcontractors, or materials.
- Developing and selecting indicators for monitoring the environmental performance of products or facilities.

In adopting LCA, companies often pursue multiple purposes simultaneously, tailoring the application to their specific organizational needs. Furthermore, one application of LCA can often trigger another as insights gained from LCA regarding product environmental performance may inform decisions related to supplier selection or strategic planning.

- **Citizen perspective:**

  LCA results can be useful in helping individuals make better decisions, both in their role as citizens and consumers. Consumers encounter LCA results, or the conclusions derived from them, consciously or unconsciously through eco-labels or other consumer information provided by producers, Consumer decisions that may be supported by an LCA can range from selecting a product with the lowest environmental impact among similar products to choosing the most environmentally friendly way to fulfill a function. LCA deriving information can also help citizens to reduce their personal impact.

In conclusion, it can be said that LCA is an important and useful tool to identify and quantify potential impacts and support decisions, from a broad range of perspectives. As it has been presented, its application is nowadays widespread, but it is important to underline that large differences exist in the application of LCA between developed and developing countries in terms of both frequency and incentives and further development in its methodology and application is still ongoing.

3.1.5 LCA limitations

Life Cycle Assessment (LCA) emerges as one of the most prominent and robust methodology for evaluating the environmental impacts of products and services (Zanghelini et al., 2018). Its comprehensive approach enables a thorough assessment of various environmental aspects, supported by transparency characteristics and a scientifically based foundation.

LCA's advantages and comparisons with other methods have been as extensively discussed. Therefore, this chapter aims to highlight some important limitations of the methodology.

For great clarity, limitations are intended to be divided into two categories: the inherent limitations of the methodology, namely the more practical limitations encountered when conducting an LCA study, which may lead to somewhat inaccurate or limited results and the limitations of LCA as a decision support tool.

1. Methodological limitations:

When performing an LCA, several practical and conceptual limitations arise (Jolliet, O. et al. 2016). First of all, conducting an LCA can be time-consuming, especially during the data collection phase. Additionally, subjective factors such as the individuals conducting the LCA and the choice of assumptions or impact assessment methods can influence the results.

Moreover, LCA shows some limitations for certain substances in specific impact categories, such as toxicity, the results may only provide orders of magnitude rather than precise values, and when impacts are highly spatially variable or associated with differences in local or regional sensitivities, as in LCA spatial and temporal dimensions are generally not differentiated (Jolliet, O. et al. 2016). Furthermore, it is important to emphasize that LCA addresses adverse environmental effects only and is therefore not the appropriate tool to consider the economic or social dimension of sustainability. In that case, other tools such as life cycle costing (LCC) or social LCA must be considered (Jolliet, O. et al. 2016). In more general terms, it is critical to understand when LCA applies and apply it just for that purpose.

2. Limitations of LCA as a decision support tool

Several authors have pointed out that, among other key issues, the application of LCA as a decision support tool faces two major challenges: uncertainty and dealing with multiple indicators (Marson et al., 2024, Laurent et al., 2020; Laurin et al., 2016; Mendoza Beltran et al., 2016, 2018b; Zanghelini et al., 2018). Uncertainty influences all aspects of LCA, and it can be caused by the inventory data utilized, which may be unrepresentative or contain intrinsic flaws, the impact assessment models, and methodological choices (Marson et al., 2018). Moreover, methodological decisions made in the scope definition might have a significant impact on the findings. Therefore, it is vital to take a critical approach and thoroughly examine the assumptions and their implications for the results of the study, paying particular attention to the interpretation and communication of results (Jolliet, O. et al. 2016). Having a comprehensive nature, indeed invariably leads to expressing the potential impacts in several different impact categories. The outcome of an LCA is therefore often complex to interpret, especially for non-experts, and usually identifying the best alternative is not an easy task. In this sense, LCA is claimed to show limitations as a decisional support tool. This aspect is central in regard to this thesis objective and will be analyzed in great detail in the following chapters.

3.2 The LCA’s open challenges

3.2.1 Normalization and weighting: challenges and opportunities

The comprehensive nature of LCA is one of the most appreciated aspects of the methodology, however, it follows that drawing the correct conclusions based on environmental indicators can be very challenging considering the wide variety of environmental impacts, which may show conflicting results (Roesch et al., 2020). Indeed, many LCA users find it difficult to interpret LCA results, especially in the case of trade-offs, and therefore seek help from normalization and weighting (Roesch et al., 2020).

As defined in the chapter above, normalization and weighting are however optional steps in LCA, and indeed ISO standards do not support the use of normalization and weighting for publishing comparative assertions in LCA (ISO, 2006a; ISO, 2006b). This is because these steps are generally associated with bias and evaluation choices that make their use still questionable.

Strong criticisms are indeed addressed to these two phases. Regarding normalization, the most discussed aspect is the possibility of bias due to the choice of normalization references, which may change the conclusions drawn from the LCIA phase (Pizzol et al., 2017). Criticism of weighting is even starker as ISO 14044 considers it to be "not scientifically based", excluding its use from LCA studies intended to support comparative assertions intended to be disclosed to the public because it is "based on value choices" (ISO, 2006a; ISO, 2006b).

Despite this, research carried out in 2015 in the context of the Life Cycle Initiative, a joint initiative of the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC), showed that, although considered complicated, uncertain and still not robust to use, both phases are considered relevant for decision-making (*Cavenago, et al., 2021*). Identifying the relevant impact categories, as well as aggregating the normalized and weighted results, and providing a single index score of the overall environmental impact of the product, is indeed helpful for the decision maker (*Cavenago, et al., 2021*).

Thus, it remains unclear to what degree researchers and practitioners are able or should appropriately and legitimately employ normalization and weighting and interpret their resulting outputs. Misunderstandings or errors while performing normalization and weighting may unintentionally or on purpose result in results that are distorted or unjustified. This would ultimately lead to a lack of confidence in LCA outcomes and, more generally, to inadequate decision support. (Pizzol et al., 2017).

To address this challenge, significant efforts have been and continue to be made by the scientific community. A notable development is the publication of the technical standard TS/ISO 14074 in 2022, which focuses specifically on "principles, requirements, and guidelines for normalization and weighting". This is a technical standard and as such address work still under technical development. Furthermore, the 72nd LCA forum held in Zurich in September 2019 served as a pivotal event where the latest advancements in these areas were reviewed and discussed. Overall, what emerges is that this aspect represents one of the open challenges of the LCA and is a topic of great interest and development.

In this chapter, the currently available normalization and weighting tools will be illustrated, highlighting their limitations and criticisms. Particular attention will be paid to the single score concept and the approaches to obtain it. Some applications of normalization and weighting and promising future developments will also be illustrated.

This chapter aims to explore the existing normalization and weighting tools, highlighting their limitations and criticisms. Particular attention will be paid to the single score concept and the approaches to obtain it. Additionally, some applications of normalization and weighting will be illustrated, alongside presenting promising future developments. TS/ISO 14074, together with the articles Pizzol et al. (2017) and Roesch et al. (2020) are considered the main references of this topic in the scientific literature and are the basis for this chapter.

3.2.1.1 Normalization

According to ISO Standard 14044 normalization is "the calculation of the magnitude of the category indicator results relative to some reference number" (ISO, 2006a; ISO, 2006b) thus, it gives information on the relative significance of that indicator under consideration.

Practically, normalization transforms an indicator result by dividing it by the indicator results for a selected reference system (ISO/TS 14074; 2022):

$$Normalized\ indicator = \frac{indicator\ result}{reference\ system}$$

Examples of reference systems may be "geographical area over a reference year" (e.g., the impact of the European Union for 2010); or "geographical area over a reference year on a per capita basis" (e.g., the impact of a European citizen in 2010) and no reference system is unequivocally superior to another (ISO/TS 14074; 2022). Results expressed per year or per person, make the results easier to understand, especially for non-LCA-experts, and thus can be used to support the communication of results.

It is fundamental to underline that normalization results without weighting cannot be used for the interpretation of high or low environmental concerns across impact categories (ISO/TS 14074; 2022), in other words, normalization provides information on relative significance and does not define importance in respect of other impact categories.

Besides assessing the relative magnitude of different impact category results and aiding in the communication of results, normalization serves as a preliminary step before weighting, as it adjusts the characterized impact results to a scale that is suitable for subsequent weighting and facilitates comparisons across different impact categories (Pizzol et al., 2017).

- **Normalization approaches**

Normalization can be performed at midpoint and endpoint level (Roesch et al., 2020) and through different approaches.

To date, various methods for performing normalization exist in literature, as reported in in Pizzol et al. (2017). The three main normalization approaches, namely: internal, external, and absolute are hereby described and illustrated in **Figure 6**.

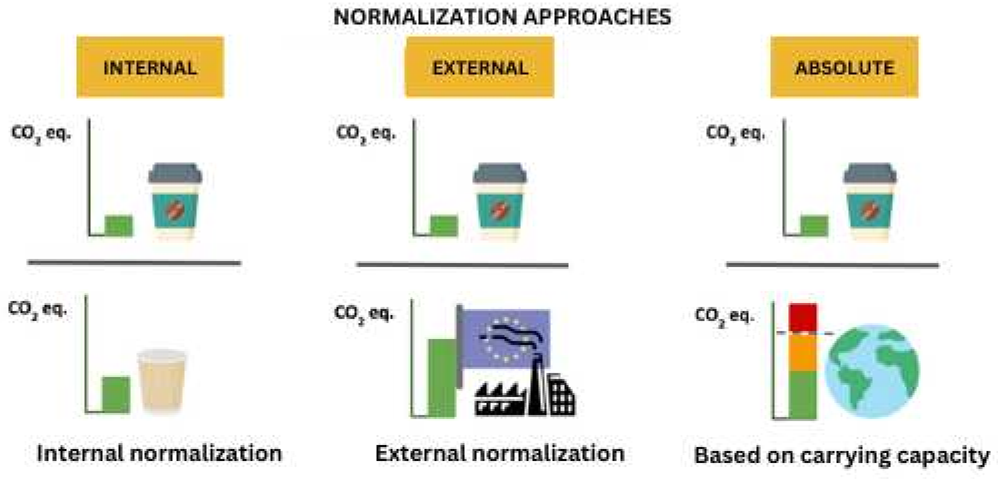

Figure 6 *Normalization approaches category (adapted from Cavenago, et al., 2021)*

1. *Internal normalization approach*

It describes the situation where the selected reference system is one of the options under study, such as a base case or best-case scenario (ISO/TS 14074; 2022). In this case, normalization can help to understand whether the order of magnitude of the results is plausible and thus help avoid macroscopic mistakes (e.g., over / underestimation of results) (Pizzol et al., 2017).

The advantage of internal normalization is that it is done from only the data already available to the study since the reference system is one of the products studied or a function of them (Cavenago, et al., 2021). By applying the normalization step, the normalized impacts related to the different impact categories are thus reported on the same (dimensionless) scale and could be aggregated to provide an overall environmental impact score of the products. However, as defined by Norris (2001), there are drawbacks to aggregating normalized impacts by weights according to the internal approach, as the weights, usually determined at a generic level and thus independent of the analyzed study, may be incongruent with the internal normalization, which is study-specific (Norris, 2001). Other internal normalization approaches exist and are part of multi-criteria decision analysis (MCDA) methods.

2. *External normalization approach*

It describes the situation where the selected reference system is external, thus independent, to the product system under study (ISO/TS 14074; 2022). Examples are (i) global normalization, in which characterized indicator results of the system(s) under study are divided by the characterized indicator results of the total activities taking place in the world over the reference duration (Pizzol et al., 2017). Or (ii) a regional production-based normalization, in which the reference system is represented by all territorial activities in a region or a country. Consumption-based territorial normalization retains, instead, a very marginal role in LCA applications (Pizzol et al., 2017).

As in this approach normalization factors are derived from data external to the study, ensuring robustness is essential (Cavenago, et al., 2021). Several biases can occur precisely related to this aspect. Indeed, the discrepancy between the life cycle inventory of the product system studied and the life cycle inventory used for the calculation of the normalization reference leads to inconsistencies, which will ultimately result in misleading findings (Roesch et al., 2020).

Benini and Sala (2016) summarize the main issues concerning external normalization by highlighting four main aspects: (i) the consistency of the spatial extent of the reference system with the system under study (global, country, region or catchment area), (ii) the consistency between the reference year and the year of the study, (iii) methodological differences between the studied and reference systems, and (iv) incomplete inventories (e.g. for toxic emissions) and missing/incomplete impact categories (Benini and Sala; 2016).

To increase consistency and improve the above-mentioned weakness, the Joint Research Centre of the European Commission, together with several researchers, is making a significant effort. An example of the application of external normalization is the case of the Product Environmental Footprint (PEF) methodology, illustrated in section X.

3. *Normalization based on carrying capacity*

This method has recently emerged and aims to adopt a more ecological perspective, prioritizing the carrying capacity of the planet rather than current levels of, for example, emissions and resource use (Pizzol et al., 2017). In this way, the aim is to assess the “absolute sustainability” of the considered product and not relative value.

In one respect, this method can be seen as an external normalization, where the reference system is the limits of the planet (Bjørn and Hauschild, 2015). Whereas, on the other hand, it can be debated whether this method is actually a normalization method and not rather a distance-to-target weighting (Pizzol et al., 2017). The normalized results would then represent the system's contribution to the current impact levels, and the results after applying load capacities would reflect the distance (over or under) of the normalized results from the thresholds (Pizzol et al., 2017). To what extent currently estimated carrying capacities and planetary boundaries reflect real ecological thresholds is a matter of debate (Mace et al., 2014; Nordhaus et al., 2012), and likewise the scientific basis of planetary boundaries and the application and feasibility of this normalization approach. Thus, further research is required on this content.

3.2.1.2 Weighting

The weighing process consists of establishing the relative importance of each impact category in relation to the others. This relative importance is expressed through numerical factors, named: weights, which are based on value choice.

By providing a single score and enabling the ranking of alternatives, weighting helps the decision-maker in situations where the tradeoffs of the impact categories results do not allow one to choose the best alternative among the others or an improvement among possible ones (Pizzol et al., 2017).

Weighting can be done at the midpoint or endpoint level and in general, the weighted impacts can be previously normalized or not, with the constraint that to be able to sum the weighted impacts and obtain a single score, they must be expressed in the same unit of measurement (Cavenago, et al., 2021).

The multi-dimensionality that characterizes the results of an LCA can thus be synthesized through aggregation. Specifically, in the case of LCA, the multi-dimensions are represented by the impact categories, which are aggregated by a linear weighted sum of the normalized impacts, as shown in the following equation:

$$Weighted\ result = \sum_{i=1}^{n} \frac{IC_i}{NF_i} \cdot w_i$$

Where: *i represents* the progressive index of impact categories, *n is the* number of impact categories considered, IC_i *is* the characterized impact, ICi/NF_i is the impact normalized by the normalization factor NF_i and w_i *is* the relative weight. As evident, this phase is unavoidably influenced by decisions that aren't solely grounded in science. Indeed, since these value choices are based on ethical, political, and social reasons, different individuals, organizations, or societies may evaluate them differently, leading to significant subjectivity in the analysis. This is the primary criticism directed towards the weighting phase, often resulting in its exclusion from LCA studies aimed at presenting comparative claims to the public (ISO, 2006a; ISO, 2006b).

- **Weighting approaches**

Various methods for defining weights have been developed over the last decades, each with its own technical and theoretical pros and cons. The four main weighting methods are binary weighting, distance to target, panel weighting, and monetary weighting (Pizzol et al., 2017) as presented in **Figure 7**. These approaches will be hereby described.

***Figure** 7 Weighting approaches (adapted from Cavenago, et al., 2021).*

1. *Binary approach:*

Among the binary approaches, the most widely used to date, are the *footprint approach* and the equal weights approach (Cavenago, et al., 2021). The former consists of assigning all the weight to a single impact category and neglecting the others; this is done, for example, with the calculation of a product's carbon footprint (CF), an approach described in detail in the technical reference standard (ISO 14067) and defined in detail in Chapter 3.1.

In a second binary approach, called *equal weighting*, all categories are instead placed on the same level of importance, and thus each of them is associated with the same weight. Equal weighting is not science-based and could be mistaken for a "neutral" weighting while it is not (Pizzol et al., 2017). Indeed, applying no weight is a weighting system as well, as the same significance is given to all categories (Zanghelini G.M. et al., 2018).

The first technique comes with an important drawback, namely the problem of burden-shifting that LCA tries to overcome. Whereas the criticism made of the second approach is that it does not give due importance to the most relevant or urgent aspects (Cavenago, et al., 2021).

2. *Distance to target approach:*

In the distance-to-target approach (Castellani et al., 2016; Muhl et al., 2020), the weights given to the different impact categories are calculated based on how close the current impacts of the system understudy are in relation to the socio-political goals that have been set for that system concerning the considered category. For example, if the impacts of the European Union reference system on climate change significantly deviate from the set targets for a given year, the weight assigned to the climate change category should be high (Cavenago et al., 2021).

This approach may seem intuitive in a decision-making context as it utilizes policy targets to determine weights. However, since all targets are treated equally, there is a question as to whether the distance-to-target method truly acts as a weighting method in terms of ranking impact relevance or if it functions more as a normalization method (Pizzol et al., 2017).

The advantage of this approach is that as being based on sociopolitical targets, it should reflect the consensus of the majority. However, the risk is that impact categories for which ambitious targets do not currently exist may be overlooked. Additionally, the approach as currently implemented does not account for damage, which may be a problem. Indeed, a change in impacts significantly below a target may still result in substantial damage, as well as a change in impacts far above a target may incur minimal additional damage, and this is not considered (Pizzol et al., 2017).

In conclusion, it is important to emphasize that targets are not valuable *per se* but obtain value from their role in achieving the overall goal (Pizzol et al., 2017). They therefore play an important role in policymaking, but in this context, it is recommended to evaluate the weight of damage itself, rather than with respect to a specific target of damage.

3. *Panel approach:*

In this approach, a panel of people is used to establish weighting factors for different environmental impact categories (Pizzol et al., 2017).

The panel considered can vary widely in terms of representativeness and LCA experience. Although it is possible to have a panel that is representative of society as a whole, in practice panelists frequently only reflect a portion of all societal views on the issue. In industry, for instance, different sectors have different hotspots and priorities, and decision-makers may serve as panelists themselves or delegate this task to subject matter experts. In such cases, the composition of the panel should reflect the decision-making scenario at hand. Whereas, if the aim is to be as representative as possible, using panelists from a single category is not the right solution.

This is the basis of the criticism that this technique is excessively subjective.

Further biases may also arise from how preferences are derived. Generally, panelists' preferences are collected via questionnaires, which opens up a number of issues, including mainly how the questionnaire is structured, and the cognitive limitations of panelists (e.g. people tend to give more importance to what they understand best, responses may be skewed according to the difficulty of understanding certain environmental issues, and more).

4. *Monetary approach:*

In this kind of approach, the weights are expressed using economic value as the unit of measurement and are defined, for example, based on the economic damage resulting from the environmental damage, or on the quantification of the costs necessary to prevent the damage itself, or based on how much the population is prepared to spend to reduce the impacts (Cavenago et al., 2021). A general advantage of this weighting approach is that monetary units may be more familiar and easier to relate to for most audiences, compared to other weighting methods (Pizzol et al., 2017). On the other hand, some people may object to its application for moral grounds, such as believing it is improper to put a monetary value on things like biodiversity or human life (Ludwig 2000). However, it is not correct to say that the absolute value of e.g. human life is evaluated, as what monetary evaluation does, is more a matter of determining the willingness to pay for marginal changes in the availability of non-market goods (Pizzol et al., 2017).

- **Cross-methods considerations**

    - ➢ Midpoint vs endpoint

Elementary flows of the LCI are assigned to the impact categories to which they contribute and assessed according to the degree of their contribution and represent the potential impact at the midpoint level. Endpoint indicators, on the other hand, are representative of different topics or "Areas of Protection" (AoP) that "defend" society's interest with regard to human health, ecosystems, or planetary life support functions including ecosystem services and resources, for example (Hauschild, M.Z. et al. 2018). Weighting may be applied at different points of the environmental mechanisms. As a result, weighting can concern inventory indicators, midpoint indicators, or damage indicators (ISO/TS 14074; 2022). Thus, it is possible to obtain single scores performing weight allocation both at midpoint and endpoint level.

In case a) the single score is defined by directly using impact category indicators (Cj) through a weighting phase: $SS = \mathcal{F}(C_j; w_{C_j}$. Where SS = single score, Cj = impact category indicator for impact category j, and w_{C_j}= weighting factor of impact category j.

In case b) the single score is calculated using damages indicators (Di) through a weighting phase: $SS = \mathcal{F}(D_i; w_{D_i})$. Where SS = single score, Dj = damage indicator for damage category i, and w_{C_i}= weighting factor of damage indicator i.

Choosing between midpoint or endpoint indicators to perform the weighting process is a controversial aspect and is sometimes case-specific. In the table below, key advantages of applying weight at midpoint and endpoint respectively are illustrated in **Table 1**.

Table 1 *Comparison between Midpoint and Endpoint for weighting*

Use of impact category indicators (midpoint level)	**Use of damage indicators (endpoint level)**
The uncertainty of the impact is lower at impacts level, as additional modelling elements are used to expand or link midpoint indicators to one or more endpoint indicator (Hauschild and Potting, 2005; Finnveden et al., 2009; Hauschild, M.Z. et al. 2018)	Performing weighting at the final damage level reduces the number of valuations that need to be made, and thereby reduces the risk of inconsistencies between the larger number of different valuations that would otherwise be required to be performed at the midpoint level in the impact pathways (Pizzol M., et al. 2017).
The level of detail decreases from midpoint to endpoint level (Roesch et al., 2020).	In panel weighting methods the understanding and ranking of several midpoint categories may result in being more challenging for respondents than in the case of few endpoint ones (Huppes and Van Oers, 2011).

As each case is specific, different needs may arise. All things considered, It is recommended to not perceive midpoint and endpoint characterization as two options to choose from, but rather perform an LCIA on both the midpoint and endpoint level (using an LCIA method that provides both) to support the interpretation of the results obtained and which complement each other (Hauschild, M.Z., et al. 2017).

- Uncertainty in weighting

The weighting factors are generated based on value choices (ISO/TS 14074; 2022). Individuals are influenced by various factors when called upon to express their values, primarily by context, followed by their experiences or knowledge. Additionally, preferences may change over time, as do the corresponding weighting factors. Consequently, established weighting factors can change significantly depending on the approach, how they were generated, the time scale, the region, and the set of indicators considered (ISO/TS 14074; 2022). Furthermore, different weighting sets may yield different results. For that reason, it is important to perform uncertainty and sensitivity analysis, when performing the weighting phase.

Hence, there is a need, on one hand, to be as transparent as possible and, on the other, to create a system that is as representative and harmonized as possible.

Moreover, when performing the weighting uncertainty analysis should be conducted.

3.2.1.3 The debate on single score

There is a strong demand for simple, understandable, and clear LCA outcomes to support decision-making, especially in the context of policy-making or company management (Kägi et al., 2015). However, despite the practicality of synthesizing the information in a single score, it represents an issue highly debated in the LCA community, still considered open (Kägi et al., 2015). The discussion focuses on how to present results in the most clear and easy-to-interpret way possible, whether through midpoint indicators, endpoint indicators, or even through a single score.

In the case of presenting results at midpoint level, potential impacts are expressed according to all impact categories, whereas in the case of endpoints, they are aggregated into Areas of Protection (AoP) and contain additional uncertainty due to the aggregation of results. When opting instead for a single score, further weighting has to be done, increasing the subjective component and uncertainty (Kägi et al., 2015).

The heart of the matter therefore focuses on the advantages and possible concerns of using a single score.

On the one hand: there is the need and necessity to present the results clearly, facilitating the decision-making process and the communicability of the results. Some authors even argue that only single-score methods provide an overall picture and help summarize a comprehensive analysis (Roesch et al., 2020; Känzig J., 2020). On the other hand, there are concerns about the transparency of single scores and whether they have a scientific basis.

In many cases, however, the results at midpoint level do not give clear answers, but there is a trade-off situation in the results. In this case, decision-makers are forced to do their own weighting or to choose midpoint categories according to their own subjective interests, resulting either in no weighting for all outcomes or extremely subjective weighting. In such cases, an endpoint or single score evaluation especially can provide decision support, based on a more scientific and transparent structure (Kägi et al., 2015) and thus be more robust and secure.

All considered, it can be said that despite skepticism about the adoption of a single score, research on this topic has definitely intensified in recent years, resulting in a broader acceptance and increased use of aggregating methods. Additionally, as LCA is evolving towards the inclusion of the other dimensions of sustainability, such as the economic or social dimension, the necessity of an aggregation strategy will be increasingly needed (Kägi et al., 2015).

In conclusion, accurately designed single-score results (through weighting) have to be preferred over single-issue results (such as carbon footprints), as the latter may neglect important environmental aspects related to the analyzed products or services. Meanwhile, it has been strongly recommended that LCA practitioners go beyond the limits imposed by the ISO standard and integrate endpoint indicators and single scores with midpoint indicators in their LCA assessments, which should never be neglected (Kägi et al., 2015). This approach should help to avoid, or at least minimize, erroneous conclusions that may be drawn, thereby increasing the credibility of LCA results and their usefulness in a more transparent decision-making process (Kägi et al., 2015).

Do present aggregate single scores provide decision support?

Currently, there is no universally recognized optimal method for weighting to derive single scores (Soares et al., 2006). Moreover, a debate persists regarding whether weighting factors should consider site-specificities or if there should be broadly accepted values. In general, the weighting methods closest to a scientific approach must be selected (Kägi et al., 2015).

Kalbar P.P. et al. in their article on weighting and aggregation in life cycle assessment question whether the current way of aggregating results into single scores in LCA provides adequate decision support. (Kalbar P.P. et al., 2016). The study analyses the current prevailing method for obtaining single scores in the LCA by analyzing the existing calculation procedures and points out that the linear weighted sum method (ReCiPe method) currently used has methodological weaknesses and is unable to consider the effect of weighting schemes and thus cannot realistically represent the perspectives of stakeholders (Kalbar P.P. et al., 2016). Furthermore, the prevailing method of calculating single scores does not take into account either the effect of so-called dominant alternatives (i.e., alternatives that have high values in all endpoints) or the interdependence of aggregated indicators (Kalbar P.P. et al., 2016).

The authors therefore propose a new way of quantifying individual scores, by proposing the use of a multi-criteria method, specifically TOPSIS. Their analysis showed the effectiveness of one such proposed new method, TOPSIS, for obtaining single scores (Kalbar P.P. et al., 2016).Integration between LCA and MCDM is indeed becoming increasingly popular, and much research is being conducted in this area. The ways of integrating LCA and multi-criteria analysis are investigated in detail in Chapter 3.3.

3.2.1.4 Key findings and recommendations

Normalization and weighting represent an open challenge in the context of LCA and currently, there isn't a universally accepted method for performing these two steps, nor a method that can be used in every situation (Pizzol et al., 2017). However, some recommendations for good practice exist and will be collected here.

In general, it is crucial to document and justify the choices made, including whether internal or external standardization is used, the normalization system employed, the weighting sets, and their derivation methods. Clear and transparent communication, along with attention to method reproducibility, is essential. LCA practitioners should also be aware of the potential risks and benefits associated with these steps and include uncertainty and scenario analyses whenever possible (Pizzol et al., 2017; Roesch et al., 2020).

Regarding normalization, several recommendations can be made (Pizzol et al., 2017; Roesch et al., 2020):

- Evaluate whether normalization is actually needed.
- It is important not to overuse normalization and not to confuse it with weighting: the comparison between categories to resolve the trade-off cannot be done at the level of normalization but requires weighting. It is also incorrect to exclude impact categories that are deemed too high or low in relation to the other categories after normalization.
- In the case of external normalization, extreme care must be used to address any potential inconsistencies (the model approach, the inventory analysis of the two systems: the one under consideration and the reference system, the source of the data, the characterization models, need to be properly evaluated and compared).

Meanwhile, for weighing the recommendations are (Pizzol et al., 2017; Roesch et al., 2020):

- Weighting damages has to be prioritized over distance-to-target.
- Stakeholders' involvement is relevant when creating the panel.
- Methods that include all impacts should be preferred. If, however, weights are applied or only one category is chosen (as in the case of footprint) then it must be clearly stated.
- Decisions made in goal and scope should not adapt to the weighting sets, but weight should be based on the goal and scope of the study.

Overall, it is evident that further development is needed in this area. Future steps, as highlighted by Pizzol et al. (2017) and Roesch et al. (2020), include developing techniques to estimate the uncertainty of normalization and weighting factors, improving the basis for normalization through the development of comprehensive and consistent global emission and resource consumption inventories, refining consensus methods, and regularly updating and expanding normalization and weighting factors to incorporate new findings and more precise data.

3.2.2 Normalization and weighting: current applications

As previously defined, the normalization and weighting phases, although considered optional in LCA, are two steps widely used by LCA practitioners. The need for more easily interpretable results has indeed led to many efforts being made and still ongoing in an attempt to further develop and improve these phases.

Many examples of normalization and weighting methods can currently be found in the literature and there are several examples of methodological developments or new approaches to this topic. In this chapter, it has been chosen to delve into two cases, where normalization and weighting are adopted, considered particularly relevant.

- **Product and organization Environmental Footprint**

An example where normalization factors and sets of weights are provided and used is found in the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) methodologies.

Responding to the necessity of a standardized approach and the harmonization of methodologies for calculating the environmental impacts of products and organizations, the European Commission issued a Communication on building a single market for green products in 2013 (EC, 2013a) and Recommendation 2013/179/EU (EC, 2013b) on the use of common methodologies, namely PEF and OEF for products and organizations respectively.

The objective is to establish a unified methodology for calculating impacts and environmental reporting, thereby enhancing the comparability of results and simplifying reporting across Europe.

The PEF (and OEF) methodology, based on Life Cycle Assessment (LCA), introduces an additional framework and specific guiding rules to ensure its application is more consistent and shareable.

Normalization and weighting phases are discussed in the methodology, and indeed are the result of great work by the European Commission and the Joint Research Centre.

PEF methodology requires the LCA results to be presented in 16 impact categories (according to the EF 3.1 method). For each of these, specific normalization factors and weights have been defined (a table collecting normalization factors and weights can be found in the Annex).

External normalization approach is adopted in this case, with global values as reference systems. Indeed, impacts of the entire planet for the year 2010 were considered as reference values, then divided by the number of inhabitants to express the impact per capita.

In terms of weighting, the weights were derived from a hybrid approach: panel and evidence-based.

The weights proposed to date by the European Commission are the result of a combination of different sets of weights obtained using different approaches. Specifically, four sets are considered:

1. The first was obtained by selecting a sample of 2400 citizens from various European Union countries aged between 18 and 65 years and administering to them a questionnaire on the perceived importance of different impact categories. This constitutes a panel weighting approach with a panel of non-experts in LCA.
2. The second set was obtained by administering the same questionnaire to 512 LCA experts. This constitutes a panel weighting approach with a panel of LCA experts.
3. For the third set, expert technicians from various impact categories were involved and were asked to evaluate certain characteristics, such as reversibility and intensity of the impacts caused, and their effects in terms of spatial and temporal distribution, considering scientific evidence.
4. The fourth set used assigns a weight to each impact category that is directly proportional to the robustness of the characterization method adopted for that category.

The normalization and weighting factors derived from these studies are the result of an incredible effort by the European Union and aim to provide a recognized and robust tool that can be considered as a reference at the European level.

The PEF and OEF methodologies are increasingly gaining relevance and importance and will be fundamental in the coming years with the introduction of the European regulation on eco-design.

- **The use of weighting in “Made Green in Italy”**

Another significant application of weighting can be observed in the Italian labeling scheme “Made
Green in Italy” (MGI). MGI is a national voluntary labeling scheme for the evaluation and communication of the environmental footprint of Made in Italy products, established under Article 21, paragraph 1 of Law No. 221/2015, and managed by the Ministry of the Environment and Energy Security. The scheme is founded on the Product Environmental Footprint (PEF) methodology as defined by the European Commission in Recommendation 2013/179/ in order to ensure harmonization of assessment methods at the European level.

The core idea behind MGI is that a widely accepted national voluntary labeling system can enhance communication regarding the environmental impact of Italian products. Moreover, it can foster the competitiveness of the Italian manufacturing system both domestically and internationally, while also promoting coordination among existing national environmental policies (Roesch et al., 2020).

Specifically, the MGI label classifies products into three categories: A, B, and C. Here, B serves as the benchmark acting as the reference point for defining performance classes, with A and C representing values superior and inferior to the benchmark, respectively. The label is assigned to products of classes A and B to make them recognizable to consumers, thereby encouraging more informed choices. In the case of class B products, companies are required to commit to improving their environmental performance.

In this context, the single score is utilized to define the benchmark, calculated as the sum of results from the three most relevant environmental impact categories identified through PEF methodology according to Product Environmental Footprint Category Rules (PEFCR).

The characterization, normalization, and weighting factors employed are those developed within the framework of PEF initiatives. In this case, the single score is not communicated on the label; instead, only the A or B class is displayed to consumers, making the product's environmental quality easily discernible.

It's crucial to note that the use of a single score does not imply that midpoint indicators are not displayed. Midpoint indicators are essential for verifying and supporting the direction of implemented improvements. Additionally, outcomes should always be interpreted within the specific context, regardless of the method's robustness.

In this case, normalization and weighting steps are not only useful but also mandatory in implementing the scheme. The scheme “Made Green in Italy” is an example of how having a single score can facilitate policymaking and provide benefits in terms of comprehending the results. Similar approaches are adopted in other European countries, each with its own pros and cons. Overall, what is evident is the need to have a support in the interpretation of results for decision-makers and a harmonized tool to obtain comparable results.

3.3 Multicriteria Decision Analysis (MCDA)

Making a choice involves analyzing the problem from various perspectives, comparing the consequences of any action taken, and finally deciding which is the most effective path; thus, the act of choosing is inextricably linked to a variety of aspects that must be considered and handled.

For many years, the only approach taken to solve decision-making problems was to consider systems as having a single criterion, by merging all the different aspects of a problem into a single objective, losing its original multidimensional nature.

This way of proceeding is not only limited, but it is also somehow not natural. Perfect rationality, simplicity, and quantifiability are not always necessarily good. Indeed, in complex problems linear optimization may be a too rigid function and it may be challenging to identify a single objective or quantify it. In such cases, more complex programming models should be adopted by considering not only one but several criteria. Indeed, in operation research, the distinction between a single objective and multiple objectives is based on the idea that in a complex decision problem, there may be a plurality of relevant aspects, viewpoints, or decision-makers that make it challenging to trace back to a single objective.

Therefore, although single-criteria analysis remains valid in some cases, over the past three decades, a new approach has been developed and attracted the attention of researchers and practitioners: the multi-criteria approach. As Howard Raiffa suggested in 1969, presenting his theory of multi-attribute utility, "if something is considered to be absolutely valid, it is certainly so for more than one reason." The basic assumption of these techniques is that one can decompose the object of analysis into simple factors. The problem is broken down into meaningful and manageable components, which are then solved through well-defined methodologies.

MCDA is a discipline that encompasses several disciplines, from mathematics, management, and informatics, to psychology and social science, with an ongoing development (Zavadskas K, et al.,2019).

3.3.1 MCDA definition and main characteristics

Multicriteria analysis (MCA), sometimes defined as MCDM: multi-criteria decision-making, is a sub-discipline of operations research. It comprehends a whole set of tools evolved to support the Decision Maker (DM) (the one who is required to produce choices) to solve in a coherent way complex decision problems characterized by a multidimensional nature.
The diversity of aspects considered may encompass the number of stakeholders involved, the variety of criteria under consideration (which may even contradict one another), the different relative importance assigned to each attribute, and other factors that contribute to the complexity of the problem.

The key goal of these methods is not only to establish satisfying solutions but mainly to provide a consistent structure for decision-making processes and to gain insight and knowledge about the problem itself (Figueira, Greco, and Ehrgott, 2016). Typically, the situations demanding the evaluation of such conflicting trade-offs do require any unique optimal solution, but it looks for various preferences that a model can generate for “what-if” analysis. This helps the decision makers to address the problem more holistically by considering various factors that are usually neglected in traditional OR approaches (Thakkar, J.J., 2022).

A broad variety of different problems are part of the multi-criteria decision-making (MCDM) domain. The problems in this area can be broadly classified into two categories (Thakkar, J.J., 2022):

- MADM: multiple attribute decision-making, which concentrates on problems where the decision maker (DM) has to select/prioritize/rank a finite number of predetermined alternatives (Zavadskas K:, et al.,2019)
- MODM:) multiple objective decision-making, which naturally involves several competing objectives that are required to be optimized simultaneously and alternatives are non-predetermined (Zavadskas K, et al.,2019).

Since the purpose of this thesis is to identify the optimal solution from a set of alternatives, it has been chosen to delve into MADM only.

3.3.2 MCDA structure and basic elements

- **Basic elements**

Numerous methods for multi-criteria decision-making exist with different structures and characteristics, but they all share the same basic element and general process.

The basic elements that constitute MCA methods are: (1) a finite set of alternatives or actions, that constitute the object of the decision; (2) a finite set of criteria or attributes that allow the evaluation and comparison of the alternatives; (3) the problem itself, which be seen as the reason why performing a multicriteria analysis.

In more detail:

- *Alternatives* are the various options or choices available for evaluation. These, represent different strategies, or solutions that could potentially solve the problem under study. Choosing what alternatives to include is usually the first thing done after setting the scope of the study and choosing the MCA methodology, as distinct alternatives require distinct criteria (Lindfors A., 2021). The purpose is to generate a representative sample of all potential alternatives in order to ensure that a sufficient number of alternatives are covered without imposing an excessive analytical burden. A fundamental aspect is that the alternative selection process is transparent and understandable to readers and decision-support users (Bausch et al., 2014).
-
- *Criteria* are the tool through which the various alternatives are compared to each other in relation to the decision maker's objective. More precisely, a criterion is a real function *f* such that it is meaningful to compare two alternatives *a* and *b*, from a particular point of view, solely based on the values *f(a)* and *f(b).* Each criterion is associated with a weight that determines the relative importance of that criterion to the decision-maker concerning the objective.

In addition to these basic elements, it is important to note that the decision-maker (or decision-makers) play a fundamental role and can be considered as a fundamental component of the process. Indeed, MCDM methods have the characteristics of placing the decision-maker at the center of the process. They are not automatable methods that lead to the same solution for every decision-maker, but they incorporate subjective information, also known as preference information, provided by the decision-maker, and this influences the results of the analysis (Zavadskas K:, et al.,2019).

Note that the decision-maker is defined as the one who has to make the decision, which practically involves one person or a group of people that participate in the decision problem (stakeholders).

Authors suggest that stakeholders should ideally participate in all aspects of an MCA, including determining the scope, selecting alternatives, choosing the interpretation method, and so forth. This involvement should not merely be instrumental, where stakeholders are utilized solely as a means to an end, such as finding weights or criteria, or as a data source (Lindfors A., 2021; Baumann et al., 2019). Indeed, the involvement of stakeholders throughout all phases will make them feel ownership over the results produced, which can increase their likelihood to act on the results (Lindfors A., 2021). This is especially true in the case of sustainability assessment when stakeholders are called to act for improvement. Moreover, it is suggested to include a wide and heterogeneous group of stakeholders as possible, not only people with technical experience and knowledge (experts), but a wider set of participants, such as potential users of a product, citizens of the studied community, or local and regional politicians (Baumann et al., 2019).

The problem definition, the alternatives, the criteria, and the people involved in the decision can be all considered as inputs of the MCDM basic process (Guitouni and Martel 1998), dealing with the comparison of alternatives in some criteria under a specific problematic to produce an output, that is a compromise solution.

The term *compromise solution(s)* is underlying a fundamental aspect of the multicriteria analysis. Indeed, although the core objective of MCDM is to support decision-makers to make better decisions, the complexity involved in the decision process and the limitations of problem structuring (e.g., insufficient information, uncertainty) may lead to not the better solution/alternative but to a compromise solution. In other words, the solution for the decision problem is not the optimal one but a satisfactory one (Guitouni and Martel 1998). This is because in general, there is no single decision that is simultaneously the best from all perspectives; therefore, the term "optimization" does not find relevance in this context. In contrast to other operations research techniques, multicriteria methods do not aim to find the "objectively best" solution, but the solution that has an overall positive impact on the system and does not try to optimize one part of the system at the cost of another (Thakkar, J.J., 2022) thanks to a critical analysis of the trade-offs.

- **Basic structure**

MCDM is roughly performed in two steps of analysis (Guitouni and Martel 1998) (both are overlapping and cannot be separated sharply from each other):

- *Construction phase*: which is about structuring the decision problem theoretically, that is i) definition of goals, scopes & alternatives, ii) identification and selection of criteria, iii) creation of stakeholder interface.
- *Exploitation phase*: which is about the practical steps to obtain the comprise solution and comprehend i) criteria performance measurement, ii) MADM criteria aggregation iii) comparison of results.
-

In practice, the basic process that converts inputs into the compromise solution(s) can be summarized into 4 main phases (Guitouni and Martel 1998): (1) *Structure the decision problem, (2) Model the preference, (3) Aggregation and evaluation of the alternatives and (4) Make recommendations.* These four generic phases are common to all methods as they form the fundamental structure of multicriteria analysis; however, the way they are executed is specific to each MCDM technique. A general scheme is proposed in **Figure 8**.

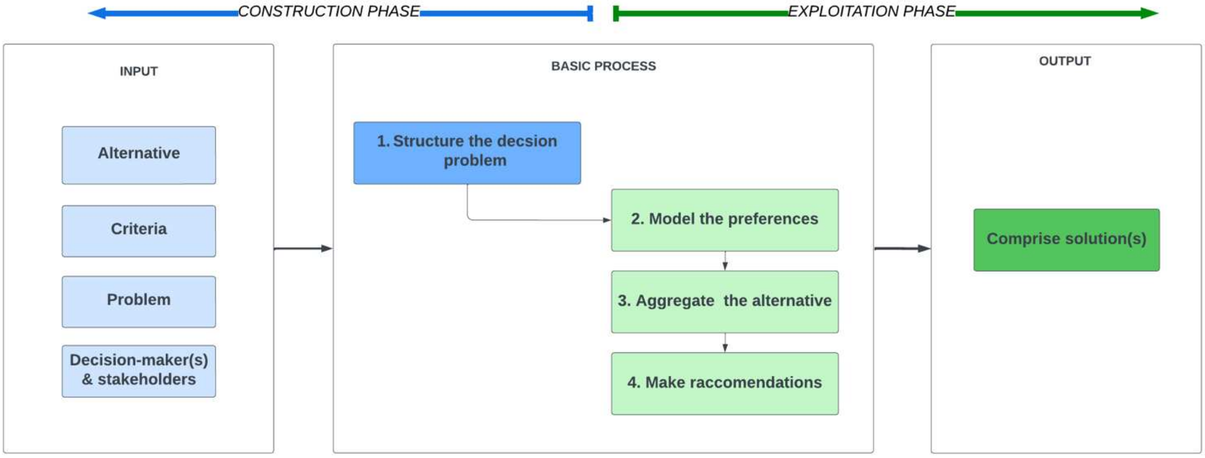

Figure 8 *MCDA basic elements and general structure*

1. Structure the decision problem

This involves the characterization of the decision-making situation, the different alternatives and their consequences, the family of criteria, the quantity and the quality of information available, the problem definition, and the identification of decision maker(s) and stakeholders involved. This step is crucial as the formulation of the decision problem is often more important than its solution (Angelo, A.C.M., 2021). Once the problem is understood and all the information collected, the evaluation matrix, can be constructed, which is the core of the analysis. The evaluation matrix is a two-dimensional matrix *mxn,* which crosses the n criteria with the m alternatives.

$$A = \{a_{ij}\}_{nxm} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{m,1} & \cdots & a_{m,n} \end{bmatrix}$$

Each element a_{ij} of the matrix represents the value of the alternative A_i (with i=1..m) for the criteria C_j (with j=1..n). In other words, the performance measurement of an alternative with respect to a selected criteria.

The *mxn* indicators can have different units and can comprehend quantitative and qualitative attributes (evaluation problems arise every time the alternatives are not measurable numerically but are evaluated by subjective judgments).

The evaluation matrix may also be defined as a “bidimensional checklist” as it allows the clear visualization of the information characterizing the problem.

Its construction can be quite complex and depends on the problem under consideration. Generally, it is made through a "forward" hierarchical type of procedure, that is, starting from the objectives to go into the details of the criteria or conversely a "backward" hierarchy from a list of criteria to the definition of the objective.

As the criteria usually have different units of measurement, it is necessary to normalize the decision matrix comprising criteria with different units of measurement to obtain a comparable scale of the criteria values. There are numerous procedures available for normalization, that encompass linear standardization or value (utility) functions. The normalization procedure will be defined according to the problem under study and the MCDM method chosen.

2. *Model the preference*

This involves expressing the preferences of the decision-maker(s) and assigning weights to the criteria. This phase may affect the MCDM process and its solution as the decision makers influence the decision-making process and they are also influenced by it (Guitouni and Martel 1998).

Weights are dimensionless numerical values that express the importance that each criteria has for the decision-maker in the context of the problem studied.

This is one of the most crucial phases of the analysis and is specific to each MCDM method.

Two main classes of techniques for weight assignments exist:

- *Direct assignment:* it's the simplest method, yet also the most uncertain. Weights are assigned directly based on a predetermined scale of scoring (e.g., 1 to 100, 1000, etc.). The result of this direct assignment is a vector $W = [w_1; \dots; w_n]$ with n equal to the total number of attributes characterizing the decision-making problem. While this method is straightforward and intuitive to use, it has some important disadvantages.

- *Comparison in pairs:* criteria are compared in pairs and a relative score is assigned. Psychologists argue that it is easier and more accurate to express a preference between only two alternatives than simultaneously among all the alternatives (Ishizaka, A. and Nemery, P., 2013). A matrix of paired comparisons is built and the values of each row of the array are then aggregated into a final vector of weights using specific functions (e.g. maximal eigenvector, least squares..). By delving deeper into the methods in chapter X. this procedure of assigning weight will be described in greater detail.

3. Aggregation and evaluation of the alternatives

Alternatives are evaluated and ranked based on how they perform on all weighted criteria.
The basic mechanism underneath the ranking calculation is at first to combine weights and standardized indicators for any alternative and then compare alternatives to each other based on values obtained. This way alternatives can be ranked based on their final value obtained.

4. Interpretation and recommendations

Here results are interpreted, and throughout the overall process of knowledge construction, the decision-maker can identify the solution. This stage goes beyond simply identifying the compromise option (Angelo, A.C.M., 2021), as it helps to analyze the robustness of the outcomes and get insight into the decision problem as a whole.
Sensitivity analysis can be performed here. This step, although optional, is recommended in case of uncertainty to ensure a proper evaluation of results.
Sensitivity analysis investigates how changes to the decision support model affect alternatives' performance, thus identifying the most sensitive components of the model that make the ranking vary.
There are three main types of sensitivity analysis regarding MCDM methods:

1. Method sensitivity: applying a different method for data standardization and (where possible) for computing final scores. It is performed to control the dependence of results on the calculation method.
2. Criterion sensitivity: adding or removing certain decision criteria. It ensures the validity of the adopted framework; more specifically, it allows us to identify redundant criteria or, worse, missing essential criteria.

3. Weight sensitivity (most applied): varying the merit judgments of certain criteria. It enables determining the degree of influence of each factor on the final decision.

Moreover, appropriate combinations of the second and third types of sensitive analysis allow the verification of different points of view of the problem.

3.3.3 MCDA methods classification

More than fifty methods belong to Multi-Criteria Decision-Making Analysis (Swarovski et al., 2019), each of which is characterized by distinct theoretical foundations and technical properties. Despite their differences, methods can be classified into distinct categories based on the reason for conducting the study, the aggregation procedure, and their characteristics. A general scheme is presented in Figure 9.

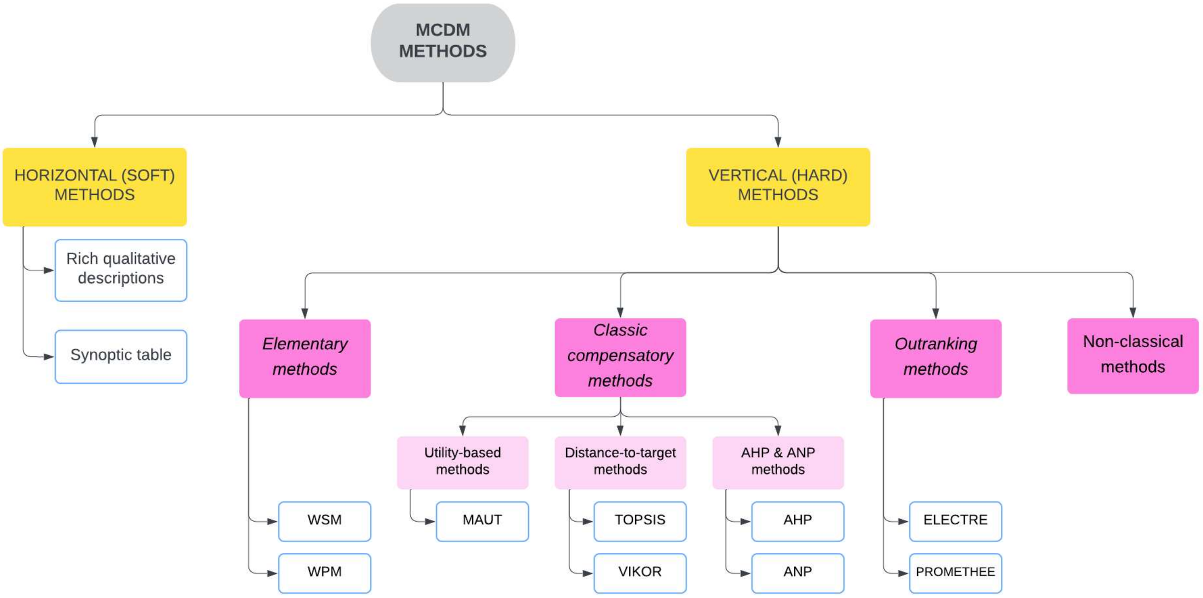

Figure 9 MCDA methods classification

According to the reason for which the analysis is conduced, methods can be classified as hard (vertical) or soft (horizontal) methods (Lindfors, 2021). Horizontal methods focus on decision support rather than decision-making, as they simply perform knowledge management and structuring, allowing the decision-maker to identify the most relevant aspect and perspective of the decision under study.

On the other hand, vertical MCA methods aim to help the decision-maker find the optimal solution. Thanks to mathematical rules the aggregation of criteria is performed and a final score or the ranking of alternatives is obtained.

Vertical methods are the most widely used in decision-making and are also the category of methods that, for the purpose of this thesis, will be used. So, the following will be analyzed in more detail as follows.

These methods can be further classified according to the aggregation procedure adopted to consider all criteria analyzed. Baumann et al. identified three main categories: elementary methods, classic compensatory methods, and outranking methods (Baumann et al., 2019). Some methods exist that do not fall into this classification and can be considered part of the non-classical approaches, which will be however not discussed. (

1. *Elementary methods*

   Elementary methods include (i) non-preference information methods without decision makers (e.g., dominance, maximin, maximax, lexico-graphic) and (ii) multi-attribute information methods with decision-maker input (e.g., weighted sum method, weighted product method). Usually, no compensation is accepted between considered criteria (Baumann et al., 2019). These approaches have the advantage of being basic and requiring minimal calculation work, but on the other hand, they do not evaluate tradeoffs or potential contradictions in the weights assigned to different criteria. These methods are mainly used for a preliminary evaluation, yet to obtain robust results, more sophisticated approaches are required. The main representative of this category is the Weighted Sum Method (WSM), which is widely used due to its ease of implementation.

2. *Classic compensatory methods*

   Classic compensatory methods, also known as the "American school," are based on assigning a utility value to each alternative. The total utility is the sum of marginal utilities that each criterion assigns to a considered action and is known as a single synthesizing criterion (Figueira et al., 2005). These methods allow to determine the order of preferences of the studied alternatives. Several commonly used methods belong to this group, such as MAUT (Multiattribute Utility Theory), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), and ANP (Analytic Network Process) and AHP (Analytic Hierarchy Process), which among these is the most frequently used. As compensatory methods, these techniques admit that a good performance for one criterion can easily be counterbalanced by another poor one and lead to the choice of a non-optimal alternative that might have a good performance on one specific criterion but a bad one on the remaining others (Baumann et al., 2019). Moreover, single synthesizing methods assume that weights are generally expressed in crisp/numeric values, however, translating vague human information into exact numerical values can be difficult when it comes to real-life situations.

3. *Outranking methods*

   Outranking methods, also known as the "European school," are based on eliminating particularly dominant alternatives. The problem is no longer addressed by defining an order of preferences, but by designing a preference relational system that synthetizes them (Roy, 2016). In this case, to assign greater importance to a criterion, concepts such as threshold, concordance, or discordance are used (Majumder, 2015).

   Typical methods are ELECTRE I, II, and III (Elimination and Choice Expressing REality) and PROMETHEE I&II (Preference Ranking Organization METHod for Enrichment of Evaluations). Concerns about outranking methods are centered around the dependency on rather arbitrary definitions of what constitutes outranking and how threshold parameters are set and later manipulated and that they lack an axiomatic basis (Guitouni e Martel, 1998).

Methods can also be examined according to how they address the incommensurability, compensability, and incomparability of data.

Indeed, multidimensionality is a fundamental aspect of MCA, which means that the problem is evaluated through numerous distinct variables.

The multi-dimensionality and diversity among knowledge areas can be described through three characteristics (Sadok et al., 2008): (1) incommensurability, the absence of a common measurement between two or more criteria; (2) compensability, that an advantage in one criteria can offset a disadvantage in another criterion; and (3) incomparability, when no rational comparisons between alternatives can be made (Lindfors A., 2021). When none of these characteristics is present a MCA is not necessary, and a single criterion would be adequate. However, in decision problems, criteria generally hold these characteristics, and this is what drives the use of MCA approach.

1. Incommensurability

The incommensurability of criteria derives from the multi-dimensional nature of MCAs (Lindfors A., 2021). Indeed, particularly when it comes to Sustainability Assessments (SA), the criteria representing the various areas related to sustainability are often incommensurable with each other. To overcome this problem, some MCAs provide analytical tools to allow comparison of alternatives by introducing common measurements. A distinction can be made between strong commensurability, where the common measurement is a cardinal scale of measurement, and weak commensurability, where the common measurement is based on an ordinal scale of measurement (Martinez-Alier et al., 1998). Aggregation methods, such as distance-to-ideal methods and utility-based methods provide a common cardinal scale of measurement, namely, utility or the distance to the ideal solution. Thus, multi-criteria problems become strongly commensurable. Meanwhile, outranking methods employ importance coefficients and produce an internal ranking of the alternatives as a result. Therefore, provide results based on weak commensurability (Lindfors A., 2021). Finally, by avoiding the use of numerical scoring or ranking, horizontal methods keep the criteria incommensurable.

2. Compensability

The second aspect of multi-dimensionality, which is compensability, is a fundamental aspect to be considered in MCA, as it is necessary and often unavoidable in decision-making, especially in policy decisions (Lindfors A., 2021). Compensability is particularly relevant in sustainability assessments, as compensation validates substitutions, thereby the application of weak sustainability (Lindfors A., 2021). Indeed, compensatory MCA allows for a large enough advantage in one area (for example, financial gains) to compensate for a disadvantage in another area (for example, environmental degradation). Thus, a compensatory MCA may legitimize alternatives that would substitute, in this example, environmental degradation for financial gains. In contrast to weak sustainability, strong sustainability ideally avoids compensatory measures as much as possible (Cinelli et al., 2014; Ziemba, 2019).

Therefore, MCA practitioners must evaluate whether, in the problem under study, compensation is acceptable and thus choose a method that is more or less compensatory accordingly. Yet, compensability is not a binary state; different MCA methods can be compensatory to varying degrees. Ziemba (2019) proposes that utility-based MCAs and distance-to-ideal MCAs are the most compensatory due to their elicitation of weights to make direct trade-offs. Outranking methods, on the other hand, are less compensatory because they use weights as importance coefficients. Including threshold values is one technique to lower the compensation level in MCA (Cinelli et al., 2014). This means that alternatives are rejected right away if their scores fall below or beyond a given threshold. These features are already present in the PROMETHEE and ELECTRE techniques, but thresholds can be used in any MCA method by simply adding them to the selected approach.

3. Incomparability

Finally*, incomparability* is an issue that all MCA methods seek to overcome (Lindfors A., 2021), as the end goal of performing an MCA is to make possible the comparison of the studied alternatives. In general, vertical MCA methods provide strongly comparable results.

3.3.4 MCDA methods selection

Despite the large number of MCDA methods, none is perfect, nor can be applied to all decision-making situations (Guitouni, A. et al., 1998). Every method has its assumptions and hypothesis based on which all theoretical and axiomatical development are made. Moreover, the great diversity of MCDA procedures, even though it may be seen as a strong point, can also be a weakness (Bouyssou, D., et al. 1993). Indeed, the massive number of methods, together with the lack of an investigative framework for choosing the appropriate procedure, leads to a lack of awareness about the method selection. As a result, many analysts and researchers struggle to clearly justify why they have chosen a particular MCDM method and consequently structure the decision problem according to the chosen method rather than the other way around, which could lead to misleading results. (Guitouni, A. et al., 1998).

This is shown in detail by Lindfors A. in his literature review on assessing sustainability using multicriteria methods, where he analyzed 280 articles on the topic. The findings reveal that only about half of the analyzed studies provide reasons why other existing MCA methods were not suitable for the purpose of their study, indicating a limited understanding of the MCA method selection (Lindfors A., 2021).

Although the absence of a defined setup for selecting the suitable procedure, some general considerations can be made.

The choice of MCDM methods should be (1) based on the decision problem situation (that is, the scope of the analysis, the stakeholders involved and their needs, the emergency of the decision…) and (2) should be able to handle properly the available input information (indeed, quality and the quantities of the information are major factors in the method’s selection).

In addition, to choose an MCDM method is to choose a kind of compensation logic, which has to be suited to the situation under study.

Lastly, although some argue that the modeling effort generally defines the richness of the output (Ishizaka, A. et al., 2013), it is not always true that complex methods drive better solutions.

Hottenroth H. et al. assessed the sustainability of the energy system transformation pathway with different methods: WSM, PROMETHEE, and TOPSI, characterized by a different complexity degree, compensation logic, and aggregation procedure. The authors defined that, the advantage associated with using a more elaborate method lies in the fact that each preference can be individually modeled according to more suitable mathematical functions and parameters; however, methods' complexity can make it difficult to trace steps, reducing the decision-makers' confidence. Therefore, the use of a simpler method can facilitate stakeholder participation and the understanding of the evaluation process.

All considered, the approach that many authors recommend is to use hybrid methods (Baumann et al., 2019). Combining different techniques can help overcome the limitations that individual methods would show if applied alone and thus would allow for more consistent results. Examples of such combinations are the use of AHP as a method for preference elicitation together with, e.g., TOPSIS or PROMETHEE used for performance aggregation. (Hottenroth H. et al., 2021).

More information will be presented about this in Chapter 3.4 since the hybrid method FAHP&TOPSIS will be the one used in this thesis.

In conclusion, despite the method chosen, it is important to (i) be as transparent as possible and always document the reasons for selecting a certain method among others; (ii) perform a sensitivity analysis on the methods, that is, utilizing multiple methods to assess how the results vary. With respect to this last aspect what emerges is that top ranks are not completely stable across methods, but there are scenario clusters which rank high, medium and low for all methods and thus provide information, not timely but more robust (Hottenroth H. et al., 2021).

3.3.5 Methods in details

In the present chapter, the hybrid method adopted in the case study of this thesis project, known as AHP&TOPSIS, will be explored in detail. This approach combines two methodologies: TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and AHP (Analytical Hierarchy Process). These two methods will be examined in depth, with a theoretical illustration followed by a detailed description of the step-by-step procedures and the main limitations of each. Finally, the integrated AHP&TOPSIS method and its functioning will be presented.

Subsequently, in the case study chapter, the following aspects will be examined in detail: (1) the reasons behind the choice of this method and (2) the practical application of the AHP&TOPSIS method in the specific case considered.

3.3.5.1 TOPSIS

TOPSIS is the acronym for Technique for Order Preference by Similarity to Ideal Solution and it is a MCDM method developed by Hwang and Yoon in 1981. It is one of the most widely used multi-criteria decision analysis methods (Aires & Ferreira, 2019).

TOPSIS method is based on the idea that the optimal solution is the alternative that has the least Euclidean distance from a positive ideal solution and similarly the farthest from the negative ideal solution (Thakkar, J.J., 2022).

This methodology is based on the creation of two artificial and imaginary alternatives (A^+ and A^-), which serve as reference points as they respectively represent the ideal solution and the ideal negative solution of the decision problem under examination. Specifically, A^+ consists of the best values of the various attributes characterizing the analyzed options, as it maximizes benefits criteria and minimizes cost criteria, while A^- is formed by the worst values, maximizes cost criteria, and minimizes benefit criteria. The objective is to select the alternative that simultaneously has the smallest distance from A^+ and the greatest distance from A^- (Behzadian M. et al., 2012). The distance is expressed by a closeness coefficient (C_i^+) calculated for each alternative. The latter are then ranked in descending order, using the coefficient obtained (Aires & Ferreira, 2019)

Step-by-step procedure:

The procedure to implement this method is structured in 5 steps outlined in detail below (Hwang, C.L. and Yoon, K., 1981 and Thakkar, J.J., 2022):

- **Step 1**: calculation of the normalized decision matrix

Once the evaluation matrix is established (equation X), it has to be normalized as different criteria will have different scales for measurement. The most commonly used approach for balancing the scales of different criteria is the linear scale transformation approach which is a deterministic method to transform input data (Thakkar, J.J., 2022). Numerous linear transformation techniques exist. The normalization method used is shown by the equation below:

$$a_{i,j} = \frac{x_{i,j}}{\sqrt{\sum_{i=1}^{m} x_{i,j}^2}} \quad i = 1,2,\ldots m;\ j = 1,2,\ldots n$$

- **Step 2**: weight definition

Weights are assigned to each criteria according to their importance. A weight vector W (2) has to be defined. The methodology does not provide information on how to define weights, they can be either random or defined by decision-makers / stakeholders:

$$W = (w_1, w_2, \ldots w_j) \quad j = 1, 2, \ldots n;\ \sum_{j=1}^{n} w_i = 1$$

- **Step 3**: calculation of the weighted normalized decision matrix

The weighted normalized decision matrix is obtained by calculating the product of the normalized decision matrix and the associated weights. The weighted and normalized value of the i-th alternative with respect to the j-th attribute is defined as (3):

$$r_{i,j} = a_{i,j} \cdot w_j \qquad i = 1,2,\ldots m;\ j = 1,2,\ldots n$$

- **Step 4**: definition of positive and negative ideal solution

Determination of the positive ideal A^+ and negative ideal A^- solution (4):

$$A^+ = \{r_1^+, r_2^+, \ldots, r_n^+\} = \{(max\, r_{i,j} \mid j \in I'), (min\, r_{i,j} \mid j \in I'')\}$$

$$A^- = \{r_1^-, r_2^-, \ldots, r_n^-\} = \{(min\, r_{i,j} \mid j \in I''), (max\, r_{i,j} \mid j \in I''')\}$$

$$I' = 1, 2, \ldots, n \ \ associated\ with\ benefits\ criteria$$

$$I'' = 1, 2, \ldots, n \ \ associated\ with\ cost\ criteria$$

- **Step 5**: distance calculation

Calculation of the distance for each alternative to the positive and negative ideal solutions:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(r_{i,j} - r_j^+\right)^2} \;; \qquad i = 1,2,\dots m;\; J = 1,2\dots n$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(r_{i,j} - r_j^-\right)^2} \;; \qquad i = 1,2,\dots m;\; J = 1,2\dots n$$

- **Step 6**: calculation of the closeness coefficient

Calculate the relative closeness coefficient of each alternative (A_i) to the ideal solution (A^+):

$$C_i^+ = \frac{D_i^-}{D_i^+ + D_i^-}; \qquad i = 1,2,\dots,m;$$

$0 \leq C_i^+ \leq 1$

$C_i^+ = 1$ shows the absolute closeness of the corresponding alternative to the positive ideal solution, and similarly $C_i^+ = 0$ shows the absolute closeness of the corresponding alternative to the negative ideal solution. And because of that, the larger the C_i^+ value, the better the performance of the alternatives.

- **Step 7**: sort the alternatives in decreasing order

Alternatives are ranked in the decreasing order of C_i^+ value: the best alternative results to be the one to which the largest value corresponds.

Method limitation:

Through this method, it is possible to use the information associated with each attribute completely and establish an order of preferences for the alternatives, even if the attribute preferences are not independent. Compared with other techniques TOPSIS method can rapidly identify the best among the alternatives, uses simple calculations, and is easy to understand (Thakkar, J.J., 2022).

Nevertheless, some important limitations exist. TOPSIS does not account for correlation among the attributes, since Euclidean distances are used (Thakkar, J.J., 2022).

Moreover, the evaluation of a certain alternative depends on the analysis of all other options considered (Hottenroth et al., 2022), thus the method may be subject to a change in the order of preferences when adding or removing an option within the decision-making process. This has been identified by several authors as one of the major weaknesses of the methodology.

Some new modified TOPSIS approaches have been developed to overcome this problem. Particularly relevant is the R-TOPSIS technique, developed by de Farias Aires and Ferreira (2019) and further improved by Yang (2020) leading to the development of NR-TOPSIS. These approaches represent valid TOPSIS implementation since they do not show rank reveal in the various analyses conducted (Aires & Ferreira, 2019).

In conclusion, another important aspect to be considered is that the methodology does not provide a way to define the weights of criteria. As a consequence, assigning weights arbitrarily or with sub-optimal reference scales may lead to inconsistency in judgments and have negative effects on the analysis results.

This problem can be solved by integrating TOPSIS with other MCDM methods, which are more sensitive and structured precisely in defining sets of weights, such as the AHP method.

3.3.5.2 AHP

AHP is a well-known and widely used multi-criteria method, it was developed by Saaty in 1970 and belongs to the group of classical compensation methods namely those of the American school. AHP is very useful in helping the decision-maker to better understand the problem under study. This is because the method involves breaking down the initial, generally complex problem into smaller and thus more easily solvable “sub-problems”. In particular, this method is based on the creation of a hierarchical structure of criteria, sub-criteria (if any), and alternatives. Assuming comparability between alternatives, the methodology provides a well-defined method for determining the weights. Indeed, criteria and alternatives are compared in pairs to assess the relative preference between them. The intensity of preference is defined through a relative measurement scale called the Saaty scale. Moreover, AHP allows the integration of quantitative data (numerical values) and less tangible qualitative factors (preferences).

Step-by-step procedure:

The implementation of the method involves four fundamental steps and two optional steps (Ishizaka, A. and Nemery, P., 2013). The fundamental steps involve (1) defining the goal of the analysis, along with breaking down the problem into simpler, more manageable elements with the consequent definition of a hierarchy. (2) Collecting the input data, (3) priority calculation through the matrix of pairwise comparisons, and finally (4) aggregating the weights and scores to determine the ranking of the alternatives.

Two more steps can be subsequently conducted: the consistency check and the sensitivity analysis. Both steps are optional but recommended as they confirm the robustness of the results (Ishizaka, A. and Nemery, P., 2013).
The AHP methodology phases will be hereby presented in detail.

- *Mandatory steps*

Step 1: Structure the problem

The first phase is mainly concerned with structuring the problem and thus consists of:

- Decide the overall goal of the problem.
- Identify the stakeholders, which can be the decision-makers, the group of experts to obtain input data, and the stakeholders.
- Decide on criteria and alternatives and then structure the hierarchy.

The construction of the hierarchy allows the problem to be visualized and structured into more manageable elements. It is structured in a minimum of three levels: the top element is the goal of the decision, the second level represents the criteria (i.e. the attributes by which alternatives can be evaluated), and the third level represents the alternatives.
It is then possible to add levels that would represent the sub-criteria when present.
An example of hierarchy is provided in **Figure 10**.

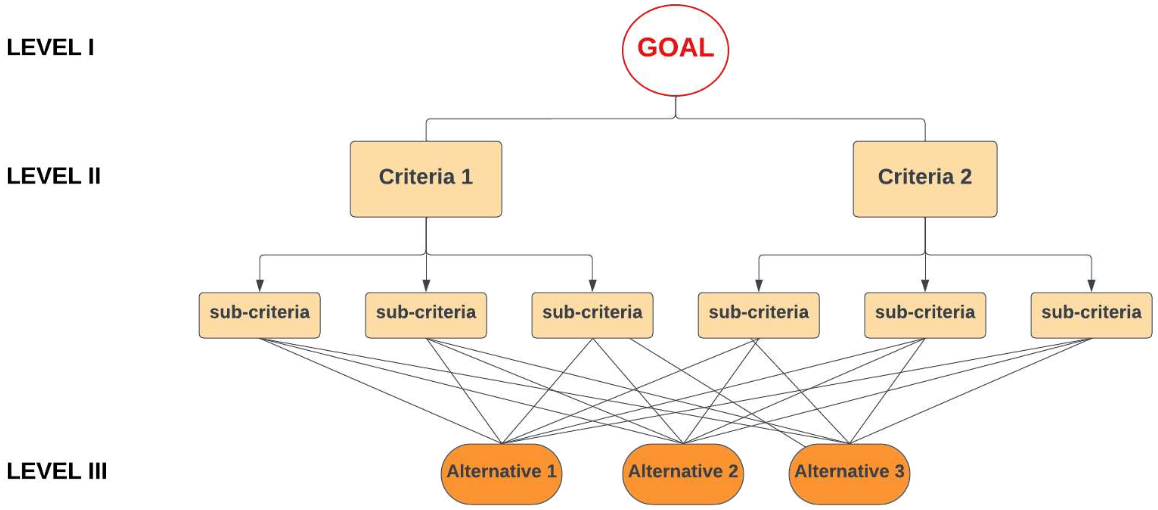

Figure 10 *Example of AHP hierarchy structure*

Step 2: Collection of input data

The input data of all alternatives for each criterion are collected to collect all information for the subsequent steps.

The data are collected in the evaluation matrix (A), which, as previously defined, is a two-dimensional matrix *mxn,* which crosses the n criteria with the m alternatives.

$$A = \{a_{ij}\}_{nxm} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{m,1} & \cdots & a_{m,n} \end{bmatrix}$$

Each element a_{ij} of the matrix represents the value of the alternative A_i (with i=1..m) for the criteria C_j (with j=1..n). In other words, the performance measurement of an alternative with respect to a selected criterion.

Step 3: Priority calculation

The third step of the methodology consists of two main stages:

1. Definition of pairwise comparison matrix, where all stakeholders' preferences are collected.
2. Determination of the vector of preference, i.e., the weights.

In the first place, therefore, stakeholders compare each factor within a level of the hierarchy, with the others in that level to decide how important each one is and assign weights. This happens for every level except the first. The comparison is carried out by resorting to Saaty's semantic scale (Saaty, 1980), i.e., a rating scale ranging from 1 to 9 (**Table 2**) in which the resulting numerical value is a function of the importance of one factor compared to another. As described in the table, if two elements have the same relevance, the result of the pairwise comparison will be equal to 1, while, as the relevance of one element increases compared to another, there is an increase in the numerical value that constitutes the outcome of the comparison.

Through this procedure, it is possible to define a numerical value starting from a judgment.

This semantic scale is widely used and psychologists, in particular, argue that it is easier and more accurate to express preferences between only two alternatives than between all alternatives simultaneously (Ishizaka, A. and Nemery, P., 2013) and that a smaller scale, say 1–5, would not give the same level of detail in a data set, whereas, with a larger scale the decision maker would be lost (for example, on a scale of 1–100, it is difficult for the decision maker to distinguish between a score of 62 and 63).

Table 2 *Saaty semantic scale used to define the priority matrix (Saaty, 2008)*

Degree of importance	Definition
1	**Equal importance**
2	Weak
3	**Moderate importance**
4	Moderate plus
5	**Strong importance**
6	Strong plus
7	**Very strong importance**
8	Very, very strong
9	**Absolute importance**

Results are reported in a matrix, called the pairwise comparisons matrix, which is a *nxn* matrix defined as follows:

$$C = \{c_{ij}\}_{nxn} = \begin{bmatrix} {}^{c_1}/_{c_1} & \cdots & {}^{c_1}/_{c_n} \\ \vdots & \ddots & \vdots \\ {}^{c_n}/_{c_1} & \cdots & {}^{c_n}/_{c_n} \end{bmatrix}$$

Each element $c_{i,j}$ of the matrix represents the relative importance that the i-th factor has in comparison to the j-th factor, expressed with Saaty's scale.

The pairwise comparison matrix has the following characteristics:

- $c_{i,i} = 1$; All elements in the main diagonal are equal to 1 as the element evaluated is compared with itself.
- $c_{i,j} \neq 0$; Comparisons are made using Saaty's scale of 1 to 9.
- $c_{j,i} = {}^{1}/_{c_{i,i}} \ \forall\, i, j$; The matrix of pairwise comparisons enjoys the reciprocity property, so the elements above the main diagonal are determined by pairwise comparison, while those below are the respective reciprocals.
- $c_{i,j} = c_{i,k} \cdot c_{k,j}$; The matrix of pairwise comparisons enjoys the transitivity property.

One of the main problems of the pairwise conformance matrix is that it may not be consistent, hence, a consistency check may be performed to detect possible contradiction in the entries. This is exactly what one of the two optional steps is about.

Once the pairwise conformance matrix has been established and its consistency evaluated, the next step involves determining the preference vector: $W = [w_1; \dots; w_n]$ with n equal to the total number of attributes characterizing the decision-making problem.

Several mathematical techniques exist to obtain the priority vector, and thus the weights, using the matrix of comparisons. These include the eigenvalue, geometric mean, and arithmetic mean. Saaty (1998) states that the eigenvalue approach is the only method that clearly addresses the problem of inconsistency.

In such case, the relative weights w_i can be derived from the following equation:

$$CW = \lambda_{max} W$$

Where:

- C is the pairwise comparison matrix;
- λ_{max} is the maximum eigenvalue for the pairwise comparison matrix;
- $W = [w_1; \dots; w_n]^T$

For a consistency matrix $\lambda_{max} = n$, while the difference, if any, between λ_{max} and n indicates the degree of inconsistency involved in the judgements. Since the matrix is hardly ever consistent, a consistency index CI was introduced, the value of which must be less than 0,1.

Step 4: **Rank the alternative**

To reach a conclusion, it is essential to aggregate the weights assigned to the criteria with the input data specific to each alternative. It is essential to take into account the relative importance of the criteria and, if available, of the sub-criteria, so that the alternatives can be evaluated in relation to all the factors involved and, consequently, with respect to the overall objective of the decision-making process. The aggregate scores, obtained after normalization, range from 0 to 1, and this allows us to identify the most suitable option, the one with the highest score, which best meets the requirements and objectives.

- *Optional steps*

Consistency check

Once the matrix of pairwise comparisons has been determined, it is necessary to assess its consistency. When several successive pairwise comparisons are defined, they may contradict each other. The reasons for these contradictions may be, for example, vaguely defined problems, lack of sufficient information (known as bounded rationality), uncertain information, lack of focus (Ishizaka, A. and Nemery, P., 2013), or errors in expressing preferences. As an illustrative example, the following pairwise comparisons are made by the decision-maker:

- A is two wants more important than B
- B is three times more important than C

What results, then, is that A is six times more important than C. To say instead that e.g. C is four times more important than A would be inconsistent and if entered into the matrix would generate misleading results.

Since priorities only make sense when derived from consistent or nearly consistent matrices, a consistency check must be applied. The threshold for defining an intolerably inconsistent matrix is unclear (Ishizaka, A. and Nemery, P., 2013). However, the most used method was developed by Saaty, and it is based on a consistency index, related to the eigenvalue method.

The matrix is defined as consistent if: CR<0.1, thus if the value of the consistency ratio CR is less than 0.1.

- Consistency Ratio: CR=CI/RI
- CI = consistency index;

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

  where n = number of criteria, and λ_{max} the maximum eigenvalue of the pairwise comparison matrix.
- RI = Random Consistency Index, which is the average CI of 500 randomly filled matrices, defined by Saaty. RI values are reported in **Table 3**.

Table 3 *Random indices from Saaty (1997)*

n	3	4	5	6	7	8	9	10
RI	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,49

Sensitivity analysis

The final stage of the decision process involves conducting a sensitivity analysis, during which the input data undergoes slight modifications to assess their impact on the outcomes. Given the inherent ambiguity in many complex decision models, conducting a sensitivity analysis enables the generation of various scenarios. These alternate scenarios may yield different rankings, potentially necessitating further deliberation to achieve consensus. If the rankings remain unchanged, the results are deemed robust; however, if alterations occur, the results are considered sensitive (Ishizaka, A. and Nemery, P., 2013).

Method limitation:

Overall, it could be said that Hierarchical Process Analysis (HAP) is an excellent tool in decision analysis. The hierarchical structure of AHP is intuitive and provides a way to better understand the complexity of the problem. In addition, AHP offers a clear methodology for establishing preferences, based on the relative importance of each attribute compared to the others. Its strength lies in its ability to guide decision-making through consensus on the evaluations of various factors and their importance in the overall prioritization of decisions. This makes it easier for decision-makers to reach an agreed decision quickly.

However, some critical issues remain. As pointed out by Ishizaka and Nemery (2013), it can be difficult to achieve consensus on expert opinions as it requires numerous pairwise comparisons. Furthermore, the methodology requires reliable data based on experience, knowledge, and judgment, which are subjective for each decision-maker and can take a long time to collect. Furthermore, AHP is subject to criticism for its ability to handle the uncertainty associated with assigning numerical values to decision-makers' judgments. This limitation could be mitigated through the use of fuzzy numbers and thus by introducing the Fuzzy AHP technique, which however won't be discussed in detail in this paper.

3.3.5.3 AHP&TOPSIS

One of the main challenges associated with Multi-Attribute Decision Models (MDMA) is the determination of weighting coefficients for the attributes that characterize the alternatives of a decision problem. Typically, the approaches used provide approximate results that facilitate rapid decision-making but are often not precise enough. Consequently, it is necessary to adopt more sophisticated methodologies such as the AHP technique and use hybrid approaches. This not only improves the accuracy of the analysis but also makes it possible to compensate for any limitations associated with a single technique.

In the present work, the hybrid AHP&TOPSIS method was chosen. This approach allows the determination of attribute weights using AHP and the evaluation of each alternative according to its own criteria using TOPSIS.

Step-by-step procedure:

The first stage of the methodology requires a detailed analysis of the problem in order to properly understand and define it. This involves defining the goal of the analysis and identifying both the criteria and the alternatives. It is also essential to structure the problem following a hierarchy, as specified in the AHP method, and to collect all input data in the evaluation matrix. Once the detailed definition of the problem and the collection of the necessary data have been completed, one can proceed with the operational steps, which include the following:

1. Normalization of the decision matrix.
2. Determination of the weights to be assigned to each attribute by conducting pairwise comparisons according to the AHP method.
3. Matrix’s consistency check
4. Weighing of the normalized decision matrix.
5. Determining the ideal-positive and ideal-negative solution.
6. Calculation of the distance of the *i-th* alternative from the ideal positive and negative solution respectively.
7. Determination of the relative closeness coefficient for each alternative.
8. Alternatives can be ranked, according to the closeness coefficient value, following a decreasing order, as the best alternative is the one corresponding to the highest coefficient value.

Each of these steps has been described in detail in the TOPSIS and AHP sections respectively, and a practical application is illustrated in the case study chapter.

3.4 LCA & MCDA

Over the years, both these methodologies, LCA and MCDA, have undergone considerable development, especially in recent times, but have proceeded in parallel without fully exploiting the potential that could result from their integration. This chapter will explore the idea of integrating the two methodologies and showcase the benefits this synergy brings. It will illustrate how this integration can be practically implemented and the results it can yield in the complex decision-making process concerning environmental analysis and the evaluation of products and processes.

To comprehend the relationship between these two approaches, it is important to first emphasize that they are both instruments that support decision-making (Zanghelini et al., 2018). However, the way they support the decision process and the output they provide is different. Indeed, LCA is considered a systematic tool to evaluate environmental impacts occurring through the entire life cycle of a product or process (KEK V. and Vinodh S., 2015). While multicriteria analysis is based on different protocols for eliciting input, structures, algorithms, and processes to interpret and use formal results in decision-making contexts (Huang et al., 2011). The complementary nature of these methodologies enables the partial mitigation of inherent weaknesses in each through their combined application. This need for integration has emerged simultaneously in both domains, with the combination of LCA and MCDA occurring in a two-way path (Zanghelini et al., 2018): on one hand, LCA requires the support of MCDA, and on the other hand, MCDA requires input from LCA. This relationship could at times be so close that some authors, including Benoit and Rousseaux (2003), even regarded LCA as an additional method inside the MCDA approaches.

3.4.1 The need for MCDA in LCA

The International Standard ISO and ILCD Handbook recommend including all relevant impact categories in LCA. As a result, LCA outcomes are presented as eco-profiles that consider various environmental aspects. This comprehensive nature of LCA is one of the main strengths of the methodology, allowing the avoidance of the burden-shifting problem, and presenting a result as complete as possible. However, this aspect may be also seen as a critical point. Since there is rarely an alternative that is the best in all impact categories, conflicting results often arise. These outcomes may exhibit strengths in certain aspects while demonstrating weaknesses in others, thereby implying trade-offs that make results interpretation difficult (Angelo, A.C.M.; 2021).

To draw conclusions from LCA outcomes is not always straightforward, multiple categories are considered, each with a different unit type, and conflicting results are often involved without a clear methodology on how to manage them. This becomes especially difficult for stakeholders or decision-makers, who generally are not LCA practitioners or experts.

Therefore, a remaining methodological challenge for environmental managers is how to construct a comprehensive judgment of environmental performance from the many indicators assessed in LCA (Zanghelini et al., 2018). This challenge can be approached using MCDM methods (Benoit and Rousseaux, 2003). Several authors noted that MCDA methodology can be applied to aid LCA with positive results (Zanghelini et al., 2018). MCDA facilitates preference measurements, drawing from its strong research tradition in analyzing and modeling value judgments (Miettinen P. and Hämäläinen R.P., 1997). It aids in analyzing and structuring the decision-making process through a holistic approach. It provides valuable methods for assessing trade-offs, offering a broader view of different aspects (Manzardo et al., 2014), and increases the usability of LCA in assessing product sustainability (Scott et al., 2016).

Overall, approaches and tools from decision analysis would be beneficial both in the planning of an LCA study and in the interpretation and understanding of the results (Miettinen P. and Hämäläinen R.P., 1997) furnishing decision-makers with guidance and support in the development of sustainable strategies (Zanghelini et al., 2018).

3.4.2 The need for LCA in MCDA

As presented in Chapter 3.3 several types of MCDA techniques exist, each involving its own framework. These techniques range from simple approaches that require minimal information to sophisticated methods rooted in mathematical programming, that require extensive information (Greening and Bernow, 2004). Despite their diversity, all multi-criteria methods share a common perspective: breaking down the overall evaluation of alternatives into assessments across several often-conflicting criteria relevant to the problem can enhance decision-making systematically (Zanghelini et al., 2018). MCDA serves various purposes, including identifying a single most preferred option, ranking alternatives, grouping, or simply distinguishing acceptable from unacceptable possibilities (Belton and Stewart, 2002).

As a result, MCDA is strongly indicated for environmental decision-making, and it is especially useful in sustainability assessments. However, especially when it comes to sustainability, the MCDA approach individually is unable to identify efficient levels of pollution production or resource use (Zagonari, 2016). Solely using MCDA to support sustainability assessments is not suggested, since MCDA, in many cases, needs input from other tools and methods Myllyviita et al. (2016). Therefore, when dealing with environmental decision-making, LCA can complement MCDA by assessing scenarios and thus provide input data to MCDA methods.

3.4.3 Integration limitation

As previously mentioned, integrating multi-criteria analysis (MCA) with life cycle assessment (LCA) offers significant benefits. However, it is important to acknowledge that this combination also has its own set of weaknesses. Collecting and analyzing the required data for this integration is a major challenge, and subjectivity may persist or even increase during the weighting stage of MCA, as with any decision-making process. Additionally, there is a risk of information loss when results are aggregated (Hermann et al., 2017).

Despite the growing interest in integrating these two techniques, the potential of MCA methods in the field of LCA is still not fully explored. Further research is necessary to fully comprehend and leverage the capabilities of their integrated applications (Myllyviita et al., 2012).

3.4.4 Possible integration

Combining LCA and MCA can be done in several ways (Angelo, A.C.M.; 2021). Here some possible combinations will be presented. As LCA integrated into MCDA is mainly adopted to provide input data, representing environmental performances of the alternatives, in this paragraph greater attention is given to the integration of MCDA into LCA.

Miettinen and Hämäläinen, point out that the greatest benefit of integrating multi-criteria analysis into LCA is in the subjective parts of the latter methodology. Indeed, the authors emphasize the importance of clearly distinguishing which aspects of LCA are subjective and which are objective. Aspects such as characterization and classification are to be considered objective, while aspects such as goal and scope definition, preference modeling, single score, and in general all parts where choices are included, are to be considered subjective. By clearly identifying this distinction, one can then also identify the parts where MCDA integration is most beneficial.

This statement is confirmed and elaborated in more detail by Zanghelini, Cherubini and Soares (2018). The authors conducted a comprehensive literature review on the integration of MCDA in LCA. Their search, conducted on Scopus and Web of Science using keywords (MCDA; LCA; and various combinations thereof), yielded an analysis of 109 articles, which were examined and mapped to identify the options by which MCDA supports LCA.

Their findings reveal that the most prevalent application occurs during the life cycle impact assessment stage, where MCDA is utilized to evaluate trade-offs among different impact categories (both midpoint and endpoint impact categories) or even between environmental impacts and others from the economic and/or social dimensions of sustainability (Zanghelini et al., 2018; Angelo, A.C.M.; 2021).

In addition to this major application, three other common possibilities emerged where MCDA supports LCA, as depicted in **Figure 11** (Figure source Zanghelini et al., 2018)

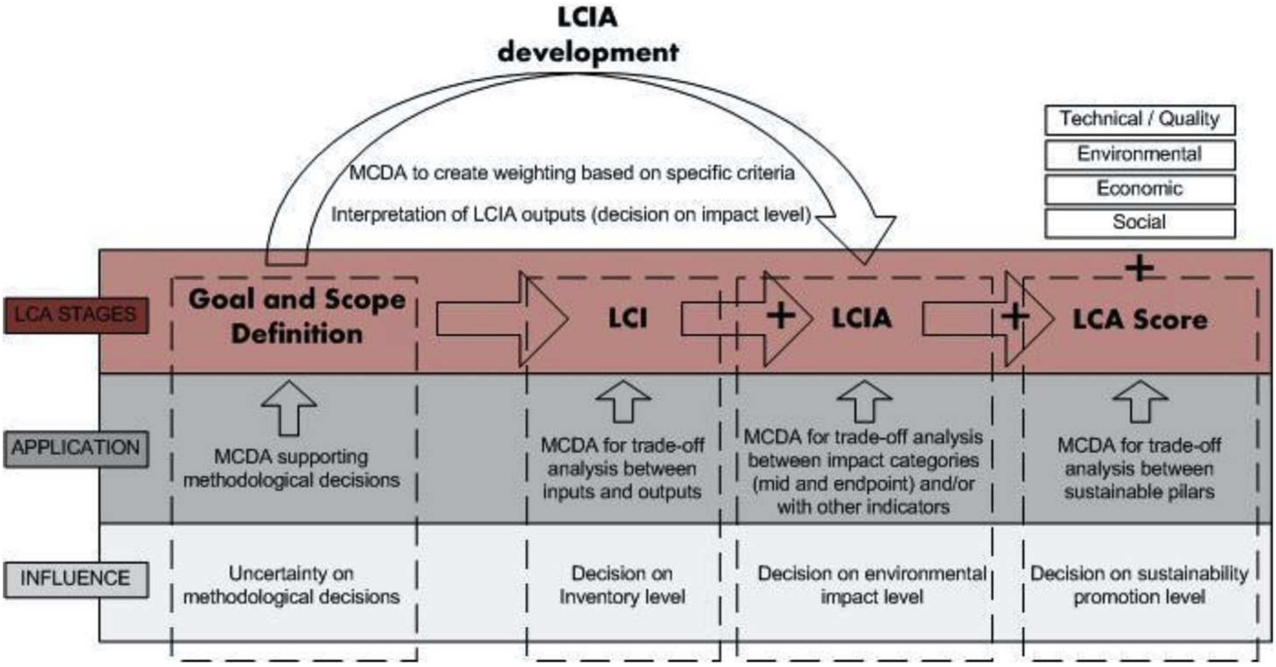

***Figure 11** Levels where MCDA may be integrated (Zanghelini et al., 2018)*

These four scenarios will be here examined:

1. **MCDA in LCA methodological decisions:**

   Although methodological decisions are made throughout the LCA, the goal and scope definition phase defines many critical decisions. Thus, at this stage, multi-criteria analysis can be used in support of the decisional process. However, integration at this stage is not common (Zanghelini et al., 2018). An example of integration at this stage is only provided by Myllyviita et al. (2012) where a panel-based MCDA was used to add environmental impacts, not previously considered as included in the LCA and highlight limitations in the impact categories of the ReCiPe methodology (Zanghelini et al., 2018; Myllyviita et al., 2012)

2. **MCDA in LCI decisions:**

   The adoption of multi-criteria analysis in the inventory analysis phase is intended to support decisions in the inventory phase, thus in the analysis of input and output trade-offs. The main motivation of MCDA applied at the LCI level is to find the best option in terms of sustainability of different alternatives (Zanghelini et al., 2018), defining that a reduction in flows (either inputs or outputs) represents the best alternative. However, even though a reduction in LCI aspects frequently represents less environmental impact, this cannot be considered a rule of thumb (as trade-offs between impact categories may occur after characterization) (Zanghelini et al., 2018).

   Compared to the use of multi-criteria analysis in the LCIA phase, few authors integrate it in the inventory phase, because the interpretation of information is preferable on environmental impacts than on inventory indications. LCIA results expressed in potential impacts seem to communicate better with stakeholders, as well as give environmental relevance to the flows.

3. **MCDA in LCIA decisions:**

   As defined previously, it is not straightforward to identify the best alternative because the differences between criteria values of alternatives cannot be easily compared in regards to the impact categories, their units, and their degree of seriousness (Boufateh et al. 2011). Thus, in the Life Cycle Impact Assessment (LCIA) phase, MCDA is used to aid the interpretation of impact categories trade-offs, at midpoint and endpoint levels (Zanghelini et al., 2018). Indeed, this appears to be the most used option for integrating MCDA in LCA, with 40% of the articles analyzed by Zanghelini et al. adopting it. The motivation derives from the complexity of interpreting trade-off results, uncertain information, inclusion of stakeholders, and the need for a single score. The need for a single score, in particular, has garnered increasing attention and is considered one of the open challenges within LCA methodology (as described in detail in Chapter X). The adoption of new methods to obtain single scores in a more rational way is required (Kalbar P.P. et al., 2016), and integration with multi-criteria analysis could bring many benefits.

When MCDA is applied at the LCIA level there is a clear preference of practitioners for WSM and AHP approaches. However, as these methods allow some compensability between criteria, outranking methods are preferred when considering problems that include different dimensions of sustainability (environmental, economic, social) (Angelo, A.C.M.; 2021).

4. **MCDA in LCIA development:**

   The before-mentioned case and this method of incorporating MCDA into the LCA are highly similar. However, there is a key conceptual distinction: in the case of MCDA in the LCIA phase, the main objective is to evaluate and make decisions concerning trade-offs between various environmental impact categories, thus facilitating the interpretation of results. Whereas in this case, the application of MCDAs is aimed at creating a weighting system to assign relative importance values to impact categories.

Consequently, there are several possibilities to combine multi-criteria analysis with LCA and that this integration brings considerable benefits.

In addition to those mentioned above, other possibilities for integration have been identified that are subject to ongoing and future research. One example is the case of using MCDA to handle the allocation problem, considered one of the most controversial aspects of LCA.

Another is the use of MCDA to elicit meanings for impact categories in a way to compel stakeholders and validate geographic conditions for decision-making (Zanghelini et al., 2018).

Finally, other cases exist that propose multi-criteria analysis as a tool to support decision-making, but in a different way to those illustrated so far. It is the case of the proposed new framework, designed to support LCA-based decision-making in the presence of methodological uncertainties by Marson et al. In this study, the use of MCDA is mentioned in the development of a weighting system for methodological combinations capable of managing divergent outcomes (Marson et al., 2024).

In conclusion, there is a clear and increasing interest in decision-making at the Trible Bottom Line level, thus in assessing the three dimensions of sustainability simultaneously, which will require further research on this topic.

4. Case study

After the initial theoretical introduction, this chapter focuses on the case study conducted in collaboration with Fashion Art.

An integrated model between LCA (Life Cycle Assessment) and multi-criteria methods is presented, intended at obtaining a single score for each evaluated alternative. This score aims to synthesize all considered environmental impacts into a single indicator, in order to facilitate the company's interpretation of the results and provide an overall value that takes into account both environmental aspects and business preferences.

As highlighted by the literature review in the previous chapters, LCA has shown some weaknesses in supporting decision-makers in the decisional process, presenting results in a complex way, especially for non-LCA experts. It also became apparent that, despite debate, there is a strong and broad demand within the LCA community for presenting results as single scores.

In this study, a methodology for obtaining a single score using multi-criteria analysis was examined. The proposed model involves the use of:

- LCA to provide the input data, i.e. the environmental performance of the alternatives expressed in terms of impact categories;
- Multi-criteria methods, in particular the hybrid method: AHP&TOPSIS, to define the set of weights and then obtain the single score for each alternative.

The weights defined by this method are intended to take into account the company's reality. They are therefore specific to the case under consideration and are therefore not intended to have universal value. Similarly, the study in this thesis aims to investigate a methodology suitable for creating single scores in the context studied and is therefore limited to the boundaries of this system.

A brief description of the conducted LCA will be first presented, followed by the methodology application and results presentation.

4.1. LCA

The LCA study was carried out by Rachele Dandolo through a collaborative project between CESQA (Centro Studi Qualità Ambiente) and Fashion Art. The results of the LCA provide the input data for the model proposed with this thesis project, and therefore, it is important to define how the LCA study was conducted and what that data represents.

4.1.1. LCA characteristics

The LCA study was conducted in accordance with the ISO 14040-44 standard, with the aim of analyzing the entire production process of a pair of high-fashion jeans and determining the potential impacts (production process data refers to the year 2022).

The functional reference unit for the entire analysis is a pair of jeans. The approach used for the analysis is cradle-to-gate, thus the system boundaries are as follows: the upper bound is the production of raw materials and the lower bound is the generation of the finished product. All stages of the production process were therefore considered, including cutting, assembly, and stitching, washing, drying, partial disassembly, laser use, stitching and packaging, second washing, ironing, final packaging and internal transport (a diagram of the processes considered is present in Annex

Figure 16). The distribution phase of the finished product to the individual points of sale or to the work center was omitted from the analysis, as it was outside the scope of the analysis.
Impacts were calculated from an inventory analysis and by the use of SimaPro software, which is based on the Ecoinvent database.
The impact categories considered in EPD 2018 are presented in Table 4.

Table 4 EPD 2018 Impact categories

IMPACT CATEGORIES	UNITS
Acidification	*kg SO2 eq*
Eutrophication	*kg PO4 --- eq*
Global warming	*kg CO2 eq*
Photochemical oxidation	*kg NMVOC*
Abiotic depletion, elements	*kg Sb eq*
Abiotic depletion, fossil fuels	*MJ*
Water scarcity	*m3 eq*
Ozone layer depletion	*kg CFC - 11 eq*

4.1.2. LCA results

Once all data has been collected, the finished product was modeled using SimaPro software. This involves inputting the raw materials and their quantities, along with details of processing operations, packaging, and transport. The output of this analysis reveals the impact of the product under study.

Results can be presented in various ways. One approach is to present the results for a single pair of jeans. Here, the impacts for each production phase (raw materials, processing, packaging, and transport) are showcased, illustrating how each phase contributes to the overall impact. These results are presented at the midpoint level, displaying impacts for each impact category. The results can be presented both numerically and as percentages, as illustrated in **Table 5** and **Figure 12**.

Table 5 *Example of one jeans impacts results*

Impact categories	U.d.m.	Raw materials	Processes	Packaging	Trasport	TOT
Acidification	**kg SO2 eq**	3,73E-02	2,73E-02	1,79E-03	2,14E-03	6,86E-02
Eutrophication	**kg PO4 --- eq**	7,98E-02	8,75E-03	5,78E-04	4,76E-04	8,96E-02
Global warming (GWP100a)	**kg CO2 eq**	7,52E+00	1,53E+01	4,93E-01	6,13E-01	2,39E+01
Photochemical oxidation	**kg NMVOC**	2,26E-02	3,42E-02	2,03E-03	3,41E-03	6,22E-02
Abiotic depletion, elements	**kg Sb eq**	2,40E-05	3,59E-05	1,79E-06	2,70E-06	6,45E-05
Abiotic depletion, fossil fuels	**MJ**	8,87E+01	1,83E+02	1,34E+01	8,41E+00	2,93E+02
Water scarcity	**m3 eq**	6,27E+00	2,54E+00	3,04E-01	3,57E-02	9,15E+00
Ozone layer depletion (ODP) (optional)	**kg CFC - 11 eq**	5,23E-07	9,36E-07	3,94E-09	1,11E-08	1,47E-06

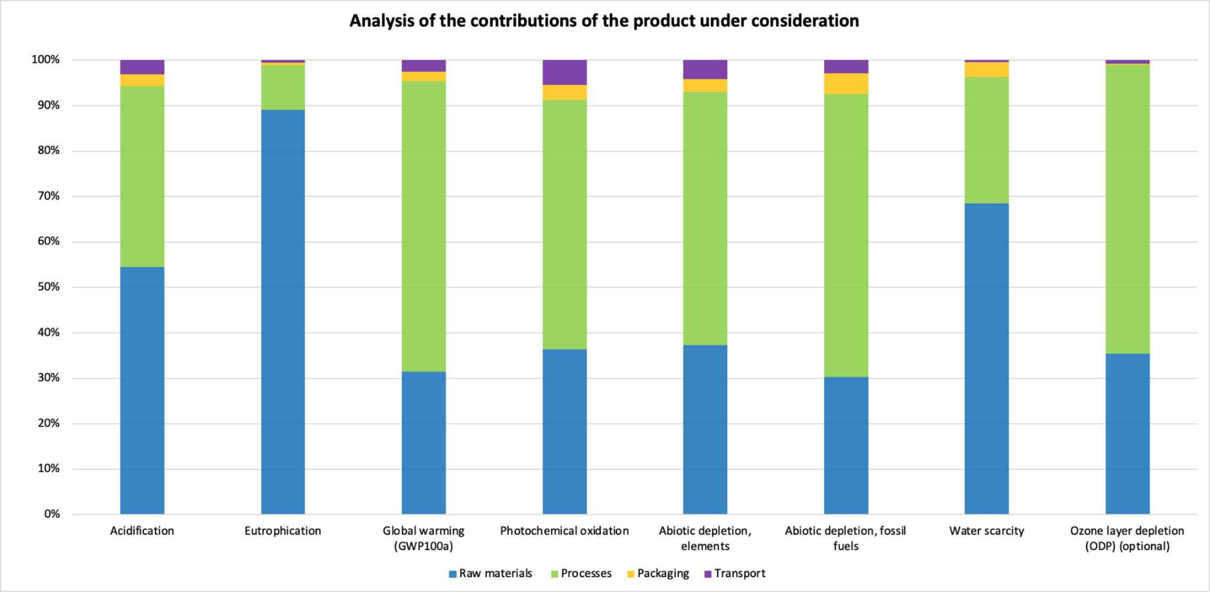

Figure 12 *Example of impacts graph for one jeans*

Alternatively, a comparative analysis of results can be presented. The impacts of two or more alternatives are compared at the midpoint level to assess their respective environmental impacts. In the example provided, two alternatives of jeans are compared, **Figure 13**.

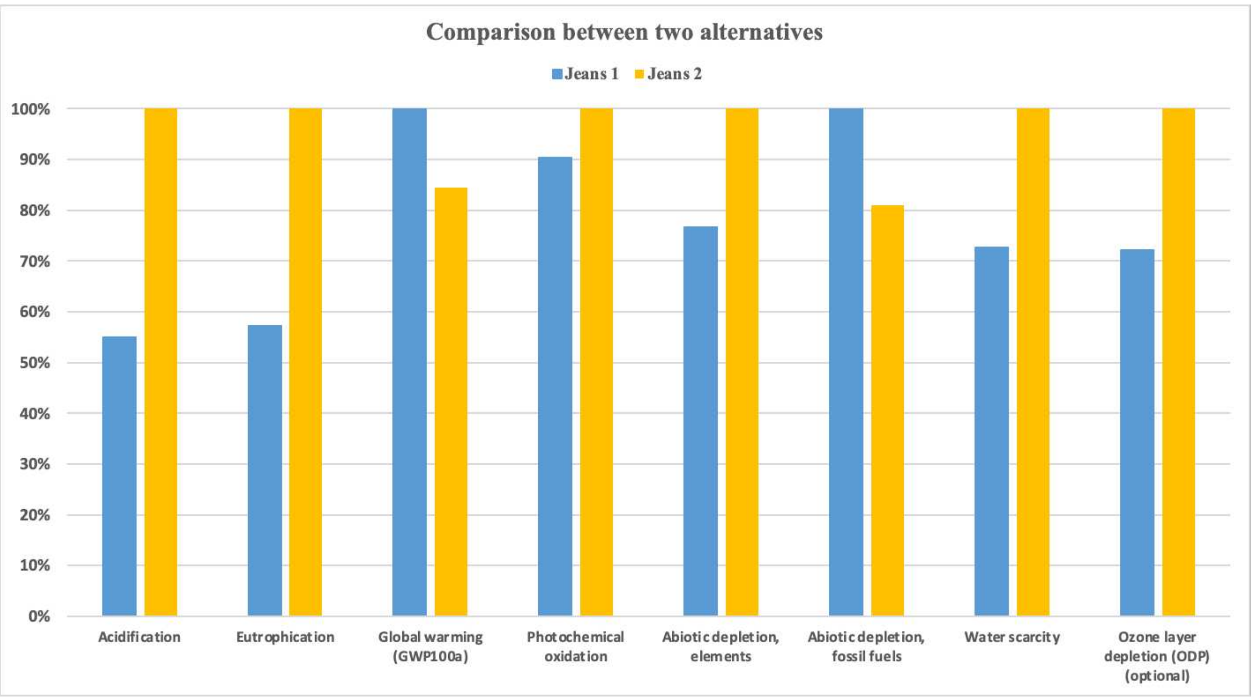

Figure 13 *Example of comparison graph between two jeans alternatives*

In both cases, interpreting the results can be challenging, especially for non-experts. Moreover, in the comparison graph, it's noticeable that determining whether one alternative is better than another is not straightforward. This is due to the fact that there is rarely an alternative that excels in all impact categories, thus necessitating the management of trade-offs in results.

To address this challenge, integration with Multi-Criteria Decision Analysis (MCDA) methods is proposed.

4.1.3. Impact categories selection

As different methods can be used to assess the LCA results, each of which considers a specific set of impact categories, some considerations have been made regarding the method to be used and whether or not to change the method used in the original LCA.

In the context of using data from the LCA study for the model adopted in this thesis, it was first considered to adopt the Environmental Footprint (EF) method, instead of EPD, to assess environmental impacts. The EF method was developed following the Recommendation of 9 April 2013 (2013/179/EU) on the use of common methodologies for measuring and reporting environmental performance over the life cycle of products and organizations, issued by the European Union. It was designed in response to the need for a uniform and standardized approach. With the Environmental Footprint method, inputs and outputs from the life cycle inventory are aggregated into 16 impact categories characterized at midpoint, as shown in the table in Annex (**Table 12**).

Although it is recognized that both the EF and EPD methods can provide robust results, the EF method was initially considered the most suitable. Besides presenting a very comprehensive set of impact categories, it is the method recommended by the European Commission and was specifically developed to create a harmonized and common system of impact categories. Indeed, future European directives will be based on these categories and currently studies to define normalization factors and reference weights use the EF methodology (Sala, et al., 2017 a; Sala, et al., 2017 b; Sala et al., 2020).

Therefore, the adoption of the EF methodology was considered to create a model more aligned with the objective of obtaining individual scores.

However, in the end, in the framework of the developed model, it was decided to stick to the impact categories proposed by the EPD 2018 method, mainly for the following reasons:

1. The AHP method does not work well with a high number of indicators. Considering that the EF (Environmental Footprint) method has 16 impact categories, it would have been necessary to make changes to the methodology to reduce the number of categories to at least 15 in order to be able to realize the pairwise comparison matrix. Therefore, it was preferred to adopt the EPD method with 8 impact categories and apply it without any modifications, rather than applying a modified EF method.

2. The impact categories play a central role in defining the weights assigned to each of them. This aspect is crucial in the decision-making process, and corporate stakeholders have been included in the process of defining the weights by means of a questionnaire. Considering that corporate stakeholders are not LCA experts, it was judged more appropriate to use a method with a limited number of categories (EPD), which was more manageable and understandable for all participants.

3. It was considered that the LCA results had previously been presented to the company following the impact categories of the EPD 2018 method. This helped to create greater familiarity of the respondents with these categories, thus facilitating decision-making and understanding of the results obtained.

In conclusion, although both methodologies are valid, it was decided to stick with the EPD 2018 method to present the results for use in the proposed model. Nevertheless, as will be presented in the application of the model, a sensitivity analysis was performed by changing the set of weights and adopting those of the EF. Furthermore, the implementation of the model with the EF's categories in a way suitable for the specific case is to be considered as an area for future research.

4.2. LCA and MCDA integration

As illustrated in Chapter 3.4, there are different ways of integrating Life Cycle Analysis (LCA) and multi-criteria methods.

In the present case study, the integration between LCA and multidimensional analysis takes place in the following ways:

1. LCA is used to provide input data to the multi-criteria method adopted (AHP&TOPSIS), thus providing for each alternative the values of potential impacts, expressed for each impact category.
2. The AHP&TOPSIS method is integrated in the impact assessment phase of the LCA, particularly in the phase related to the interpretation of the results. This goes beyond the simple identification of impacts and provides a useful tool to assist in the interpretation of trade-offs between impact categories. It also involves corporate stakeholders in the decision-making process, allowing individual scores to be created that reflect the organization's specific preferences and values.

4.3. AHP TOPSIS method application

This chapter will provide a detailed description of the step-by-step procedure of the model proposed in this thesis, which integrates multi-criteria methods and Life Cycle Analysis (LCA) to obtain a single score.

The hybrid AHP TOPSIS method is used, with the aid of LCA to provide the input data.

The AHP TOPSIS method was implemented on the open source software R studio, with the package ahptopsis2n: Hybrid Method for Multiple Criteria Decision-Making (MCDM) (Coutinho R., 2021).

- **Step 1. Problem definition and hierarchy structure**

The first phase involves defining the problem and the structure of the hierarchy.
Thus, the objective, criteria and alternatives must be defined:

- Objective:
  This objective is not necessarily coincident with the objective of the thesis, but is derived from it. Indeed, as previously defined, the overall objective is to steer the company in a more environmentally sustainable direction. This is operationally declined by evaluating production and identifying impacts. With this method specifically, the aim is to obtain, for each alternative, a single score that aggregates the impacts of all impact categories. The objective of the analysis conducted here is therefore to evaluate the best alternative in environmental terms, i.e. the one with the lowest impact.

- Criteria:
  The criteria used to evaluate the alternatives, based on the objective set, are the impact categories, defined in the previous section (Table X). Thus the 8 impact categories of the EPD 2018 method for which impacts are calculated. In this case, all criteria represent cost (there is no criteria that is a benefit) and thus the more cost are minimized, the best.

- Alternatives:
  the alternatives constitute the object of the evaluation and in this case are the output of Fashion Art's production, thus jeans. Specifically, 4 jeans models were considered, for which all LCA data were available. These 4 models have different aesthetic characteristics (color, wash, pattern, prints...) but all are long denim trousers, and therefore a comparative analysis can be made.

Once the initial data has been defined, the hierarchy can be structured as in **Figure 14**.

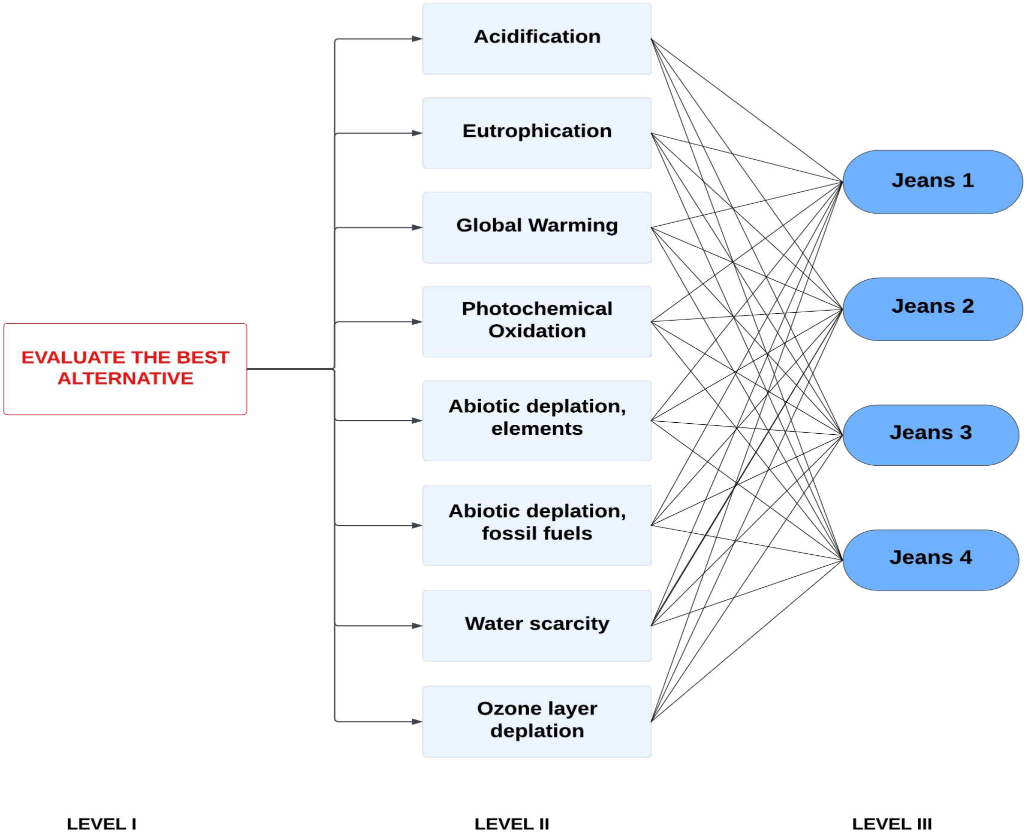

Figure 14 *Hierarchical structure of the case study*

- **Step 2. Evaluation matrix**

Once the problem is defined and all the information collected, the evaluation matrix can be constructed, which is the core of the analysis (Table 6).

Each element a_{ij} of the matrix represents the value of the alternative A_i (with i=1,2,3,4) for the criteria C_j (with j=1,...,8). Thus, for each alternatives, impacts are presented for all impact categories.

Table 6 Case study evaluation matrix

	Jeans 1	**Jeans 2**	**Jeans 3**	**Jeans 4**
C1	1,53E-01	6,88E-02	4,96E-02	1,25E-01
C2	1,89E-01	8,98E-02	7,77E-02	1,57E-01
C3	2,48E+01	2,41E+01	1,34E+01	2,01E+01
C4	8,47E-02	6,25E-02	3,92E-02	6,85E-02
C5	1,08E-04	6,48E-05	4,03E-05	8,36E-05
C6	2,96E+02	2,95E+02	1,66E+02	2,36E+02
C7	2,50E+02	9,21E+00	1,15E+01	2,07E+02
C8	2,49E-06	1,48E-06	9,96E-07	1,95E-06

- **Step 3. Weights definition**

According to the AHP TOPSIS method, the set (vector) of weights is calculated from the pairwise comparisons matrix, as described in chapter 3.3.5.3.

To ensure that these weights also reflect the company's needs, a questionnaire was conducted, that required filling in the pairwise comparisons matrix using Saaty's semantic scale.

The questionnaire was administered to two separate groups with a total of 16 people:

- A panel of experts in Life Cycle Assessment (LCA), mainly the LCA team of SpinLife, a spin-off of the University of Padua.
- Company stakeholders, in particular the Fashion Art team involved in the project, consisting of the company CEO, the sustainability team and the product team.

The idea is to reflect on the one hand the importance of the impact categories most involved in the jeans production process, and this should be represented by the LCA panel of experts. On the other hand, the company's needs, and this is expressed through the company panel.

Subsequently, the data were collected. The final pairwise comparison matrix is calculated by considering for each element of the matrix the average of the values obtained for that element.

The pairwise comparison matrix considered is shown in **Table 7**.

Table *7 Case study pairwise comparison matrix*

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
C1	1	2	1	3	3	2	2	3
C2	1/2	1	1	3	3	2	1	3
C3	1	1	1	6	6	5	2	6
C4	1/3	1/3	1/6	1	1	1	1	1
C5	1/3	1/3	1/6	1	1	1	1	1
C6	1/2	1/2	1/5	1	1	1	1/2	3
C7	1/2	1	1/2	1	1	2	1	6
C8	1/3	1/3	1/6	1	1	1/3	1/6	1

Additionally, the consistency check was then performed (Table 8). Since the matrix was found to be consistent CR< 0.1 the analysis was proceeded with.

Table 8 Case study consistency check

λ	RI	CI	CR
8,4594	1,41	0,0656	0,0465

The weights are then derived from the decision matrix directly through the functions of the R package ahptopsis2n. **Table 9** summarizes the weights obtained in percentage value.

Table 9 *Weights estimated through AHP methods*

Impact categories	**Calculated weight [%]**
Acidification	20,2%
Eutrophication	15,5%
Global warming (GWP100a)	26,9%
Photochemical oxidation	6,4%
Abiotic depletion, elements	6,4%
Abiotic depletion, fossil fuels	7,6%
Water scarcity	12,6%
Ozone layer depletion (ODP) (optional)	4,6%

- **Step 4. AHP TOPSIS implementation**

Once the two matrices governing the system, namely the evaluation matrix and the pairwise comparison matrix, have been determined, they need to be input into the R software, which applies the method. The steps outlined in Chapter 3.3.5.3, specific to the AHP TOPSIS method, are then executed, which include:

1. Normalization of the evaluation matrix,
2. Determination of the positive ideal and negative ideal solutions (in this case, the positive ideal solution is an artificial solution where all costs, i.e., impacts, are minimized. Conversely, in the negative ideal solution, they are maximized),
3. Determination of the distance of each alternative from the ideal solution,
4. Calculation of the closeness coefficient C_i^+.

- **Step 5. Results and alternatives ranking**

TOPSIS allows that the overall performance of the system to be represented by a single score, which in this method is exactly closeness coefficient, just calculated. The value of C_i^+ range between 0 and 1, the higher the value of the score, the smaller the distance between the examined case and the ideal solution and, consequently, the better the alternative's performance.

Table x shows the scores obtained for each alternative, graphically represented in **Table 10** and **Figure 15** Case study single score representation

Table 10 *Case study single score results*

Alternatives	Score obtained	Rank
Jeans 1	0,0902	4
Jeans 2	0,4934	2
Jeans 3	0,8989	1
Jeans 4	0,3552	3

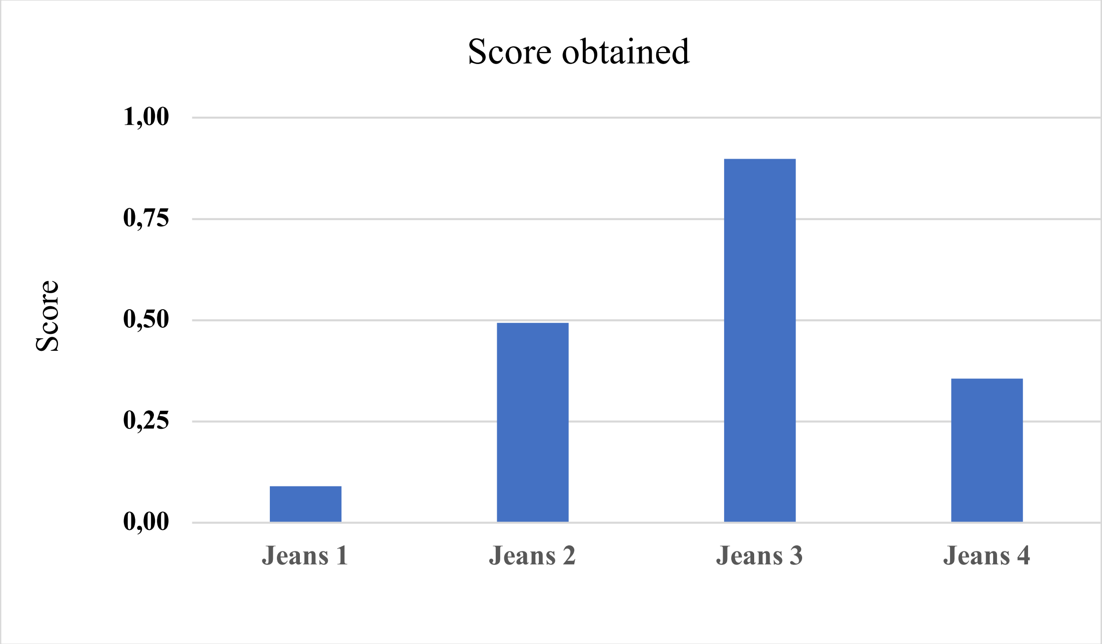

Figure 15 *Case study single score representation*

This results in jeans option 3 being the best alternative, while jeans option 1 is the worst.

Investigating the characteristics of the jeans analyzed, it is found that the differences between the two jeans mainly concern the amount of fabric and the type of cotton of the jeans. Delving into the characteristics of the analyzed jeans unveils notable distinctions primarily concerning the fabric utilized. In particular, having found through LCA that the most impactful phase is the raw material phase, Jeans 1 is the option with more fabric used (twice as much fabric) and consequently more impacts related to the raw material phase. In addition, beyond the quantity of fabric, another crucial factor contributing to the environmental impact disparity between the analyzed jeans options lies in fabric characteristics. The fabrics used for jeans 1 and 4 are fabrics derived from classic cotton and not organic cotton, like the other two. It follows that their impact is much higher, as the production of inorganic cotton is much more impactful than organic cotton. This explicitly results from Simapro software when looking in detail at the impacts of raw materials and the individual jeans results of the LCA analysis. It is shown that an organic raw material, rather than a traditional one, results in many differences, reducing impacts considerably.

The fabric of these two jeans (1 and 4) also consists of 66% inorganic cotton, 28% viscose, 4% polyester and 2% polyamide, with related impacts of the production process of auxiliary materials besides cotton, especially viscose. In contrast to the jeans (2 and 3) made from 97% organic cotton and 3% elastane.

Notably, jeans 1 is in black denim, which, according to the findings of the Life Cycle Assessment, stands out as one of the most environmentally impactful fabric types, due to the processing it requires. In contrast, jeans option 3, which emerges as the optimal choice, displays characteristics that align more favorably with sustainable principles. With a reduced fabric requirement and possibly a less environmentally intensive washing process.

4.3.1. Sensitivity analysis

As presented in chapter 3.3.2, three main types of sensitivity analysis can be performed when applying a MCDA method, i.e., method sensitivity, criteria sensitivity, and weight sensitivity.

In this case, a sensitivity analysis was conducted by changing the weights adopted and evaluating how the results change with different weights. In particular, the new weights considered are those provided by the Environmental Footprint methodology.

As previously described, the EF methodology has 16 impact categories and weights are assigned to each of them. Since only 8 impact categories are considered in this analysis (based on EPD method) and not 16, the weightings used in EF 3.1 had to be scaled before the actual comparison could be made. This was done by setting the sum of the weights of the 8 EF categories considered equal to 100% and determining the new resulting weightings for each of them proportionally.

The weights derived from EF 3.1 are summarized in **Table 11** Environmental Footprint 3.1 weights.

Table 11 *Environmental Footprint 3.1 weights*

Impact categories	EF_weights [%]
Acidification	9%
Eutrophication	13%
Global warming (GWP100a)	29%
Photochemical oxidation	7%
Abiotic depletion, elements	10%
Abiotic depletion, fossil fuels	12%
Water scarcity	12%
Ozone layer depletion (ODP) (optional)	9%

With these weights, the TOPSIS method was then applied, and the results evaluated. Indeed, it was no longer necessary to adopt the hybrid method since the addition of the AHP was used to determine the weights via the comparison matrix, whereas they are now directly defined by the EF 3.1. The evaluation matrix obviously remained unchanged.

The single score obtained is different, as the weights have changed, but the ranking of the alternatives was the same, confirming that jeans 3 is the best and jeans 1 the worst.

5. Results and discussions

In this chapter, the main object to discuss how the proposed method meets the objectives set at the beginning of the analysis and highlight critical aspects.

The application of the method led to the definition of single scores and allowing the rank rank of the alternatives. The results showed that jeans 3 was the best option, while jeans 1 was the worst, while the options of jeans 2 and 4 showed intermediate levels, with jeans 2 performing better. This can be attributed to the characteristics of the jeans, in terms of fabric quantity, raw material type and processing, as explained in detail in the previous section.

The resulting single score reflects the product characteristics in terms of the highlighted impacts of the LCA and ranks the results in concordance with them.

It can therefore be said that the integration of the LCA with decision analysis, and in particular the hybrid AHP TOPSIS method, presents a possible solution to the problem of obtaining a single score and thus making the interpretation of results easier.

However, some critical aspects emerge in the method, which we would like to highlight here, pointing out possible future steps to comply with these weaknesses. The single score results produced by the TOPSIS method are closely linked to the alternatives present. As the evaluation of a certain alternative depends on the alternatives present. Given the limited number of alternatives assessed, divergent results, including shifts in ranking, may arise with the expansion of the evaluated set.

It is therefore deemed necessary, on the one hand, to carry out future analyses considering a larger set of alternatives and, on the other hand, to evaluate the alternatives with other MCDM methods or TOPSIS itself, in its modified form NR-TOPSIS by Yang (2020). This aspect must be assessed particularly carefully if the tool is to be used for eco-design, i.e. to assess potential impacts at a design stage. In this case, in fact, a method so closely linked to the alternatives considered would not be advisable.

Another critical aspect is certainly that of the definition of weights. Even though the hybrid AHP TOPSIS method provides a methodology for defining weights from pairwise comparisons of alternatives, it proved particularly difficult to define the degree of importance of alternatives when these are the impact categories of an LCA. While LCA experts can express their preferences based on an assessment of where impacts mainly occur, expressing preferences on the part of corporate stakeholders is much more complex. In fact, it emerged that the corporate side not only lacks the basis for expressing a preference for impact categories, but rather needs a support tool precisely in defining which aspects to prioritize. Consequently, it was difficult to translate the decision-makers' preferences in a way that is usable in the manner of the AHP. It follows, therefore, that deriving weights as proposed by this methodology is currently highly affected by subjectivity and that further research is needed on this issue. There are several approaches that can be taken, such as keeping stakeholders out of the evaluation, using standard values (like those suggested by the Environmental Footprint), and creating procedures that help the business decide which impact categories to give priority to to derive weights from them.

Overall, this approach can be described as a first step in decision support and integration between LCA and multidimensional analysis. It provided a valid solution, but one that still has important areas for improvement. It highlights the importance of the problem of defining weights and prioritizing impact categories.

6. Conclusions

In this study, Life Cycle Assessment and Multi Criteria Decision Analysis were integrated to attempt the formulation of a single score that provides a clear and easily interpretable indication of the environmental performance of the alternatives evaluated.

Starting from the needs of the textile sector to move toward more sustainable solutions, an in-depth investigation of the methodologies for impact assessment was conducted, identifying the LCA study as a robust tool able to support this objective with a quantitative and comprehensive approach. Indeed, it allows the evaluation of product and services throughout their life cycle and on different environmental impact categories. However, it turns out that evaluating LCA outcomes is not always simple, as the nature of the results is complex and trade-off situations often occur. To support decision-makers in such complex situations, decision analysis tools were considered. Multi-criteria analysis appears to be a valid tool, specialized specifically in the evaluation of alternatives on different criteria and the integration of stakeholders into the analysis. Multi-criteria methods were therefore investigated and how such methods could be integrated with LCA. Finally, an integrated method of LCA and MCDM was proposed, involving the application of the hybrid AHP TOPSIS method.

This method was then applied to the case study of Fashion Art, a manufacturing company engaged in the luxury sector and specialized in the production of jeans. In particular, the model evaluates 4 jeans alternatives out of 8 environmental impact categories, to obtain a single score that synthesizes the environmental performance of the alternatives in a single indicator. In this way, it was possible to combine the LCA results and present them in an easily understandable way. This single score synthesizes all information in a way that provides clear information but does not eliminate the multi-dimensionality typical of the LCA study and in addition considers the company's needs.

Using the single score, it was possible to rank the alternatives. The results showed that Jeans 3 was the best option, while Jeans 1 was the worst, while the options of Jeans 2 and 4 showed intermediate levels, with Jeans 2 performing better. This reflects what the LCA showed, as jeans 1 and 4 have almost twice as much fabric and are made of non-organic cotton, which leads to higher impacts.

It can therefore be concluded that the integration of LCA and multi-criteria methods is a possible solution to the growing need for a single indicator and their integration brings considerable benefits. However, some critical points have also emerged that need further development. In particular, the method, as it stands, is characterized by considerable subjectivity due to the way in which preferences are derived. Indeed, even though the AHP TOPSIS method has a methodology for defining weights, it is particularly difficult to define the degree of importance of the criteria, when these are the impact categories of an LCA. This critical aspect made it possible to note that the business side needs a tool to define which aspects, hence impact categories, to prioritize. This aspect of forcing an in-depth investigation of the system under scrutiny is typical of multidimensional analysis and, if pursued, can bring decisive advantages.

Overall, the proposed methodology has on the one hand made it possible to obtain an indicator that summarizes the results of the LCA and makes them more manageable, and on the other hand to gain greater awareness. However, it remains a method still at its early stages and needs future study and development.

The fashion industry is at the center of a transition phase towards more sustainable patterns, and solutions that allow measuring sustainability and, above all, communicating it are increasing and will require more and more attention.

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mia mamma, mio papà, Emma e Dede: la sicurezza, la vita, la cura e la gioia.
Vi sono grata e vi voglio bene.

8. Annex

***Table 12** EF 3.1 midpoint impact categories (adaptation from JRC analysis.)*

Impact cathegory	Indicator	Unit	Description
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO2 eq	Measures the greenhouse gas emissions contributing to global warming.
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11eq	Evaluates substances that deplete the ozone layer, leading to increased UV
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	Measures the potential adverse effects of substances on human health through
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	Measures the potential adverse effects of substances on human health through
Particulate matter	Human health effects associated with exposure to PM2.5.	Disease incidences	Assesses the emissions of fine particles that can penetrate the respiratory system
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235	Assesses the exposure to ionizing radiation, which can have harmful effects
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOCeq	Evaluates the formation of ground-level ozone, which contributes to smog and
Acidification	Accumulated Exceedance (AE)	molH+eq	Measures the acidifying emissions
Eutrophication, terrestrial	Accumulated Exceedance (AE)	molNeq	Measures the nutrient enrichment of terrestrial ecosystems, leading to
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg Peq	Evaluates the nutrient enrichment of freshwater bodies, leading to algal
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg Neq	Assesses the nutrient enrichment of marine ecosystems, causing harmful
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	Evaluates the potential toxicity of substances released into freshwater
Land use	Soil quality index	Dimensionless (pt)	Measures the occupation and transformation of land, including impacts
Water use	User deprivation potential (deprivation-weighted water consumption)	m3 world eq. deprived water	Evaluates the consumption and depletion of freshwater resources.
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sbeq	Evaluates the extraction and depletion of metal resources,
Resource use, fossil	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	Evaluates the extraction and depletion of metal resources,

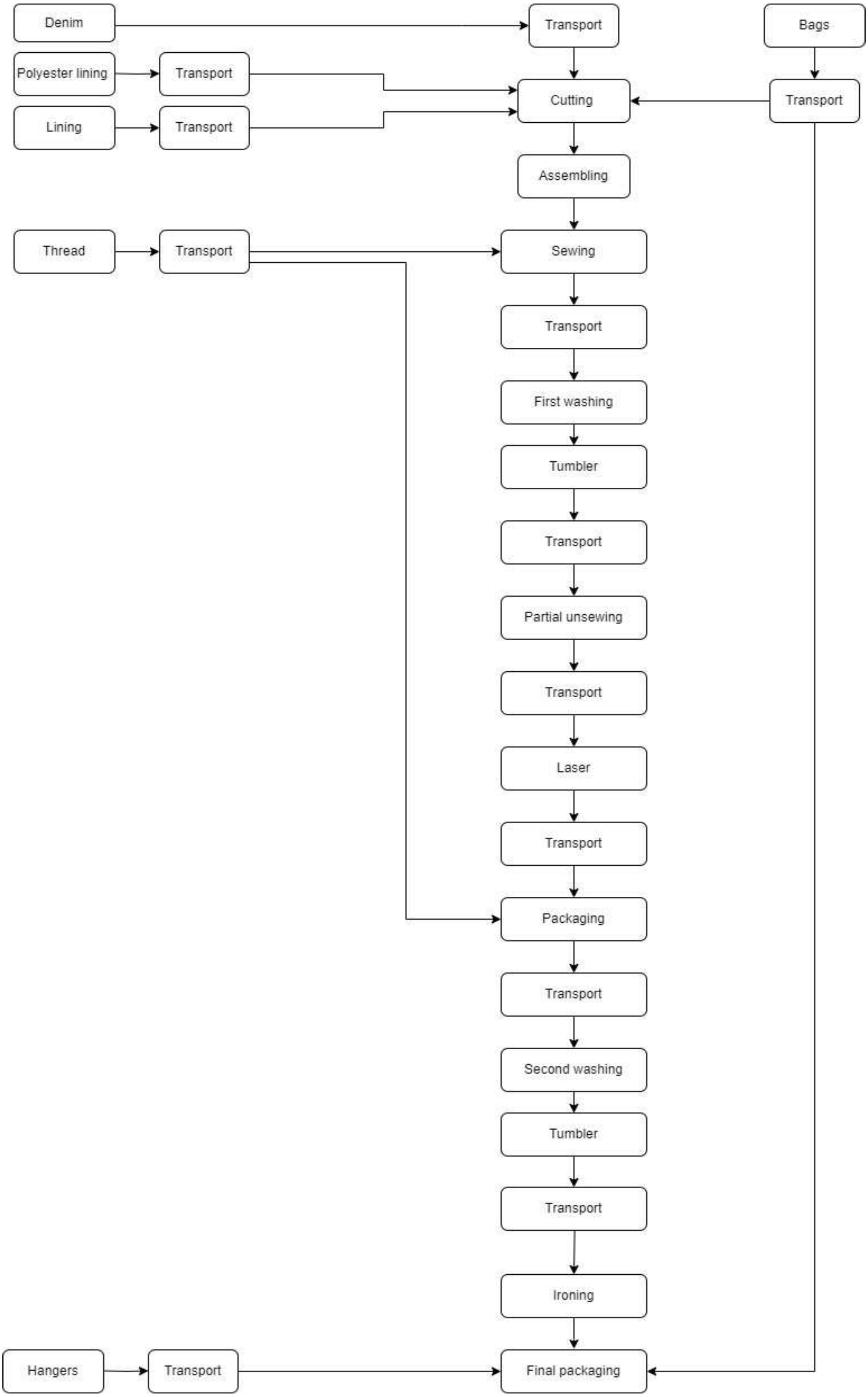

Figure 16 *Flow chart of the production process of a pant*

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