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Abstract

This thesis explores the application of life cycle assessment (LCA) methodology and the life cycle energy (LCE) framework in manufacturing processes through four case studies developed during the PhD programme. The main objective is to evaluate significant technologies, systems and innovations for the manufacturing sector, contributing to the scientific discussion on environmental sustainability. In a general perspective, the environmental impact of case studies applied to the automotive field was evaluated.

This thesis begins with an introduction to sustainability in major manufacturing processes, outlining the LCA methodology, its history, relevant regulations and the steps required to conduct a life cycle analysis. Factors influencing environmental impact are examined, looking at three of the main subtractive, additive and casting manufacturing techniques and analysing their potential to improve environmental performance throughout the life cycle. The first case study analyses a component from the automotive field, comparing three of the main production techniques by applying the process of topological optimisation; thus, optimising the geometry of components to assess how lightweighting can contribute to sustainability. The results show that the benefits of topological optimisation applied to the additive manufacturing (AM) process are evident with a reduction in cumulative energy demanded (CED) of approximately 65% compared to approximately 41% and 25% for standard machining (SM) and casting process (CP), respectively. The latter considerations are valid without considering the impact of the moulds for the CED of CP in order to make a comparison with AM and SM without taking into account the number of parts to be produced. However, from an environmental sustainability point of view, CP is influenced by the energy contribution of the moulds, which weigh on the production of a few parts. The study was therefore completed by also considering the contribution of the moulds and weighting it against the batch size.

Nevertheless, the results show that, to emphasise this influence and weigh the contribution of each phase, it is necessary to carry out more detailed LCA studies with different geometries, changing the percentage of volume to be removed from the initial billet before obtaining the desired product. In fact, in general, LCA is competitive with AM if the shape to be produced is simple and, therefore, far from being topologically optimised.

Starting from these results, additive manufacturing as an alternative to conventional processes is analysed, examining different sustainability parameters and also considering different recycling scenarios and energy mixes. These were chosen to assess the impact, both in terms of energy (CED)

and environmental sustainability, of countries using energy from renewable and non-renewable sources. The advantage of SM as a less environmentally impactful process compared to AM was observed at least up to a 90% reduction in billet mass due to the energy consumed in the manufacture of the product. This result is only consistent if the chip generated in the SM process is recycled properly, otherwise the material energy impact for the SM process is markedly impactful, with the break-even point between the two processes being between 40% and 80% of the billet material reduction. Furthermore, as the production phase increases, the environmental impact of the choice of production site begins to become increasingly relevant due to the peculiarities of the countries' energy sources. In fact, looking at the CED, the environmental impact of oil sources is more relevant when compared to nuclear and/or hydroelectric energy sources. Nuclear energy, on the other hand, loses its environmental competitiveness, even compared to oil, when specific midpoint and endpoint indicators are taken into account.

On the other hand, by analysing components in the automotive sector, it was possible to assess how the use phase has a considerable impact on the environmental impact of the component, so in order to lighten the masses being transported as much as possible, the focus of the thesis shifted to the analysis of another case study that is lightened by joining two different materials, namely steel and composite materials. Specifically, a conventional solid steel gear, a lightweight gear and a hybrid gear were compared from the point of view of sustainability, using life cycle energy quantification. In addition, two end-of-life (EoL) scenarios were considered: a conventional open-loop scenario with partial recycling and a closed-loop scenario with full recycling, including thermal recycling for carbon-fibre reinforced plastics. The overall CED rating for the ‘greener’ approach results in the values of 898.92 MJ, 649.10 MJ, 697.87 MJ considering full, lightweight and hybrid gear, respectively. In this scenario, the lightweight and hybrid solutions are comparable, with a CED difference of approximately 7.50 per cent. On the other hand, the hybrid gear achieves a CED saving of 28.82% compared to the full gear.

Finally, the focus shifted to the end-of-life processes of polymer matrix composites, evaluating recycling and remanufacturing strategies from an energy (CED) perspective in order to develop sustainable approaches according to material type and field of application. In detail, polypropylene-carbon fibres (PP-CF), polypropylene-glass fibre (PP-GF), polyether-ether-ketone-carbon fibre (PEEK-CF) and polyether-ether-ketone-glass fibre (PEEK-GF) at different reinforcement volume fraction percentages and three end-of-life processes were compared, namely, energy recovery by combustion, reuse by thermoforming and finally recycling of the reinforcement by pyrolysis. When analysing the different end-of-life scenarios and filling percentages, the main results show that if the composite has a low matrix value (PP) and a high reinforcement value (CF), both end-of-life processes, i.e. recycling and reforming, minimise the energy impact. On the other hand, if the composite consists of a high-value matrix (PEEK) and a low-value fibre (GF), reforming is more energy-efficient, although its advantages are more evident for low-value fibres; recycling is not always more advisable than combustion. In fact, if the composite consists of low-value (GF) fibres, combustion is preferable. To present a comprehensive overview of the work, the graphical abstract in Figure 0.1 was provided.

The conclusions offer a discussion of the main issues that emerged, highlighting how the LCA approach can be used not only to evaluate, but also to guide the development of more environmentally friendly technologies, providing a baseline for the future of the manufacturing sector.

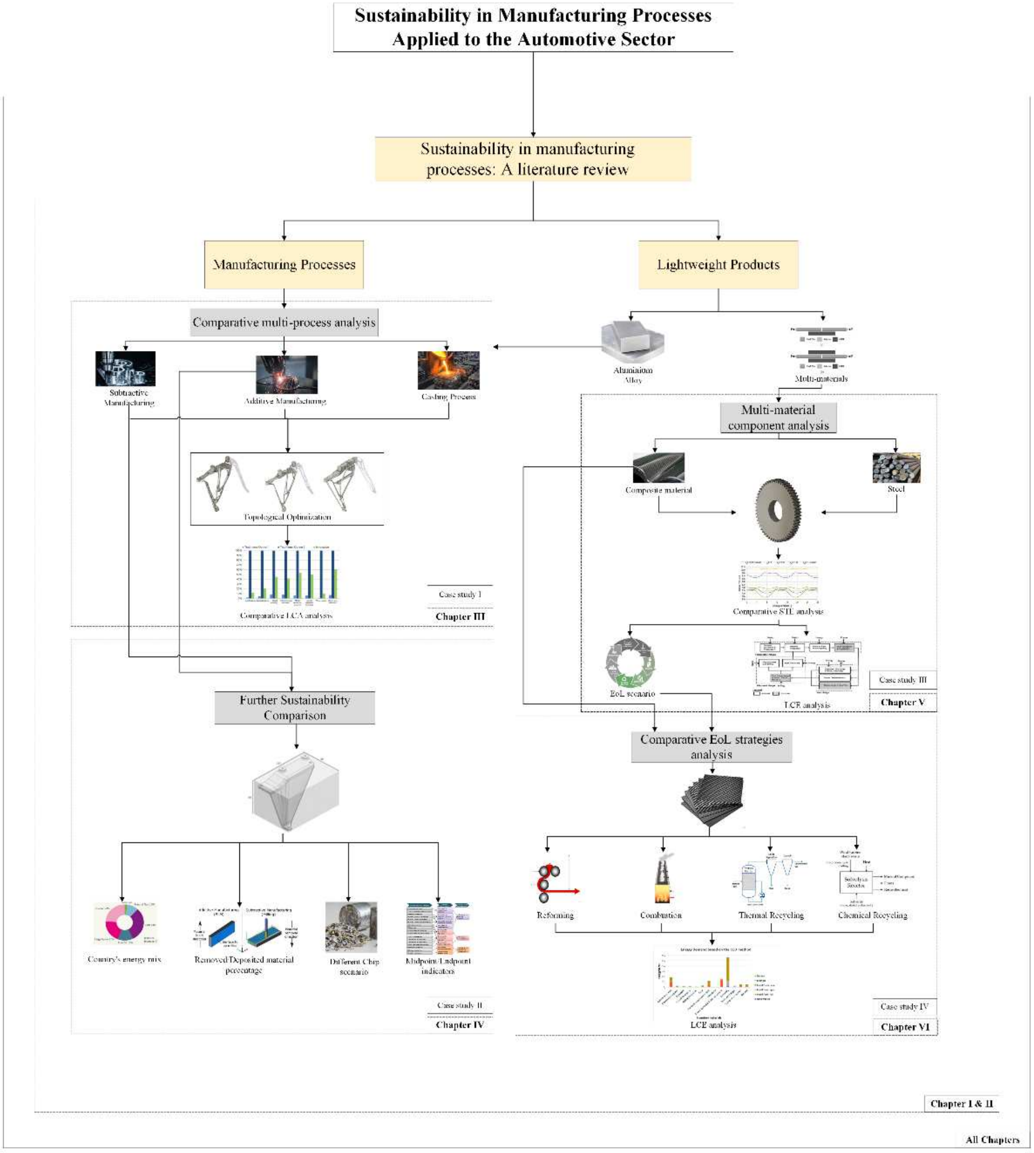

Figure 0.1 Graphical Abstract.

Impact Statement

The area of application of this PhD research interlaces both the academic and industrial sector. The research offers a solid platform through methodological work and practice that academic and industrial field could use to assess the technology development process. The applications of LCA methodology, coupled by EoL framework on different materials and manufacturing processes considering different scenarios, provides feedback to technology developers on environmental performances and hence helps identify critical points and potential optimization routes for the assessed systems. The methodology, applied in this thesis, is scalable to different processes, products, materials and end-of-life strategies as demonstrated by the four case studies investigated.

The PhD research presented in this thesis was co-funded by the Profiltek S.r.l. company. The project brought together participants from academia and industry who set challenging innovation goals to promote sustainable innovation through different research and development projects and through the implementation of ad hoc system for the management and control of plants equipped with 4.0 technology.

Finally, the main outcomes of this research were disseminated through conventional communication channels, i.e., scientific papers, international conferences, seminars, and through less conventional channels, such as social media (explanatory clips and presentations) in order to reach out to the general public as well as the scientific audience.

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List of Abbreviations

AM	Additive manufacturing
AVE	Average
m_b	Billet mass
CO_2	Carbon dioxide
CF/GF-RTP	Carbon fibre or glass fibre-reinforced thermoplastics
CFs	Carbon fibres
CE	Circular economy
m_c	Component mass
CNC	Computer numerical control
CFRPs	Continuous fibre-reinforced polymers
CFRTPs	Continuous fibre-reinforced thermoplastics
CED	Cumulative energy demand
DALY	Disability Adjusted Life Years
H_d	Disposal energy
EE	Embodied energy
H_{mc}	Embodied energy of the composite
EoL	End-of-life
H_{pc}	Energy consumption of the composite manufacturing process
H_{ppc}	Energy consumption of the composite pre-manufacturing process
H_c	Energy of the formed composite
$H(net)_{recycled\ content}$	Energy recycled content method [MJ]
$H(net)_{substitution}$	Energy substitution method [MJ]
$H(net)_{substitution(R)}$	Energy substitution method with recycling [MJ]

EU	European Union
FRPs	Fibre reinforced polymers
FVF	Fibre volume fraction
R	Fraction of recycled material
Gt	Gigaton
GFs	Glass fibres
kgCO$_2$eq	kg of carbon dioxide equivalent
kgCueq	kg of copper equivalent
kBqCO-60eq	kilobecquerel of Cobalt-60 equivalent
LCA	Life cycle assessment
LCIA	Life Cycle Impact Assessment
LCI	Life cycle inventory
LCI	Life Cycle Inventory
H_m	Material extraction energy
MJoe	Megajoule oil equivalent
PEEK	Polyether ether ketone
PEEK-CF	Polyether-ether ketone-carbon fibre composite
PEEK-GF	Polyether-ether ketone-glass fibre composite
PP	Polypropylene
PP-CF	Polypropylene-carbon fibre composite
PP-GF	Polypropylene-glass fibre composite
H_{rc}	Process energy recycling
r	Recyclability of the material
RCHIP	Recycled chip
H_{rc}	Recycling energy

r_1	Recycling rate of chip
SLM	Sintering Laser Melting
Species.yr	Species lost per year
SM	Subtractive machining
WCHIP	Wasted chip

Thesis Outline

This thesis presents four case studies, carried out during the three-year PhD course, concerning the application of the LCA and LCE methodology in manufacturing processes, with the aim of assessing production systems, technologies and product innovations that are significant for the sector, bringing a contribution to the scientific discussion on the topic.

Specifically, the thesis work is structured as follows: the first chapter provides an introduction to environmental sustainability in the main production processes, briefly outlines the history of the LCA methodology, the regulations governing it, and the steps that must be followed to carry out a life cycle analysis of a system, highlighting the main aspects that must be analysed and improved in order to reduce its environmental impact. In particular, it was first evaluated which parameters can influence the environmental impact and how the main techniques for volume invariability, subtractive and deposition of material can be selected to optimise the environmental performance of a product taking into consideration the entire life cycle. In this context, the main materials commonly used in production contexts were investigated. For this purpose, the Life Cycle Assessment (LCA) methodology was used to carry out objective evaluations.

The following chapters refer to the case studies examined and are described as follows.

In the second chapter, the main manufacturing processes, i.e. subtractive manufacturing, additive manufacturing and casting process, were investigated as possible manufacturing routes achieving an optimized geometry of the component for each of them. The topology optimizations were performed considering each process' peculiarities, introduced as constraints. The same strength for a given set of loads and boundary conditions was the goal of each analysis. The component's lightening can be considered environmentally friendly just after assessing the impacts associated with all the stages of the product' life cycle. Indeed, the overall considerations on the most environmentally safe strategies can, therefore, change according to the specificities of the optimized shapes.

In the third chapter, subtractive and additive manufacturing processes were investigated by analysing and comparing different configurations and sustainability parameters. In fact, the additive manufacturing (AM) process has been considered as an alternative to the conventional manufacturing process, i.e. Subtractive Manufacturing (SM), allowing the production of components peculiarities by innovative design and performance. In this context, sustainability assessment is essential to evaluate the appeal of the investigated technology.

In the fourth chapter multi-material components were investigated from the environmental perspective. A novel approach by using hybrid products, which combine both metal and composite materials to select a more promising solution in the automotive sector.

In the fifth chapter the impact of end-of-life processes and the main strategies applicable to a case study on polymeric composite materials were evaluated, with a specific focus on the manufacturing, remanufacturing and recycling route in order to develop a sustainable guidance depending on the composite material required.

In conclusion, some indications will be given on the main critical issues encountered, in order to draw a conclusive view of the aspects on which it will be necessary to focus attention on the coming years to improve the environmental sustainability of the manufacturing sector. Specifically, the retrospective LCA methodology, usually performed after production and commercial deployment, is used to filter out environmentally unacceptable technologies and is used as a tool to maintain environmental compliance. This provides the baseline against which the environmental performance of the different technology is compared. The environmental performance of these production systems is discussed from several perspectives. The objectives of the Thesis are presented in the next section.

Introduction

The concept of sustainability represents the ability to be self-sufficient without compromising the needs of the next generation. Specifically, the term sustainability can be linked to three types of sustainability: environmental, social and economic. The environmental sustainability is related to the preservation of the natural resources, on the other hands, social sustainability concerns the sustainability of social conditions in order to ensure a good trade-off between health, happiness, safe living, and quality of life in a specific area, e.g., the corporate environment. The economic sustainability refers to the economic growth of a given context that will ensure its development. The production system that meets the aforementioned conditions can be defined as a sustainable system.

Nowadays, sustainability pillars must be included in production processes to optimize operations to reduce the overall impact. Sustainability related to manufacturing processes can only be achieved if the three pillars of sustainability, from the ecological to the social and economic perspectives, are intersected. In detail, using renewable resources, improving occupational safety and health, and improving the quality of life in the workplace can be summarised as the requirements of sustainability. Looking at environmental sustainability, for each analysed scenario greenhouse gas emissions (GHG) must be considered. Specifically, to reduce the impact on the environment, the GHG emitted during the entire supply chain must be evaluated. Since the beginning of 21st century and until 2019, GHG emissions had followed an increasing trend mainly due to the increase in emissions from emerging economies. As a result, the atmospheric concentrations of GHG substantially increased enhancing the natural greenhouse effect, which may negatively affect the life on the Earth. For this reason, to reduce the global GHG several Countries are developing national emissions inventories and implement mitigation actions. CO_2 emissions are the main contributors to global GHG emissions. CO_2 are still increasing at world level despite climate change mitigation agreements. To reduce the CO_2 emissions of each enterprise, and consequently worldwide, several processes and materials involved in the production of goods and services should be investigated. In order to investigate the processes sustainability in the industrial field, the energy consumption of each process should be taken into account. Indeed, the energy consumption is strictly linked to CO_2 emissions. For these reasons, the research question underlying this doctoral thesis is as follows:

"How could manufacturing processes and material selection be optimized from a sustainable perspective?"

To response to the research question several processes were investigated from a sustainable point of view. More specifically in this PhD thesis, the main manufacturing processes were investigated, starting by subtractive processes, via casting processes or volume invariability through to the additive deposition process. The aim of the work was to investigate the production processes from the point of view of sustainability to better understand how the most sustainable process can be selected, but also how the appropriate materials can be chosen. During the three-year period, diverse case studies were analysed with the aim of providing an overview of the main challenges concerning environmental sustainability that the manufacturing sector is called upon to face in this historical period of great change, highlighting the aspects that are most critical.

In detail, the starting point of the research work was the study of machining processes, which start from a volume of material through progressive removal steps to obtain the final component. At the same time, for specific case studies, it is possible to choose the casting process which, by using moulds, allows the material to be cast to obtain the desired component. In this process, there is minimal loss of material, e.g. from burr channels and finishing operations, compared to the final part. At the same time, it is necessary to consider the mould production process from the point of view of sustainability, as it has a certain impact on the environment.

The complete opposite concept to the previous ones is the additive deposition process that allows the material to be deposited only in the desired places for the final output. In this respect, if the component placement process is optimised, material waste can be minimised.

Therefore, starting with the main production techniques, the impacts that process parameters, such as energy source, geometry, processing technique, and production batch affect the sustainability of the process were analysed.

On the other hand, the optimisation of production processes does not only depend on the selection of the correct process parameters but also on the efficiency of production systems both in terms of energy and the management of the resources used in the production process. In this perspective, part of the thesis work was carried out in collaboration with the Profiltek S.r.l. company in which a production management system was developed to optimise the material's flow. Specifically, the production management system was re-engineered with parallel interconnection of the machines equipped with 4.0 technology. All this resulted in an increase in productivity with a consequent increase in the flow of products within the company, which allowed innovative solutions to be developed. On the other hand, since the reference area is processing technologies and systems (IIND-04/A), the focus was on manufacturing processes. In this field, the manufacturing process and related issues of multi-material steel-aluminium products were investigated.

Considering sustainability, not only the process parameters but also the choice of materials must be properly evaluated during the design phase. For this reason, this thesis work investigated what happens from an environmental point of view when only one material is used, or several materials are combined to create a multi-material product. More in detail, therefore, the main production processes during the production of an aluminium alloy component were compared. The latter was chosen for its extreme lightness and varied field of application.

In this context, the lightweight of components, and therefore, the low specific weight of the material chosen at the design stage, is a key factor for sustainability. Indeed, when considering application fields in which the component during its service life must be transported, it must have a mass that is as optimised as possible to optimise consumption. On the other hand, the optimisation process could result in damage to the environment. Therefore, to obtain scientific evidence, the environmental impact was quantified to be a guide in the strategic choice of selecting the appropriate production process.

The analysis from a sustainable point of view was, therefore, extended to components made by combining different materials, such as steel and composite materials, which guarantee high mechanical performance while maintaining a compromise of lightness that allows optimisation of the product's life cycle throughout its useful life, also considering the use phase and the subsequent end-of-life process. In order to best explore the behaviour of innovative ultralight materials in the context of sustainability, various composite materials were therefore investigated. Specifically, composites with a thermoplastic matrix, i.e. poly-lactic acid (PLA) and polyether-ether-ketone (PEEK), reinforced with continuous fibres, i.e. glass fibre (GF) and carbon fibre (CF), were examined. In detail, these two types of matrices and fibre were chosen for their different mechanical properties and widely application field.

Research Objectives

This thesis investigates the possibility of using the LCA methodology for an assessment of the analysed processes. Their overall footprint can be optimised by using environmental parameters in the systems management. The overall goal is to define a guidance framework for the evaluation of manufacturing systems and the adopted materials and consequently use the framework in the industrial field on selected a more sustainable production technique according to manufacturing constraint. In order to achieve this, a literature review is conducted. The aim of this first step, "Objective 1", is to review the main trends in the assessment of manufacturing processes to understand the main challenges, research gaps, and to define the properly methodological framework.

Building on the main findings of the literature review, the "Objective 2" of the work is to apply the methodological framework within a specific production process and material. In particular, the aim is to define a framework to be added to the LCA methodology in order to ensure that different scenarios can be evaluated in the analysed processes.

After having defined the methodological framework and consequently different approaches for the assessment of manufacturing processes, the focus of the thesis shifts on the case studies selected from academic and industrial sector. The four case studies are composed from different materials and, consequently, diverse manufacturing techniques. At the end, the "Objective 3" is to compare conventional production systems and materials with innovative ones. Investigating how the projection of the environmental impacts varies with different batch size and optimization process. The subset of the objective consists in calculating case-specific environmental impacts for each of the selected manufacturing system; the case study is subjected to different analyses, i.e. hotspot, scenarios, indicators, and manufacturing technique. Understanding how the results of the environmental impact assessment can be used for providing guidance in the next steps of a process/product development for each one of the investigated case studies.

The aim of the "Objective 4" is to identify the potential intervention points in the process to optimize their environmental performances and to give a clearer understanding of the analysed process without a specific case study by adding a specific approach in the selected methodological framework. In this case the sub-objective 4.1 is to shift the application of the framework to assess the environmental performance of a multi-material and multi-process case study. On the other hand, the sub-objective 4.2 is to apply the selected framework on a composite case study.

Finally, the aim is to outline conclusions on the environmental performance of manufacturing processes from conventional to innovative materials and therefore discuss the environmental implications of different EoL strategies, alongside with possible future works as follow ups to this research.

1. Chapter I: Literature Review in Sustainable Manufacturing

1.1 Chapter Summary

In this chapter, the state of art of the manufacturing processes is reviewed from a sustainable perspective. The review starts with a description of the investigated manufacturing processes to analyse the process parameters that can influence the efficiency. Starting with the study of the influence of lubricants, tool consumption and total energy required by the process. The chapter follows with a review on attempts to evaluate the environmental performance of the additive manufacturing processes, according to geometry, quality, technology and material constraint. The LCA methodology framework was reported to assess the sustainability of the analysed process. Practical applications and methodological works are examined thoroughly in this section, to build awareness of failures and successes, filter out unproductive information and extract knowledge to be carried on and further developed. Finally, the chapter concludes with a summary of the pending challenges and outlines potential solutions to embed in the thesis for the assessment of manufacturing technologies and materials.

1.2 State-of-Art of the Investigated Manufacturing Processes: A Sustainability Perspective.

Typically, traditional forming processes are techniques used to modelling raw materials into specific shapes, usually used in the production of metal, ceramic and plastic objects. These methods consist of giving the material the desired shape by moulds, tools and specialised machinery. Shaping is a fundamental step in manufacturing as it determines the final geometry of the product and influences its mechanical and functional properties. Specifically, the choice of the manufacturing process depends on material properties, on the complexity of the shape to be obtained, on the production volumes and the specific requirements of the final product. To have an overall view on the traditional manufacturing processes, in this thesis, machining, additive and casting processes were investigated.

1.2.1 Machining Processes from Sustainable Perspective

Looking at machining processes, they involve shaping parts whose dimensions and surface quality are determined by cutting with operations for removing chip in machine tools. The machining process is typically used to achieve high dimensional and surface quality. Machine tools use electrical energy to remove excess material in the form of chips with the help of cutting tools and to bring a product to the desired shape. The other operations involved in the machining process to obtain the desired shape from workpiece are turning, milling, drilling and grinding. The choice of materials used in the machining processes is a key factor in a sustainability design, indeed based on the selected materials could be introduce different level of complexity. The effort, cost and time involved in the machining process depends on the material for example, composite, heat assisted alloy or superalloy require more energy than machining a low carbon steel as demonstrated by[1–3]. More in detail, according to [4, 5] when machining superalloys, excessive heat and high cutting force could be generated in the machining zone, these factors are responsible of surface quality and cutting tool's life. In order to reduce these problems during the machining operation several cutting fluids are used to optimise the process. Specifically, the flood cooling is the most used technique to reduce the high temperature reached in the cutting zone. According to Yildmir et al. using the latter method, the spray nozzle is directed into the cutting zone of the workpiece to reduce the excess heat [6]. On the other hand, cutting fluids are combined with other additives to optimise machining processes, significantly increasing economic, environmental and social aspects [7, 8].

On the other hand, according to Debnath et al., the disposal costs of cutting fluids can be up to four times higher than the purchase costs because conventional cutting fluids cannot biodegrade and must undergo additional disposal treatments [9]. The impact of the selected material for the machining process is significantly higher than the impact of lubricants, therefore choosing the right material at the design stage is crucial in terms of the process' sustainability. In fact, from an environmental point of view, the high energy consumption associated with the lubricant is offset by the high cycle times. On the other hand, in terms of human health perspective, the negative aspects due to carcinogenic chemicals mineral coolant must be taken into account [10, 11]. Lubrication method during machining operation is addressed for the negative effects on the environmental and human health, although the use of cutting fluids increase the machining efficiency by reducing the temperature on workpiece and friction in the cutting zone, as demonstrated by [12]. At the same time, worldwide are coolant less harmful for the environmental and social sustainability, i.e. dry machining, minimum quantity of lubricant (MQL), cryogenic cooling, high pressure cooling and biodegradables oils [13].

Nowadays, the scientific community is analysing the adaptation of sustainable production practices in the machining industry, as can be seen from the various analysed studies. Indeed, the machining sector has an important share in the manufacturing industry, in this context different approaches such as choice of sustainable cutting variables can be investigated to reach the concept of sustainable production concept. Firstly, life cycle assessment (LCA) – based studies, secondly investigations based on total energy consumption, thirdly research studies based on economic, environmental and social sustainability.

LCA – based studies take into account several variables, for instance Campitelli et al., in their study investigated the flooding lubrication and MQL method [14]. They claimed that energy consumption, compressor usage and lubrication method are important parameters that increase environmental impact. Whereas, according to Mia et al., the cryogenic cooling was more sustainable to dry cutting and improving the performance of the process [15]. In another study was investigated the sustainability of conventional and cryogenic machining process; the authors state that initial costs for setting up the cryogenic machining system are higher than traditional cutting process, but the production costs per part could be reduced by about 30% when the cryogenic machining was applied, even if there are issues about the reliability of the process in the industry sector [16]. Several studies evaluate the environmental impact of lubricant methods applied in machining processes in order to evaluate the best scenario in terms of environmental impact and process optimisation [17–21].

More in detail, the industrial sector in the US accounts for about 51% of total electricity consumption, and a significant portion of this percentage is consumed by machine tools for metal forming/cutting operations. For this reason, to evaluate the sustainability of the process following several studies have investigated the energy consumption trends.

According to Khan et al., in a machining process typically there are three main phases during which there is an energy consumption rate, i.e. startup phase, run time phase and machining phase [22]. The latter is the higher energy consumption due to process and material parameters, whereas the firstly and secondly are constat during the process.

According to the above, diverse studies have been conducted to investigate the different way to account the energy consumption of the machining tool during the total machining process. By analysing the literature, according to the research study proposed by [23], they have been calculated the machining efficiency and modelled the processing time. Specifically, through their model they accounted the tooling changing time per workpiece, actual cutting time, air cutting time as reported in the study [23]. They observed that the greatest environmental impact is observed when the total machining time is calculated, which refers to the total time spent on the machine tool for machining a component.

On the other hand, other studies have been focused on the energy efficiency models, more in detail, according to the firstly approach observed by Peters the energy efficiency can be defined as the ratio of power required for cutting to the total power consumed by machine a tool [24]. Another approach used to calculate the energy efficiency of the process is based on the total expected chip evaluated by [25]. According to this approach the energy efficiency depends on the energy expected to extract the material per unit volume. And more in the other research study different energy consumption models were developed. In detail, the models investigate direct and direct consumption energy. Mori et al., in their study proposed the energy consumption model that covering each step involved in the machining process, i.e. standby, idle time, actual cutting and stopping of the spindle on the machine tool [26].

Whereas in a recently published studies, according to Gupta et al. and Khan et al., the total energy consumption can be estimated by accounting the power consumption for each step, i.e. standby, spindle, air cutting, cutting, lubricant [22, 27]. In order to evaluate the Cumulative Energy Demand (CED) Liu et al. proposed another model able to quantify the total energy consumption in machining process including direct energy required in machine tools and indirect energy consumption required, i.e. cutting tool, workpiece and coolant energies [28]. In this thesis this approach was used to quantify the sustainability of the machining process.

During machining processes, different technical constraints, for instance too complex shape of the component, conformal cooling channels within small component, high inclination angle or small features in the target component, can hinder the machining process. In this case, the subtractive process encounter limitations, while the opposite concept, i.e. the additive manufacturing process can be applied in order to overcome the limitations occurred in the conventional process. For this reason, in the next section the AM will be investigated.

1.2.2 Additive Manufacturing Processes from Sustainable Perspective

In comparison to the conventional machining, i.e. Subtractive machining, the additive manufacturing could be an innovative sustainable process if the properly parameters were set. This is mainly due to the potential of AM technology to create complex shapes with fewer wastes, optimize material consumption, and shorten production times [29, 30]. The latter is true, if it is compared with conventional machining and when the rate between solid cavity ratio of the component is low. In this condition, during the conventional machining the tool have to remove a lot of material; on the other hand, the additive manufacturing have to deposit a low quantity of material and therefore, this requires short production time.

Generally, the prototyping phase is a costly process. On the other hand, by using the AM technology the cost and development time can be reduced. According to Diegel et al., the additive manufacturing process continues to be a functional tool to enable eco-friendly product to address both design quality and cost efficiency [31]. Furthermore, the AM may use a recycled material to reduce the product environmental impact [32]. Another concept that can be investigated, with the aim to reduce the quantity of virgin material used during component production, is the use of additive technique to repair, remanufacture, and update tooling also shows an opportunity for significant reductions in costs and energy consumption [33]. From a sustainable point of view the weight of a target component is a key factor. Indeed, the use phase or the transportation phase can be optimized if the component's weight is optimized, for instance the emissions due to fuel consumption can be minimized. Petrovic et al., claim that by using the AM can be achieve up to 40 per cent of reduction in material waste compared to conventional manufacturing. Indeed, more than 95 per cent of the residual materials can be recycled [34]. In their study, Gebler et al. pointed out that a component manufactured by additive manufacturing can reduce the environmental impact from the energy consumption point of view between 2.54 – 9.34 exajoule (1 EJ = 1018 J) during the entire life cycle[35]. More in detail, according to literature review of several study that investigated different additive manufacturing processes from an environmental point of view, i.e. powder bed fusion (PDF) [36], laser sintering (LS) [37], additive laser manufacturing (ALM) [38], selective laser sintering (SLS) [39, 40], selective laser melting (SLM) [41], direct metal laser sintering (DMLS) [42], fused filament fabrication (FFF) and fused deposition modelling (FDM) [43], stereolithography (SLA) and binder jetting (BJ) [44, 45], the energy consumption and the material energy, required to extract mineral resources and process it to obtain raw materials, are the main factors that contribute in the environmental impacts of the AM process.

According to mainly analysed studies, the investigated sample provides a picture of the environmental impacts of geometry related and material related parameters of AM. Considering geometry parameters, part orientation, weight, base area, cross-sectional area, complexity of the shape, number of layers along z-axis and number of target component were investigated [40, 46–49]. While, considering materials parameters, the material density, emissions due to material, recyclability and shrinkage rate were analysed [49–53]. The outcomes revealed that the sustainability of the AM process is affected 4.76% by the cross-sectional area, 9.52% by the base area, 14.28% by the part weight and surface area, 23.80% by the volume part, 38.00% by the material, shape complexity and volume fraction, 57.14% by the number of layers along z and finally, all analysed studies consider the part orientation as the most impactful factor.

Another category of research studies investigated process related parameters to minimize the environmental impact. More in detail, the studies investigated the application of eco-design approach in the AM. This approach aims to optimise the environmental impact from the initial concept of the product to its other life phases such as production, use, and disposal. The application of this approach in AM can optimize energy and material consumption [39]. Other researchers studied how the environmental impact varies with the nesting and optimal layer thickness of the SLS process[40]. The results showed that energy reduction can be achieved by optimising the orientation of the part, thereby increasing nesting efficiency. In addition, higher nesting efficiency may also lead to a reduction in powder waste and environmental performance improvements. Other studies developed a correlation between process parameters and sustainability, such as the component's geometry and orientation, the laser energy and thickness of the slice. For instance, it has been found that the lowest laser energy is obtained when the laser works perpendicular to the workpiece and that the thickness of the part slice has a greater effect on laser energy than the orientation of the workpiece [54–56]. Another relevant parameter that is investigated in the literature is the layer thickness. This parameter has a relevant impact on the energy consumption and printing time. Whereas printing speed parameter has been taken into account in the environmental sustainability of AM. Indeed, printing parts at high speed while maintaining the print's quality can result in lower energy consumption [57, 58]. In the meantime, increasing the powder feed rate leads to increasing the deposition volume resulting in lower energy consumption [59].

The outcomes of the analysed studies pointed out that the powder feed rate is inversely proportional to the energy consumption while the scanning speed and laser power are proportional to the energy consumption. On the other hand, the increase in scanning speed led to a reduction in process time and consequently in energy consumption per unit.

1.2.3 Casting Process from Sustainable Perspective

On the other hand, in conventional manufacturing (CM), which is widespread throughout the world, components are manufactured using formative and/or subtractive (SM) manufacturing processes. In formative methods, the final geometry of the component is obtained by casting the material within the mould. In the latter case, there are various casting processes (CPs) such as sand casting, lost foam casting or lost wax casting, etc. On the other hand, there are conventional deformation processes which, by applying forces, allow a plastic deformation of the material mass in the solid state until the desired geometry is achieved. Among these are mass deformation processes such as forging, rolling, extrusion, etc [60]. Other studies taken into account the sustainability of formative process in comparison to additive manufacturing [61, 62].

On the other hand, the whole product's life cycle has to consider reducing the environmental impact. M. Santiago-Herrera et al. 2024, in their work analysed the sustainability of a gearbox manufactured with a conventional production process, i.e. a casting process, and an additive manufacturing process, i.e. a direct energy deposition process. The authors state that the casting process is more environmentally friendly for the specific case study [63]. Further environmental parameters and design choices have to be investigated in order to get a more comprehensive overview.

1.2.4 A Comparison between Additive and Machining Processes

Many research studies have compared the environmental impacts of various AM technologies and conventional manufacturing (CM) approaches [52, 64, 65]

Priarone and Ingarao have compared the environmental impacts of production metal parts using CM and a hybrid process based on AM assisted by machining [64]. The authors claims that the hybrid process, i.e. AM assisted by CM is more environmentally efficient. Specifically, in another study, researchers argue that the SLM process is more sustainable than traditional forming and machining processes, in particular way, when producing complex structures and significant weight reduction was required, as above reported [65].

1.2.5 Parameters Related to the Materials

Looking at environmental aspect, material characteristics could be investigated, indeed, when the sustainability of the process have to be optimized this is a key factor. According to several research studies and technical report the selected materials used during the design phase contributes in a significantly way for the sustainability. In accordance with the above the main manufacturing materials investigates are metals, e.g. low-carbon steel, aluminium alloy 6061, plastics, e.g. PLA, and composite materials.

In order to select the key parameters not only the aforementioned processes have been analysed in this thesis, as well as different materials. Specifically, different metals and alloys such as stainless steel, nickel-based alloys, titanium alloys, as well as some aluminium alloys can be processed via CM and AM. Several studies investigated the sustainability of process with a selected material, such as titanium alloy or AISI steel [22, 66–68] in conventional processes. Whereas, in another study Baumers et al. presented a comparative environmental analysis of two metal additive manufacturing process in order to evaluate titanium and steel material [51].

Due to their versatility and ease of use, polymers and continuous fibre reinforced polymer (CFRP) are also two types of materials that are widely used in various applications both for AM and for joining with traditional materials such as metals. Main research studies have analysed the effect of material parameters on the energy consumption in the sustainability of AM process, for instance the use of biodegradable materials and the effect of density of the selected material [63, 69, 70]. Researchers have explored the potential of these materials for use in construction applications. Through detailed case studies, they have analysed the use of CFRP as a sustainable alternative to conventional materials for their lightness [71]. On the other hand, the end of life of CFRP has taken into account. Further investigations by Utekar et al. and Gonçalves et al., provide a comprehensive study of composite recycling methods at the end of life of a component. These studies assess various recycling processes, considering the balance between energy demand due to recycling process, and the mechanical performance of reclaimed fibers [72]. Gonçalves expands on this analysis by evaluating energy efficiency and economic aspects of different GFRP recycling methods, emphasizing the need for affordable recycling solutions that do not compromise the quality or structural integrity of the reclaimed materials [73]. Arif et al. contribute to this field with an in-depth study of composite recycling methods, highlighting high-voltage fragmentation (HVF) as an innovative, low-energy technique with high recycling rates[74]. Their research discusses HVF’s potential as a scalable and environmentally friendly method, making it a viable solution for composite waste management. By comparing various recycling methods, Arif’s study emphasizes the importance of balancing environmental impact and energy consumption to achieve sustainable recycling outcomes [74].

1.3 LCA Methodology

The first studies attributable to life cycle assessments date back to the late 1960s and early 1970s, a period remembered for the oil crisis and the energy debate. Recently, there has been a great increase in the scientific community's interest in LCA studies. Supporting the interest shown by researchers is the number of articles published in academic journals, in fact from 1998 to 2024 there has been an increase in LCA studies from 100 to more than 1200 [75].

The Life Cycle Assessment (LCA) methodology was applied in this work to carry out an assessment of the sustainability of manufacturing processes. In this work, processes were modelled to assessment the environmental impact in order to give guidelines for selecting a technology more suitable from an environmental perspective.

1.3.1 LCA Framework

LCA, or life cycle analysis, is a measurement of the environmental impacts from the life cycle of a product, process, or service [76]. The different parts of a life cycle, called life cycle phases, can have multiple impacts on the environment. LCA makes it possible to assess the product's total impact or the impact of the different phases. This can help decision-makers to make informed choices regarding product development, marketing, strategic planning, and policymaking. The methodology is standardised through a few different standards. This work was written according to the ISO 14040 and 14044. There are four main phases to LCA, described by these standards:

1. Goal & scope
2. Inventory analysis
3. Impact assessment
4. Interpretation

The LCA is used to assess the environmental impacts by using the life cycle of a product. If the production process is considered, environmental impacts are assessed from the raw material processing. This phase is also called “Cradle”, which is part of the term “Cradle-to-Grave”. The term “grave” is derived from the last piece of material processing, when materials are recycled, disposed of, or lost. Indeed, the LCA is an iterative method as described in figure 1.1.

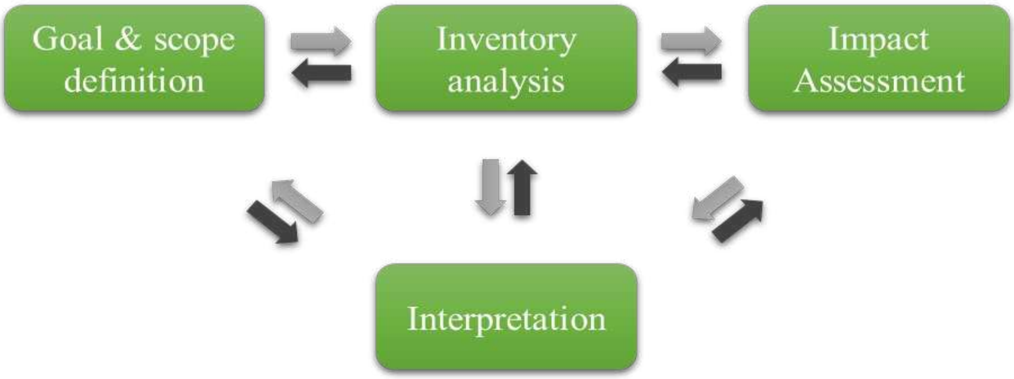


Figure 1.1 Illustration of the four LCA phases according to ISO14040 and their iterative relations[77].

1.3.2 Goal & Scope

The goal and scope describe the how and why for the analysis and ensures that the LCA is performed consistently. LCA gives a model of a complex reality, meaning multiple simplifications must be made. Carefully definition of the scope and goal ensures that these simplifications do not influence and distort the results too much. The most important choices made in the study are described in the goal and scope [9-10]. The goal and scope should be defined with the commissioner and should be clearly defined and consistent with the intended application [76, 78]. The goal should describe the intended application of the product, process, or service. The reasons for the study should also be described in this part, along with the intended audience and who the paper will be disclosed to. The scope describes the product system studied, meaning the functions of the system or systems in the case of comparative studies. This includes the functional unit, which describes the function of the system in line with the goal and scope. All inputs and outputs are considered in relation to and normalised to this unit. The scope also describes the system boundaries, which describes what are taken into consideration and what is left out. This will depend on money, time, resources, and what is wanted by the commissioner. The allocation procedures describe how allocation of impacts is made when they are based on a choice. E.g., how much of the impact is given to the product and the by product. Methodology and impact categories based on impact assessment and interpretation must be described in the scope as well, along with the data requirements, assumptions, and limitations [76].

1.3.3 Functional Unit

The functional unit quantifies the function of the investigated product. Its primary purpose is to provide a reference to which input, and output data are normalized; therefore, the functional unit have to be clearly defined and measurable. Since LCA studies are commonly performed to compare alternative ways of performing a given function, the functional unit also serves as a basis for comparison.

System Boundary

System boundaries separate the technical system, which comprises all activities that are part of or affected by the product life cycle, from the environment. Material or energy flows between processes are referred to as technical flows, while flows between processes and the environment, i.e. those that cross system boundaries, are referred to as elementary flows. For instance, an elemental flow is defined as a material or energy that added to the system and is obtained directly from the environment without previous transformation. On the other hand, this is not practical due to the lack of data and therefore, it is necessary to decide which flows include in the system boundaries. The assumptions have to be included in the definition of the objectives and scope.

1.3.4 Inventory Analysis

The second step in an LCA, when using the ISO 14040 / 14044 is the life cycle inventory, in which an overview of the materials and processes used during the production of functional units was presented. In the inventory analysis, the environmental inputs and outputs were studied. Environmental inputs represented something taken out of the environment and added to the products life cycle. On the other hand, environmental outputs were taken from the products life cycle and added to the environment. These data provide a complete overview of the inventory [76, 77]. The inventory analysis consists of four steps: preparing for data collection, data collection, calculation, and allocation. The reliability of the data depends on the reliability of the source and must be documented [76]. A fundamental action, necessary before starting data collection, is to identify all the processes involved in the system under investigation. This can be done by starting with discriminating the unit process that has as its output the reference flow, which is the flow that satisfies the function quantified by the functional unit. During the LCA cut-offs of process unit can be applied on reference flows or life cycle phases, if these are not quantitatively relevant. For instance, the cut-off implies to not account for one or more elements, if these do not carry more than 5% of the total environmental impacts.

1.3.5 Life Cycle Impact Assessment

The third phase of an LCA conducted by ISO 14040/14044 standard, is life cycle impact assessment. At this phase, conclusions are drawn in order to make better and more informed decisions. The environmental impacts collected and modelled in the inventory analysis are classified into categories [78]. This allows evaluation of the potential environmental impacts. First impact categories, category indicators, and characterisation models are selected. It is important that the subjective choices (assumption) made are documented. Then the classification step is done, during this step the inventory results are assigned to the impact categories. This is based on the impact assessment method chosen. Finally, the calculation of category indicator results is done, this step is called characterisation. This step is performed by multiplying the inventory results with characterisation factors, usually using a program. The calculation provides the contribution to impact for each category indicator. Characterisation factors are provided by the assessment method. There are two main types of impact categories, as they can be described on two different levels. There are the midpoint effects, which describes the effects on nature, e.g., acidification, global warming, ozone depletion, etc. The other category is endpoint effects, which are the consequences of the midpoint effects, e.g., less biodiversity, shorter length of human life, and resource depletion [76].

1.3.6 Impact Assessment Method

According the LCA methodology different standardised method are available in literature in order to quantify different environmental parameters. In this thesis the two most common used methods were reported. First one is the IMPACT world + V1.01 method [79]. Second one is the ReCiPe 2016 Endpoint (H) V1.06 method [79].

IMPACT world + Midpoint

The IMPACT world + method, is the update of the IMPACT 2002+, LUCAS, and EDIP method [12]. According to the developers, most of the regional impact categories have been spatially resolved and all the long-term impact categories have been subdivided between shorter-term damages (over the 100 years after the emission) and long-term damages. There are two versions of this method, each one analyses the midpoint indicator, the other one the endpoint. In this LCA study only midpoint indicators will be studied. The impact categories of the Midpoint version are based on the following models:

- Global Warming Potential (GWP100) and Global Temperature Potentials (GTP100) are used for, respectively, climate change short- and long-term impacts. Those two indicators are needed because they express different impacts: GTP100 (climate change long-term) are impacts related to long-term cumulative warming (e.g., sea level rise), while GWP100 (climate change shorter-term) are impacts related to a rapid increase in temperature to which humans and species must adapt very quickly. The unit of these impact categories is kg CO2 eq.
- Marine acidification impact is based on the same fate model as climate change, combined with the H+ concentration affecting 50% of the exposed species. Therefore, this impact category indicates the acidification of marine water due to gas emissions. The unit is expressed as kg SO2.
- Marine eutrophication impact indicates the enrichment of ecosystems due to emission of nutritional elements. The unit is expressed as kg N eq.

- For mineral resources depletion impact, the material competition scarcity index from de Bruille (2014) is applied as a midpoint indicator. This impact category indicates the abiotic depletion from mineral resources. The unit is expressed as kg Sb eq.
- Terrestrial and freshwater acidification impact assessment is based on Roy et al. (Roy et al. 2014; Roy et al. 2012a; Roy 24 et al. 2012b) and combines, at a resolution of 2 °x 2.5 ° (latitude and longitude), global atmospheric source-deposition relationships with soil and water ecosystems sensitivity. Therefore, it indicates the acidification of soils and water due to gas emissions. The unit is expressed as kg SO2.
- Freshwater eutrophication impact is spatially assessed at a resolution grid of 0.5 °x 0.5 °, based on a model from Helmes et al. (2012). Therefore, it indicates the enrichment of ecosystems due to emission of nutritional elements. The unit is expressed as kg PO4 eq.
- Freshwater ecotoxicity and human toxicity impact is based on the parameterized version of USEtox for continents. The developers considered indoor emissions and differentiated the impacts of metals and persistent organic pollutants for the first 100 years from longer-term impacts. Therefore, USEtox calculates characterization factors for human toxicity and freshwater ecotoxicity at midpoint level. The characterization factor for human toxicity impacts (human toxicity potential) is expressed in Comparative Toxic Units (CTUh), the estimated increase in morbidity (disease) in the total human population, per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue. Unit: [CTUh per kg emitted] = [disease cases per kg emitted]. The characterization factor for aquatic ecotoxicity impacts (ecotoxicity potential) is expressed in Comparative Toxic Units (CTUe), an estimate of the potentially affected fraction of species (PAF) integrated over time and volume, per unit mass of a chemical emitted. Unit: [CTUe per kg emitted] = [PAF × m^3 × day per kg emitted].
- Impacts on human health related to particulate matter formation are modelled using the USEtox regional archetypes to calculate intake fractions and epidemiologically derived exposure response factors. The unit is expressed as kg PM2.5 eq.
- Photochemical oxidant formation, ozone layer depletion, and ionising radiation are based on ILCD handbook recommendations. The model calculations were updated to take into account the most recent values of the World Meteorological Organisation's (WMO, 2014) ozone depletion potential. The impact categories indicate the creation of smog by emission of gases, the emission to air by the destruction of the ozone layer, and the emission generated through nuclear reactions, respectively. The units are kg NMVOC eq, kg CFC-11 eq, and Bq C-14 eq, respectively.

- Water consumption impacts are modelled using the consensus-based scarcity indicator AWARE. Therefore, it indicates the impact on terrestrial and freshwater species and on the increase of malnutrition. The unit is expressed as m3 world eq.
- Impacts from land occupation and transformation on biodiversity are based on de Baan et al. (2013). Therefore, it indicates the impact on terrestrial species. The unit is expressed as m2yr arable.

ReCiPe 2016 Endpoint (H)

The ReCiPe method is a combined midpoint and endpoint assessment method, with main contributors being RIVM, Radboud University, CML and Pré Sustainability [23]. This method calculates 18 midpoint indicators and 3 endpoint indicators. Relations between the midpoint and endpoint indicators can be seen in figure 1.2. In this LCA study, only the endpoint categories will be studied, as midpoint was performed by the IMPACT world + method.

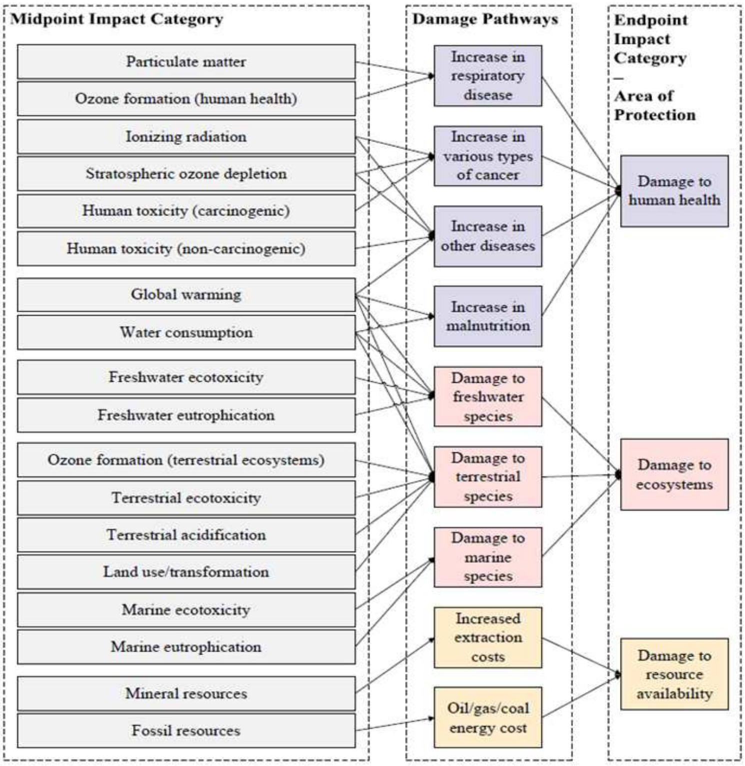


Figure 1.2 Overview of the ReCiPe method structure.

The endpoint categories, their units and descriptions were explained as follow:

- Damage to human health, this endpoint impact category indicates the damage to human health, and it is measured as lost years of life per person per year. The unit is expressed as DALY (Disability Adjusted Life Years)
- Damage to ecosystems, this endpoint impact category indicates the damage to ecosystem diversity, and it is measured in species/year. The unit is expressed as species. Yr
- Damage to resources, this endpoint impact category indicates the increased extraction cost of minerals and fossil fuels. The unit is expressed as USD (2013).

1.3.7 Interpretation

This phase involves interpreting the results of the inventory and impact assessment phases and possibly drawing conclusions and recommendations for improving the environmental performance of the system studied. In this phase, therefore, opportunities to minimise the impact associated with a product are evaluated.

First, the results of the analysis are presented and the main aspects highlighted. An evaluation is then carried out which consists of the following points:

- completeness check, to ensure that all relevant information and data necessary for interpretation are available and complete;
- sensitivity check, to assess the reliability of the final results and conclusions by determining any uncertainties in the data, allocation methods and calculations;
- consistency check, to determine whether the assumptions, methods and data are consistent with the set goals and objectives.

Finally, conclusions are formulated highlighting the limitations of the study and reporting any recommendations for improving the environmental impact. The phases of an LCA are not always separate from each other and influence each other in an iterative process. The availability and quality of data, for instance, can influence the choice of system boundaries, the interpretation phase can lead to a revision of the project's purpose and scope. Because of these interactions, LCA is not a linear analysis but a process that must be continually revisited and updated over time. As the analysis deepens, new data may replace old data through a process of revised calculations and assumptions. It should be noted that LCA is not only a means of environmental protection but also an important tool for strengthening competitive dynamics and cost reduction and control.

1.4 Conclusions

The literature review highlighted past and current trends in the application of LCA methodology and offered a glimpse of possible parameters to be taken into account when analysing different production processes. The methodology is developing in a direction where factors from the economic and social spheres are integrated into the life cycle assessment of a technology. However, the literature review identified several challenges in defining different end-of-life approaches. Hence, the main challenge represents the robustness of the life cycle inventory.

Currently, the main uncertainties concerning the reliability of the results mainly concern the level of subjectivity of the assessments, both in the inventory phase and in the subsequent impact analysis, and the possibility of finding data and information consistent with the analysed processes.

On the other hand, there is a lack of practical examples in the literature of comparative LCA between different processes with different end-of-life scenarios and assessments of the waste obtained from the manufacturing processes. Furthermore, there are limited assessments available for the environmental performance provided by the application of new production routes instead of conventionally adopted systems.

Building on the results of the literature review, the next chapter of the thesis will report on the application of the methodology adopted and an introduction to the four case studies submitted for assessment.

2. Chapter II: Applied Framework and Introduction to the Analysed Case Studies

Part of the content of this Chapter was published in:

- International Journal of Material Forming
  Borda, Francesco, La Rosa, Angela Daniela, Filice, Luigino, Gagliardi, Francesco, 2023. Environmental impact of process constrained topology optimization design on automotive component' life
- Journal of Cleaner Production
  Borda, Francesco, Ingarao, Giuseppe, Ambrogio, Giuseppina, Gagliardi, Francesco, 2024. Cumulative energy demand analysis in the current manufacturing and end-of-life strategies for a polymeric composite at different fibre-matrix combinations
- Advances in Materials and Processing Technologies
  Borda, Francesco, La Rosa, Angela Daniela, Filice, Luigino, Gagliardi, Francesco, 2024. Environmental comparison of opposing manufacturing strategies at changing of energy sources, EoL approaches and shape peculiarity for an automotive component

2.1. Chapter Summary

In the previous chapter, the literature has been reviewed. A critical review of the previous analysed parameters of each different manufacturing technologies in a sustainability perspective were investigated in order to assess the current research gaps and helping to identifying challenges.

Starting from these assumptions, this chapter introduces the analysed framework with the aims of integrating the existing LCA methodology with additional assessment steps and considerations to overcome the gaps emerged in the literature review. The methodological approach is described, and four case studies for different materials and manufacturing technologies, selected from industrial field, are presented.

2.2 The Framework

Methodological choices are determined by the objective of the study and the posed research questions. In order to understand the evaluations carried out, the choices and research questions must be clearly defined. This requires the definition of the goals and scope of the work. In this section the frameworks coupled to the conventional LCA methodology were described. Specifically, one of the objectives of this thesis work is to define the variation of the environmental impact of a component made using different manufacturing techniques when varying the end-of-life strategy and consequently the impact of the starting material on the overall impact of the final product.

In this context, two fundamental concepts in the calculation of end-of-life effects have been adapted to the materials and processes investigated. The analysis considered two different methods to assess the product's EoL. The first one is the recycled content, and the second one is the substitution method. The first one attributes the full benefit of recycling to the beginning of the material life cycle, reducing the impact of input materials. The second method, on the other hand, attributes the environmental credits of recycling to the end-of-life phase. Equations (2.1-2.2) detail the above methods, respectively.

$$H(net)_{recycled\ content} = (1-R)\cdot(m_b)\cdot\ h_m + (R)\cdot(m_b)\cdot\ h_{rc} + (1-r)\cdot(m_c)\cdot h_d \quad (2.1)$$

$$H(net)_{substitution} = (m_b)\cdot h_m - r\cdot(m_c)\cdot(h_m - h_{rc}) + (1-r)\cdot(m_c)\cdot h_d + (m_b - m_c)\cdot h_d \quad (2.2)$$

where, *R* is the fraction of recycled material in a new material and *r* is the component recyclability at the end of its life. Whereas *mb* and *mc* represent the initial billet mass and the component mass, respectively; *hm* represents the aluminium alloy's material extraction specific energy, *hrc* represents the recycling process's specific energy. Finally, *hd* denotes the disposal specific energy referring to the landfilling of waste material.

The two applied frameworks allow assessments to be made from the point of view of the total energy required, which is closely linked to the emission of carbon dioxide. For this reason, the quantification described in the previous equations expresses energy values in MJ units. More in detail, the discussed frameworks were applied in different context to quantify the material waste carried out from manufacturing processes, as discussed in a properly way in the next chapters. The applied methods have been applied in this thesis work and have been coupled with the LCA methodology in order to obtain overall assessments of the impact of the investigated case studies and processes.

Finally, in the interpretation of the results arising from the application of the aforementioned methods coupled with the LCA analysis, it is worth considering that the different scenarios and assumptions for process and material modelling choices should not be considered as the end result but provide a set of expected answers and not the answer. Indeed, the goal of this approach is to establish the necessary basis for discussing and guiding research and development, and to provide a solid platform for discussing with all parties involved the critical points to focus on.

2.3 The Case Studies

In this thesis the proposed framework coupled with LCA methodology is applied to four case studies that originate from both academic and industrial field. The case studies are briefly introduced below, and subsequently examined separately, in the next four chapters of the thesis.

2.3.1 Case Study I

The first case study looks into the manufacturing of a bracket used in the automotive sector with different manufacturing techniques coupled by the topological optimization methodology. Specifically, the bracket was studied from literature perspective in order to assess the more sustainable manufacturing process. The aim is to define the critical points in the manufacturing process to minimize the environmental impact by selecting the properly manufacturing process based on the constraint. At the same time, understand under which conditions the analysed system can result in performance gains over another one.

2.3.2 Case Study II

The second case study focuses on the comparative analysis of an automotive component manufactured by different manufacturing techniques. This research aimed at performing a life cycle assessment (LCA) of an automotive component manufactured by both the proposed manufacturing techniques, i.e. subtractive manufacturing and additive manufacturing, at changing the volume ratio between the final shape and the initial enveloping billet.

2.3.3 Case Study III

The third study explores the effects on the environment from multi-material product by analysing different EoL scenarios. Specifically, the analysed case study focused on a hybrid metal-composite component in the automotive sector. The aim of the study is to provide guidance to LCA practitioners to quantify the effect of the application of multi-material components in the automotive industry and compare it with conventional processes and materials.

2.3.4 Case Study IV

Finally, the fourth case study investigates different scenarios of EoL of a composite sample without a specific function in order to explore the environmental effect of the material considering different EoL strategies. This research aimed at providing guidance for the selection of the most suitable EoL strategies, taking into account the continuous fibers reinforced thermoplastics material properties, as a decision support tool that, practically, can be employed in choosing the most energetically convenient path.

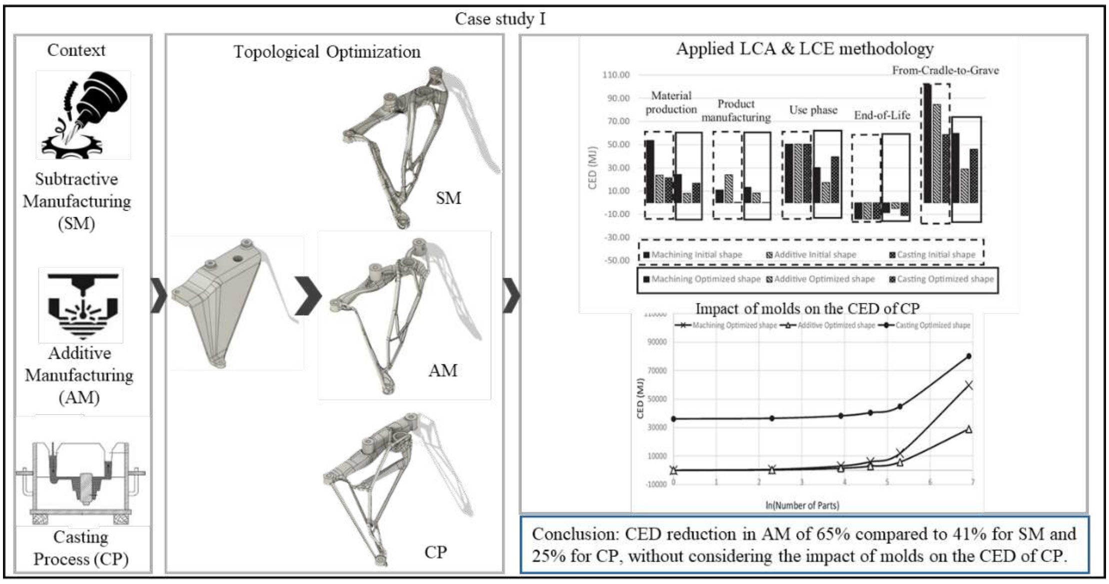
3. Chapter III: Sustainability Analysis of the Subtractive, Additive and Casting processes.

Part of the content of this Chapter was published in:

- International Journal of Material Forming
  Borda, Francesco, La Rosa, Angela Daniela, Filice, Luigino, Gagliardi, Francesco, 2023. Environmental impact of process constrained topology optimization design on automotive component' life

3.1 Chapter Summary

The components' lightweighting has been pursued, especially in the transport industry, for greenhouse gas reduction. In this perspective, according to Huang et al. lighter parts can result in an energy and material savings, these parameters are strictly linked to carbon dioxide emissions [52]. On the other hand, according to other research studies the volume of a part can increases the energy consumption during the manufacturing phase [43, 49]. One of viable solutions to optimise the part's weight is via topological optimisation (TO) method [80]. TO, being able to allocate the material within a provided design space, is a mathematical method that can support the design of lightweight components, preserving, at the same time, their mechanical performances. On the other hand, this method can guarantee a lighter component, however, this could lead to disadvantages depending on the process used to manufacture the component. By utilizing topological optimization (TO) in AM can improve the sustainability due to brief manufacturing time, lower material and energy consumption [81, 82]. On the other hand, from a sustainability perspective, conventional manufacturing techniques, such as subtractive manufacturing (SM) and casting processes (CP), coupled by TO must be carefully considered. Consequently, the research presented in Chapter 2 assesses the environmental sustainability of AM, SM, and CP processes, with a specific focus on their integration by the TO method. In this chapter, the standard shape of a component, specifically an automotive bracket, was topology optimized by estimating the impacts of the new designs from an eco-friendly point of view. A subtractive, an additive and a casting manufacturing process were considered as possible manufacturing routes achieving an optimized geometry of the component for each of them. The topology optimizations were performed considering each processes' peculiarity, introduced as constraints. The same strength for a given set of loads and boundary conditions was the target of each analysis. The component lightening can be considered environmentally friendly just after assessing the impacts associated with all the stages of the product's life cycle. Indeed, each phase of the product's life cycle can be affected, differently, by the performed topology optimization taking into account the peculiarities of the employed manufacturing process. The overall considerations on the most environmentally safe strategies can, therefore, change according to the specificities of the optimized shapes. The topology optimization showed its utmost potentiality, from a sustainable point of view, if applied to additive manufacturing techniques for the advantages arisen by the capability to manufacture complex shapes benefiting also of reduction time process owing to less material to be deposited. Finally, to present a comprehensive overview of the work, the graphical abstract in Figure 3.1 was provided.



Conclusion: CED reduction in AM of 65% compared to 41% for SM and 25% for CP, without considering the impact of molds on the CED of CP.

Figure 3.1 Graphical abstract.

3.2 Introduction

Topological optimization (TO), widely used in aerospace, mechanical, bio-chemical and civil engineering, has been developed to provide a mathematical tool to the designers helping them in the minimization of the amount of used material in parts' construction [83]. Specifically, TO aims at maximizing the component performances taking into account specific sets of structural loads, boundary conditions and constraints [84]. Furthermore, the TO analyses have to be fine-tuned taking into account restrictions related to the manufacturing strategies chosen for the part production [85]. Hence, considering the constraints introduced by the selected manufactured process, the TO can propose different geometries of a component, characterized by different weights. This is a relevant matter considering that, generally, material reduction in component's production is often strictly related to the greenhouse gas (GHG) emissions, especially if components for the transport industry have to be produced [85]. Focusing the attention, as a matter of fact, on the transport sector, currently, the average emission target for the entire EU fleet for new passenger cars is 95 g CO2eq per km and terms such as 20 g CO2eq per km or also zero emissions per km have been discussed [86]. Indeed, the strategy adopted by the European Union (EU) for adapting to climate change will lead Europe to become climate neutral by 2050 [87]. Therefore, optimizing the parts' geometry results in improving environmental performances [88]. Specifically, Upadhyayula et al. [89] claimed that fuel consumption in internal combustion engine vehicles is reduced by 6% for each 10% reduction in weight of the vehicle.

Luk et al. [90] introduced the concept of part functionality claiming that the reduction of the vehicle weight and the related fuel saving must be strongly associated to the capacity of the part to fulfil its assignment. Finally, Bian et al. [91] implemented a lightweight design in commercial vehicles to reduce fuel consumption by 20%. The components' environmental performance must take into account not only the product design, but also its production, use and disposal phases. In this way, a complete impact's assessment can be achieved [92]. Eco-design by topological optimization moved in this direction considering the sustainability analysis criteria such as carbon emission reduction, energy efficiency and carbon footprint reduction [93]. Furthermore, artificial intelligence technology makes possible the development of increasingly sophisticated optimisation software to design sustainable, efficient and environmentally effective products [94, 95]. In this context, DeBoer et al. [60] carried out an LCA analysis of 3 different additive manufacturing processes. The novelty of the proposed work is the implementation of the topology optimization combined with a Life Cycle

Assessment (LCA) analysis taking into account different production routes for manufacturing a specific component. An automobile part, i.e., a bracket was the selected component to be optimized, topologically. Several studies have been proposed aiming at quantifying the environmental impact of vehicles [96]. The LCA was chosen because it allows including all phases of the product's life cycle, from the extraction of raw materials to its manufacturing phase, from the use phase of the produced component to its EOL [97]. Specifically, Subtractive Manufacturing (SM)[83, 98], Additive Manufacturing (AM) [99, 100] and Casting Process (CP) [101, 102] were proposed as possible process routes to produce the component. In detail, SM is performed by a 5-axis standard milling machine, AM employs the laser sintering 3d printer and the CP makes use of steel moulds. The bracket's geometries with and without topology optimization were analysed considering the restrictions related to each of the manufacturing processes. As a result, three optimized geometries were obtained guaranteeing for each of them the same mechanical strength of the starting shape. Subsequently, the LCA analysis was implemented for each geometry considering the related process employed in its construction. In addition, focusing on significant impact categories, considerations on the performance of each process taking into account the number of the parts to be produced were also provided.

3.3 Materials and Method

A bracket is a component generally used to improve the reliability and accuracy of adjacent mechanical components reducing vibrations and oscillations. Damping brackets can reduce noise and material wear helping in preventing critical components from breaking or malfunctioning [103]. The brackets' number required in an automotive can vary from none to two or more [104]. The initial geometry of the investigated bracket's typology, whose weight is of 0.140 kg, was extracted by literature [105]. The main sizes of the box required to envelop this geometry are: 135x60x80 mm (Fig. 3.1). The material, constraints and structural loads, applied in a single condition, were also extracted by literature [105], see Fig. 1. Three topology optimized shapes, reported in Fig. 3.2, were designed starting with the geometry extracted by literature. The simulations were performed by Autodesk Fusion 360 software [106] with the aim of reducing the mass of the component guaranteeing a minimum allowable space and preserving a safety factor of 2 compared to the yield strength of the material. The finite element simulations were set by meshing the parts by Inventor Professional. This pre-processor employs just solid elements for the geometry's discretization. Specifically, tetrahedron elements (4 physical points and 10 nodes for interpolation) were utilised. The average element size of the mesh is 0,1. The number of elements was: 2682 for the standard shape and 23,127, 23,889 and 26,249 for the shapes optimised respectively for the additive, machining and casting process. In Fig. 3.3, the distributions of the stress generated on these parts, due to the imposed loads and constraints, were calculated and displayed as proof of comparable mechanical strength for each of the designed shapes. The weight of each geometry employed in the study was reported in Table 1. A relevant information that affects the LCA analysis is the total material's weight that has to be considered for each manufacturing process considering the wasted part, too. According to that, the initial volume of the billet used in machining was calculated considering the volume required to envelop the machined part. The material wasted to create the supports in the additive process was, instead, numerically estimated by Markforged Eiger software [107] and added to the net-weight of the additively manufactured shapes. No waste material was considered for the casting process [108]. This information is also reported in Table 3.1. Furthermore, the impact of raw material in casting was compared to the one resulting from the production of the billet or of the powder used, respectively, in the SM and AM processes.

Table 3.1 Weight of the designed geometries.

Manufacturing process	Bracket's weight (kg)	Overall employed material (kg)
Machining (Initial Shape)	0,14	1,75
Additive (Initial Shape)	0,14	0,83
Casting (Initial Shape)	0,14	0,14
Machining (Optimized Shape)	0,08	1,75
Additive (Optimized Shape)	0,05	0,28
Casting (Optimized Shape)	0,11	0,11

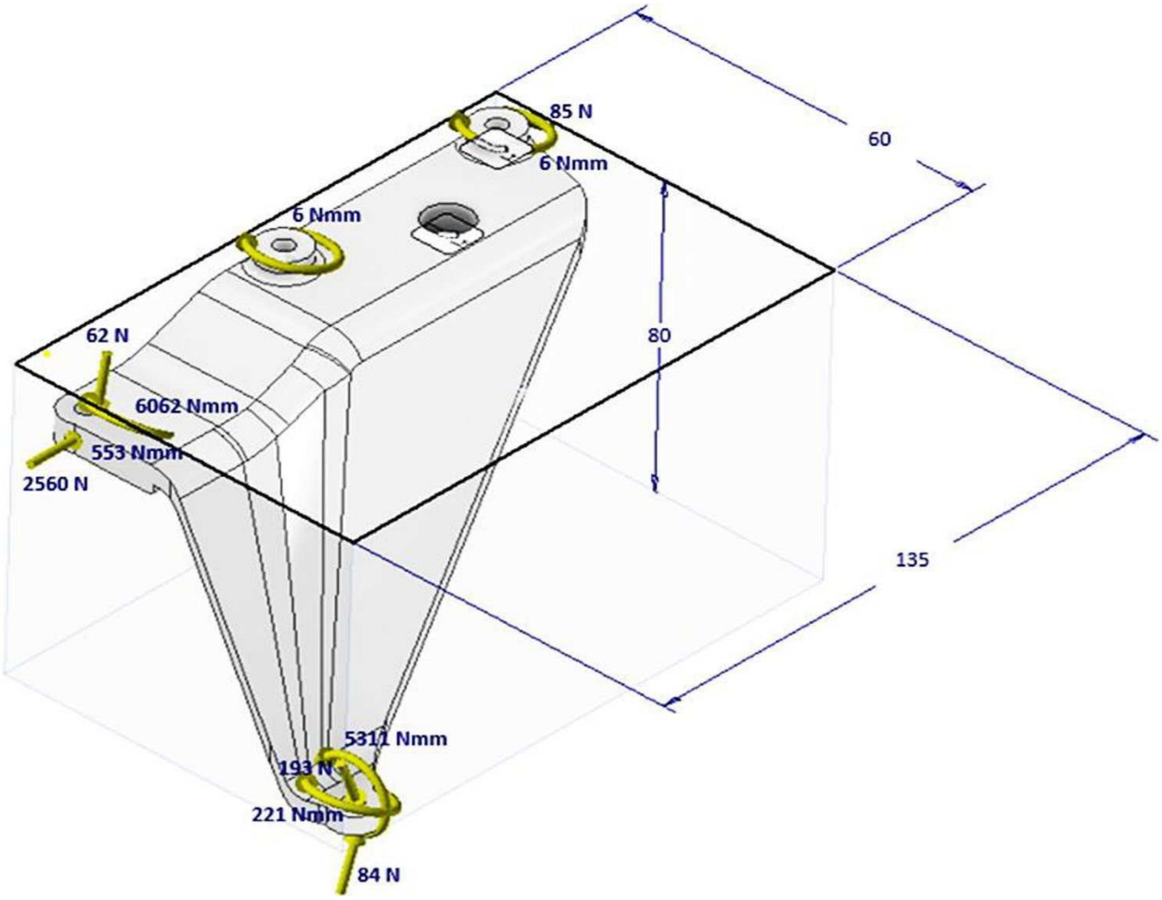


Figure 3.2 Main dimensions of the box to envelop the bracket and used structural loads and constraints

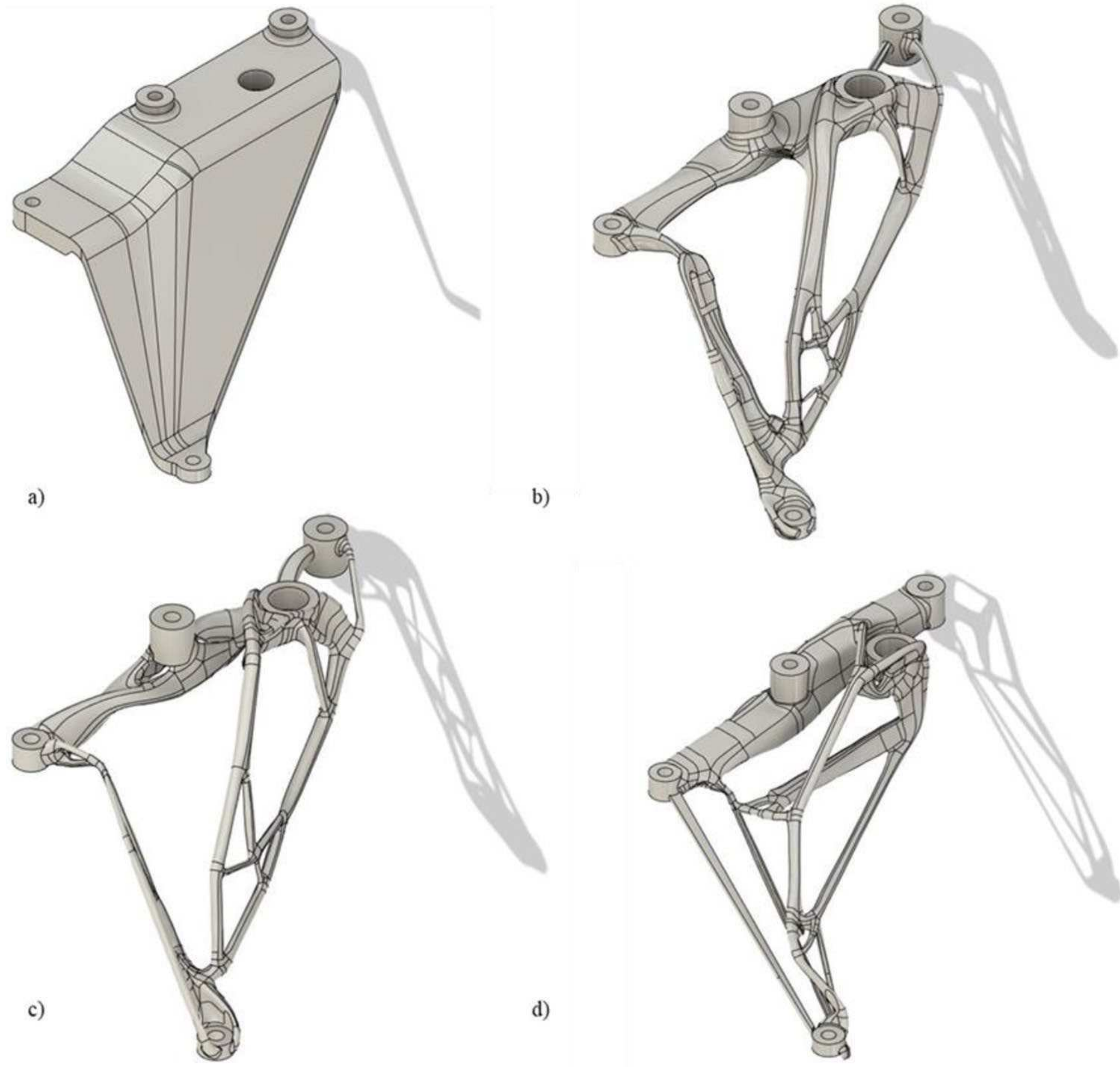


Figure 3.3 The geometries employed in the analysis: a) initial shape, b) optimized shape manufactured by SM, c) optimized shape manufactured by AM and d) optimized shape manufactured by CP

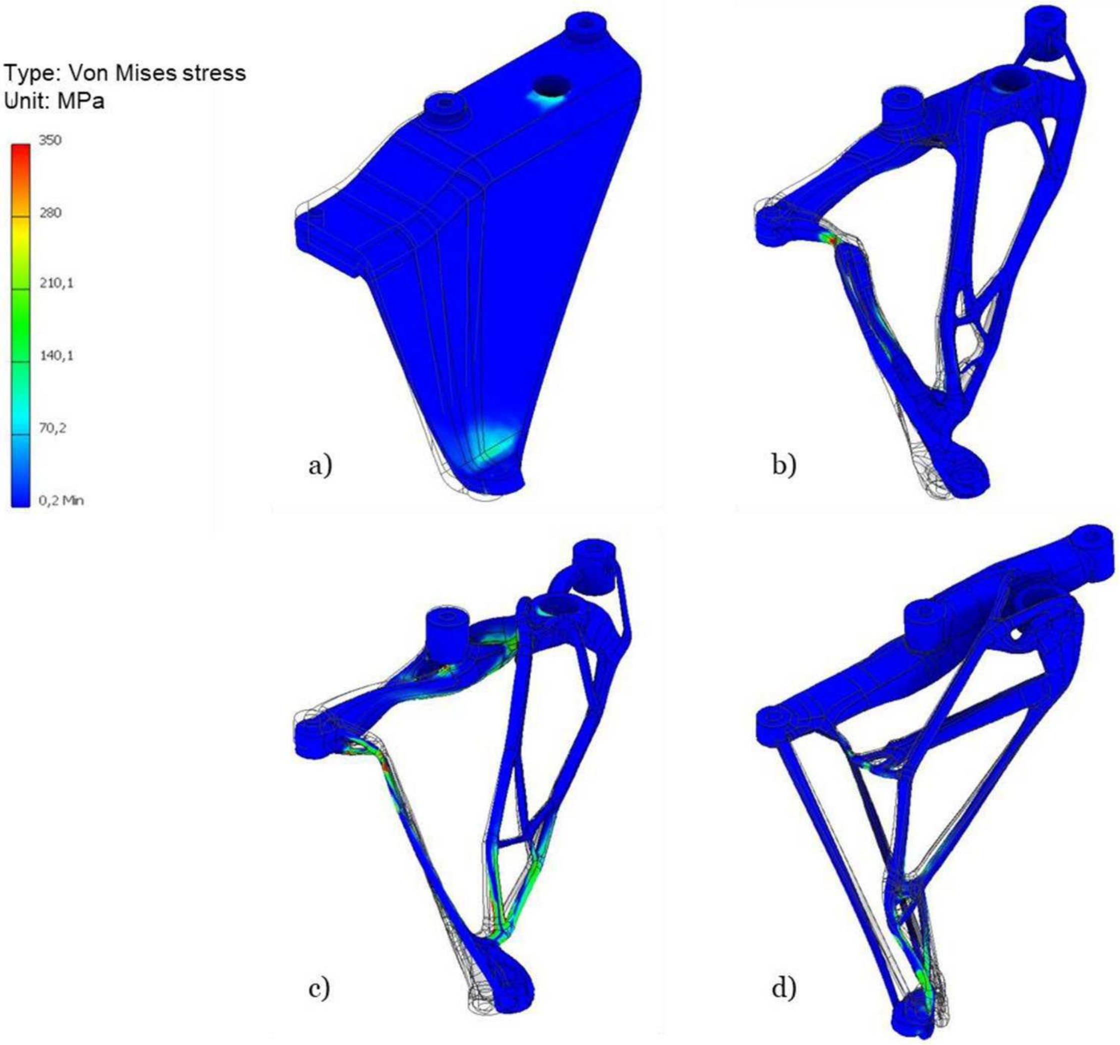


Figure 3.4 Von Mises stress distribution in the geometries employed in the analysis due to the applied loads: a) initial shape b) optimized shape manufactured by SM, c) optimized shape manufactured by AM and d) optimized shape manufactured by CP

3.3.1 Life Cycle Assessment

Comparative LCA of 3 different process routes, namely SM, AM and CM processes, in manufacturing an automotive component was conducted. The comparison included the topological optimisation modelled for the 3 different processes assessing optimised versus non-optimised shapes extracted by considering the constraints ascribable to each manufacturing route. Mid-point evaluation focused on global warming potential (GWP) and cumulative energy demand (CED), and end-point damage on human health and ecosystems were reported. The LCA study involves four main phases detailed as follows. The product system studied is an automotive component that is manufactured by different manufacturing routes. The functional unit, chosen for the present study, is a yield stress-constrained formulation inside this component, named bracket. The bracket is constrained by the space, within which it has to be installed in accordance with the applied loads and constraints. The yield strength cannot exceed a limit tied to the properties of the material, which the bracket is made of. The system boundary includes all the unit processes: raw materials extraction, product manufacturing, use phase and EOL, as schematized in Fig. 3.4. The study excludes the transport impact between the unit processes. Material recycling was assumed in closed loop and avoided impacts were allocated to the same manufacturing process [109].

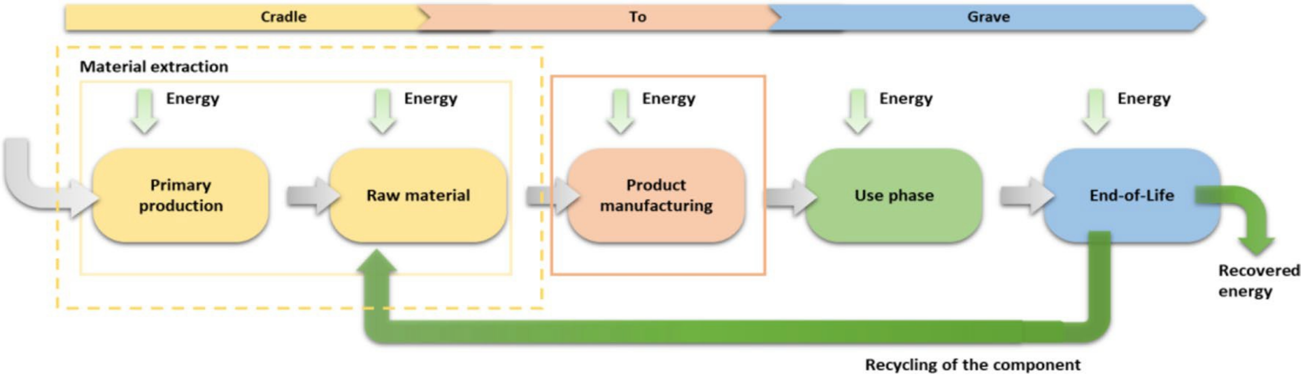


Figure 3.5 From-cradle-to-grave analysis

Life Cycle Inventory (LCI) consists of an inventory list of data collected for all the processes indicated in the system boundaries. The Ecoinvent V.3 database provided by SimaPro 9.3 software and information extracted by literature were combined as well as data modelled and calculated for the different geometries, e.g., detailed values of energy and masses, as summarized in Table 3.2.

Table 3.2. LCI literature data and calculated data for the entire life cycle.

	Material extraction		Product manufacturing	Use phase (MJ/kg)	EOL (MJ/kg)
	Primary production (MJ/kg)	Raw material (MJ/kg)			
SM	149,56 [79]	2,90 [110]	25,20 (MJ/h)	56,60	2,90 [110]
AM	149,56 [79]	1,65 [60]	22,17 (MJ/h)	56,60	1,65 [60]
CP	149,56 [79]	-	2,90 (MJ/kg) [110]	56,60	2,90 [110]
Mold	63,73 [79]	4,40 [110]	600,00 (MJ/kg) [111]	-	4,40 [110]

Selected methods for the Life Cycle Impact Assessment (LCIA) are, the Cumulative Energy Demand (CED), the Ecological Footprint (EF) Method (adapted) V1.01 / Global (2010)/with tox categories (midpoint) and the IMPACT 2002 + V2.15 / IMPACT 2002 + (endpoint), all available in the SimaPro 9.3 software used for the evaluation [79]. The analysis focused on the quantification of the energy required for the materials extraction employed in each manufacturing process by using the code library. Once extracted, the material is processed to get a billet to be machined or powders to be laid down, additively. The demanded energy required to perform this transformation before SM or AM was detected in literature (Table 3.3). The energy ascribable for making the CP billets was neglected assuming that the material is melted directly before filling the mould. For CP, instead, the impact of the mould, made of H13 tool steel, on the energy demand, was quantified and taken into account in the analysis [110]. The energy required for the mould was considered as constant for both standard and optimized brackets, being related to the component's three dimensions, which were constrained in the performed topology optimization. The energies for manufacturing a single bracket by each of the investigated processes were summarized in Table 3.4. Specifically, the SM energy impact was quantified considering the power of a standard milling machine [65] and the working time extracted by Denkena et al. [112]. The times of the different printing phases and the required powder were quantified by Gao et al. [113]. Finally, the energy demand for casting was quantified considering the required energy per mass of the produced component [110]. Specifically, the energy for the mould's production was quantified considering both its weight, which is based on the dimensions of the bracket's geometry, extracted by Autodesk Inventor software [106], and the machining phase required for its manufacturing [111]. To complete the analysis of the product manufacturing, the finishing phase was also considered having the same impact, proportionally to the component weight, for each designed bracket. The energy related to the finishing phase was quantified by Cecchel et al. [114]. The percentages of recycled materials in each manufacturing process were investigated for both aluminium [115] and H13 steel [116]. The impact of the products' use phase was evaluated considering that each bracket, mounted on an economic car, which is powered by a diesel engine, covers a distance of 250,000 km in its life [117]. The fuel consumption was quantified in 0,3 L per 100 kg mass transported for 100 km [86]. The density of the fuel was taken from literature [118]. Finally, the product's EOL phase was also considered. The percentages of materials, which can be recoverable, considering both aluminium for the brackets and steel for the moulds, were estimated according to literature [110, 116].

Table 3.3. Energy parts required for the achieving the raw material used in manufacturing.

Process	Quantity of raw material (kg)	Energy for obtaining raw material (MJ/kg)
Machining (Initial Shape)	1,75	2,90—Billet [110]

Additive (Initial Shape)	0,83	1,65—Powder [60]
Casting (Initial Shape)	0,14	-
Machining (Optimized Shape)	1,75	2,90—Billet [110]
Additive (Optimized Shape)	0,28	1,65—Powder [60]
Casting (Component)	0,11	-
Casting (Mould – Both Shapes)	60,12	85,00 [110]

Table 3.4. Energy for manufacturing the brackets considering the analysed processes.

Process	Power (kW)	Working time (h)	Energy (MJ)
Machining (Initial Shape)	7,00 [119]	0,44	11,08 [119]
Additive (Initial Shape)	9,65 [113]	0,70	24,19 [113]
Casting (Initial Shape—Part)	-	-	0,46* [110]
Machining (Optimized Shape)	7,00 [119]	0,53	13,46 [119]
Additive (Optimized Shape)	9,65 [113]	0,24	8,29 [113]
Casting (Optimized Shape—Part)	-	-	0,36* [110]
Casting (Both Shapes—Mould)	-	-	36.072,00 [111]

3.4 Results and Discussion

The outcomes reported in this section summarize the global warming potential quantified during the investigated case study. Specifically, GWP results are schematized in the networks of Figs. 3.5 – 3.10 that report the unit processes involved in manufacturing technique. CED results are synthesized in Table 3.5, where the contributions of the four phases are detailed. According to that, the electricity market of Norway was considered to align the consumed energy in manufacturing to the other CED's contributions. In Table 3.5, the consumed and the recovered, by recycling, energies were labelled by

OUT and IN, respectively. Furthermore, the contributions related to the produced component and to the used moulds for CP were also distinguished. Looking at Table 3.5, therefore, the from-cradle-to-grave CED can be evaluated, in detail. The charted data in Fig. 3.11 allow observing how the volume of the manufactured components affects the considerations on the processes' CED performances, deeply. For the initial bracket's geometry, the CP, reported without the moulds' contribution for a first examination, resulted to be the process that burdens less on the environmental resources. This observation changed if the optimized geometry was considered. Making explicit the CED subdivision, the following considerations arise:

i) Material production: this is energy-intensive for the initial shape of the SM process being impacted by the processed mass. The CED ascribable to SM passes from 53,68 MJ to 24,43 MJ moving from the initial to the optimized shape. This reduction moves SM to be closer to CP (16,30 MJ), which does not take consistent benefit from the optimization being 21,50 MJ its CED required for the initial shape. The AM, instead, owing to the process capability of taking the product's shape to its extreme, in terms of volume reduction, resulted in a relevant CED reduction passing to be higher than CP's CED for the initial shape (23,72 MJ) to a reduction quantifiable in about 65% (8,14 MJ).

ii) Production manufacturing: the CED for this LCA phase, at least for AM and SM, is strictly related to the time required to complete the process. For that reason, manufacturing of the optimized shape results in an increasing of CED for the SM respect to the initial shape, respectively 13,35 MJ and 11,08 MJ, considering that, more material needs to be removed if the part is obtained by the same billet size, being this a function constraint to be respected. The contrary happens for AM, where less material needs to be deposited because of the reduced volume of the optimized shape. Specifically, AM's CED passed from 24,19 MJ for the initial shape to 8,29 MJ for the optimized shape. Finally, the impact of this phase weighs marginally for CP's CED, respectively 0,46 MJ for the initial shape and 0,37 MJ for the optimized one, being considered just the energy portion required to cast the material.

iii) Use-Phase: this LCA phase is strictly related to the mass of the component. Therefore, the optimization shapes impact less than the initial one on CED aside from the considered process. The demanded energy reduction is more evident for AM, arriving at 17,32 MJ, owing to the process capability to achieve a stressed material distribution. This phase for SM and CP weighs 30,31 MJ and 39,30 MJ, respectively. The CED is affected in the amount of 50,52 MJ from the initial bracket's dimension.

iv) End-of-Life: the considerations, effective for the Use- Phase, can be mirrored for this last LCA phase. In this case, the values have to be considered as recovered energy that, therefore, reduces the demanded energy of the product life cycle. More is the mass of the bracket; more is the gotten back energy considering a proper waste management without considering landscape as possible choice. In detail, the recovered energy is equal to -13,85 MJ, -8,33 MJ, -4,76 MJ and -11,89 MJ respectively for initial and optimized SM, AM and CP shapes.

v) From-Cradle-to-Grave: a complete view of the impact for each process considering initial and optimized shapes can be achieved adding up the detailed energy aliquots of each LCA phase. Herein, the advantages arisen by topology optimization for AM result to be evident with a CED reduction of about 65% respect to about 41% and 25% for SM and CP, respectively. As written above, the considerations were performed without considering the impact of the moulds for CP'CED to be able to get a comparison to AM and SM without taking into account the number of parts to be produced. Anyway, CP is environmentally affected by the energy contribution related to the moulds, which weigh on the production of few parts, consistently as shown in Table 3.5. The study was, therefore, completed considering also the contribution of the moulds and weighing it with respect to the batch size (Fig. 3.12). Focusing the attention on CP, it results clear how this manufacturing solution is not competitive from a sustainable point of view up to a consistent number of parts is produced. Other midpoint categories are reported in Table 3.6. Finally, taking to into account the IMPACT 2002 + V2.15 / IMPACT 2002 + (endpoint) method, four damage categories were assessed, which are detailed in Figs. 3.13, 3.14.

Table 3.5. CED for each phase of the LCA for the investigated process solutions if one bracket is manufactured

<table>
<tr><th rowspan="2">CED
(MJ)</th><th colspan="6">Material Production</th><th colspan="6">Product Manufacturing</th><th colspan="3">Use Phase</th><th colspan="6">End-of-Life</th><th colspan="6">from-cradle-to-grave</th></tr>
<tr><th colspan="2">OUT</th><th colspan="2">IN</th><th colspan="2">NET</th><th colspan="2">OUT</th><th colspan="2">IN</th><th colspan="2">NET</th><th>OUT</th><th>IN</th><th>NET</th><th colspan="2">OUT</th><th colspan="2">IN</th><th colspan="2">NET</th><th colspan="2">OUT</th><th colspan="2">IN</th><th colspan="2">NET</th></tr>
<tr><td>Machining Initial shape</td><td colspan="2">267,00</td><td colspan="2">213,32</td><td colspan="2">53,68</td><td colspan="2">11,08</td><td colspan="2">0,00</td><td colspan="2">11,08</td><td>50,52</td><td>0,00</td><td>50,52</td><td colspan="2">1,41</td><td colspan="2">15,26</td><td colspan="2">-13,85</td><td colspan="2">330,01</td><td colspan="2">228,58</td><td colspan="2">101,43</td></tr>
<tr><td>Additive Initial shape</td><td colspan="2">125,22</td><td colspan="2">101,50</td><td colspan="2">23,72</td><td colspan="2">24,19</td><td colspan="2">0,00</td><td colspan="2">24,19</td><td>50,52</td><td>0,00</td><td>50,52</td><td colspan="2">1,37</td><td colspan="2">15,26</td><td colspan="2">-13,89</td><td colspan="2">201,30</td><td colspan="2">116,76</td><td colspan="2">84,54</td></tr>
<tr><td rowspan="3">Casting Initial shape</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td rowspan="3">50,52</td><td rowspan="3">0,00</td><td rowspan="3">50,52</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td></tr>
<tr><td rowspan="2">24,56</td><td rowspan="2">3478,58</td><td rowspan="2">3,06</td><td rowspan="2">0,00</td><td rowspan="2">21,50</td><td rowspan="2">3478,58</td><td rowspan="2">0,46</td><td rowspan="2">36060,00</td><td rowspan="2">0,00</td><td rowspan="2">0,00</td><td rowspan="2">0,46</td><td rowspan="2">36060,00</td><td rowspan="2">1,37</td><td rowspan="2">0,38</td><td rowspan="2">15,26</td><td rowspan="2">3480,22</td><td rowspan="2">-13,89</td><td rowspan="2">-3479,84</td><td>76,91</td><td>39538,96</td><td>18,32</td><td>3480,22</td><td>58,59</td><td>36058,74</td></tr>
<tr><td colspan="2">39615,87</td><td colspan="2">3498,54</td><td colspan="2">36117,33</td></tr>
<tr><td>Machining Optimized shape</td><td colspan="2">267,00</td><td colspan="2">242,57</td><td colspan="2">24,43</td><td colspan="2">13,35</td><td colspan="2">0,00</td><td colspan="2">13,35</td><td>30,31</td><td>0,00</td><td>30,31</td><td colspan="2">0,82</td><td colspan="2">9,15</td><td colspan="2">-8,33</td><td colspan="2">311,48</td><td colspan="2">251,72</td><td colspan="2">59,76</td></tr>
<tr><td>Additive Optimized shape</td><td colspan="2">43,00</td><td colspan="2">34,86</td><td colspan="2">8,14</td><td colspan="2">8,29</td><td colspan="2">0,00</td><td colspan="2">8,29</td><td>17,32</td><td>0,00</td><td>17,32</td><td colspan="2">0,47</td><td colspan="2">5,23</td><td colspan="2">-4,76</td><td colspan="2">69,08</td><td colspan="2">40,09</td><td colspan="2">28,99</td></tr>
<tr><td rowspan="3">Casting Optimized shape</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td rowspan="3">39,30</td><td rowspan="3">0,00</td><td rowspan="3">39,30</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td><td>Part</td><td>Mould</td></tr>
<tr><td rowspan="2">16,30</td><td rowspan="2">3478,58</td><td rowspan="2">0,00</td><td rowspan="2">0,00</td><td rowspan="2">16,30</td><td rowspan="2">3478,58</td><td rowspan="2">0,37</td><td rowspan="2">36060,00</td><td rowspan="2">0,00</td><td rowspan="2">0,00</td><td rowspan="2">0,37</td><td rowspan="2">36060,00</td><td rowspan="2">0,01</td><td rowspan="2">0,38</td><td rowspan="2">11,90</td><td rowspan="2">3480,22</td><td rowspan="2">-11,89</td><td rowspan="2">-3479,84</td><td>55,98</td><td>39538,96</td><td>11,90</td><td>3480,22</td><td>44,08</td><td>36058,74</td></tr>
<tr><td colspan="2">39594,94</td><td colspan="2">3492,12</td><td colspan="2">36102,82</td></tr>
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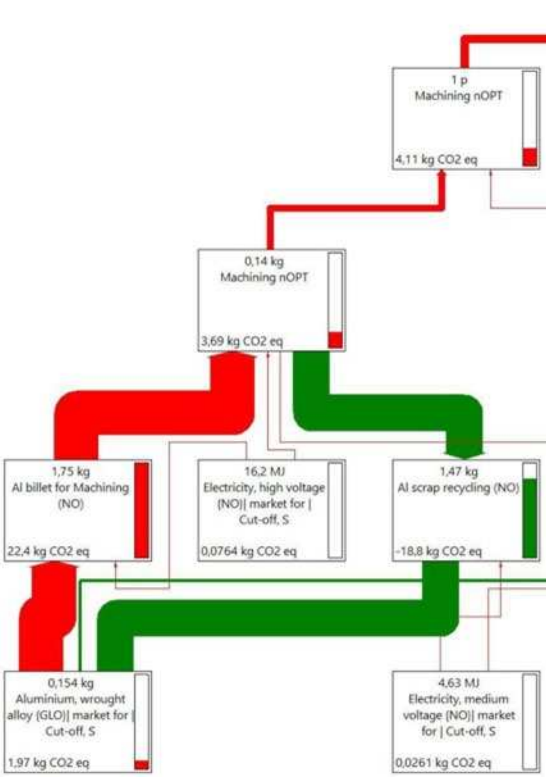


Figure 3.6 GWP network considering the initial shape manufactured by SM

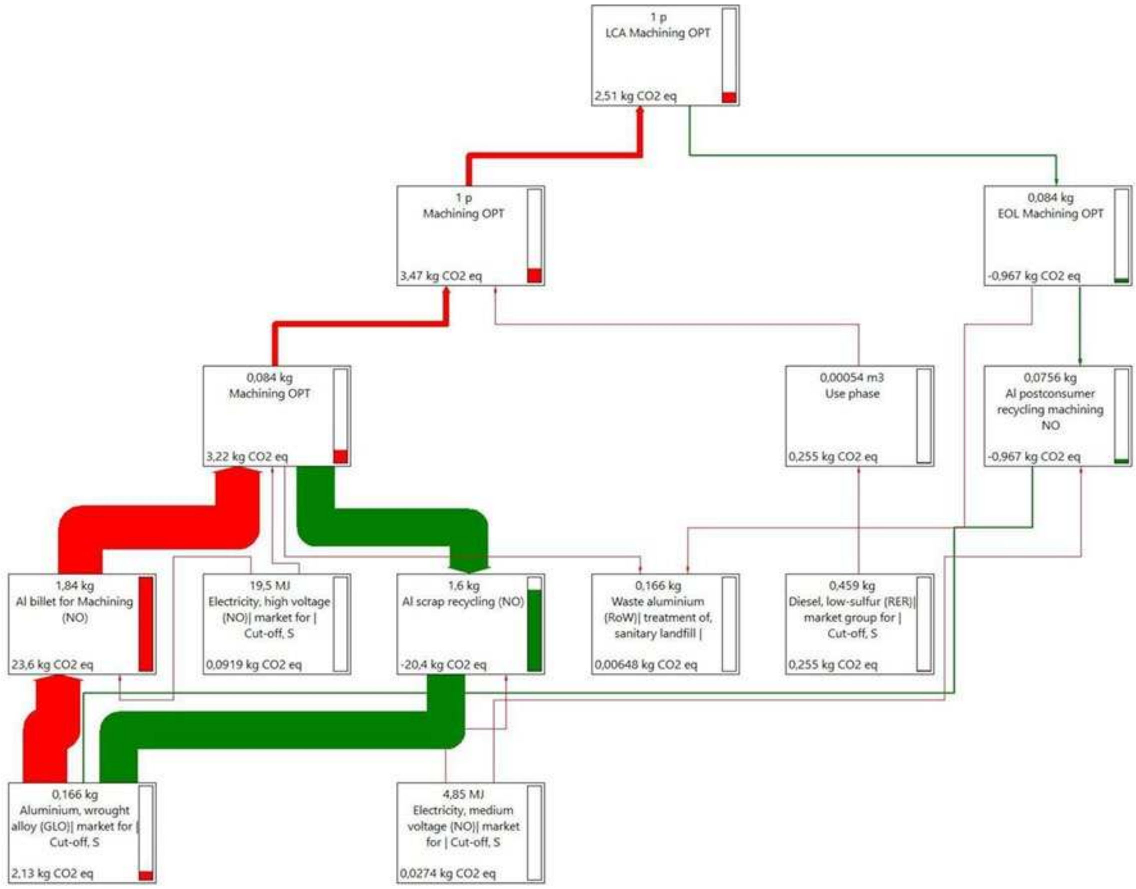


Figure 3.7 GWP network of the optimized shape manufactured by SM

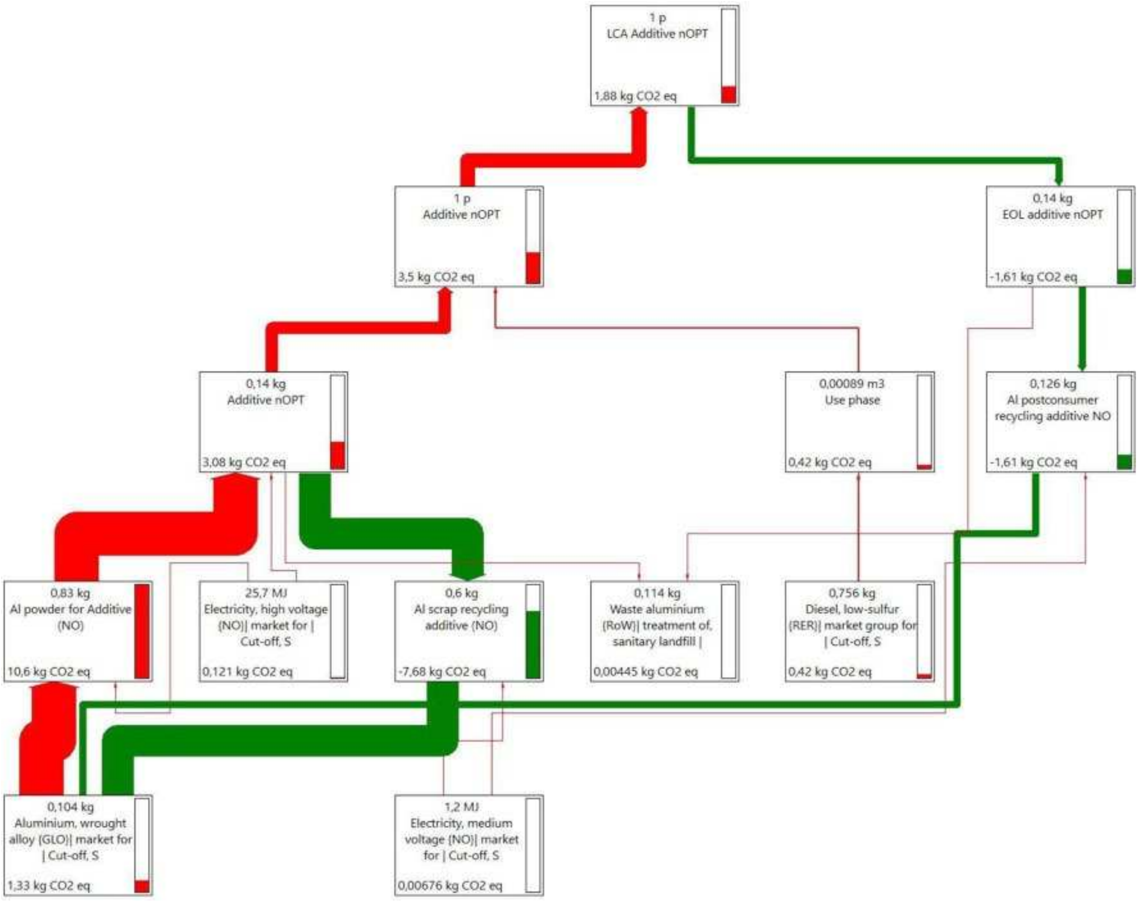


Figure 3.8 GWP network of the initial shape manufactured by AM

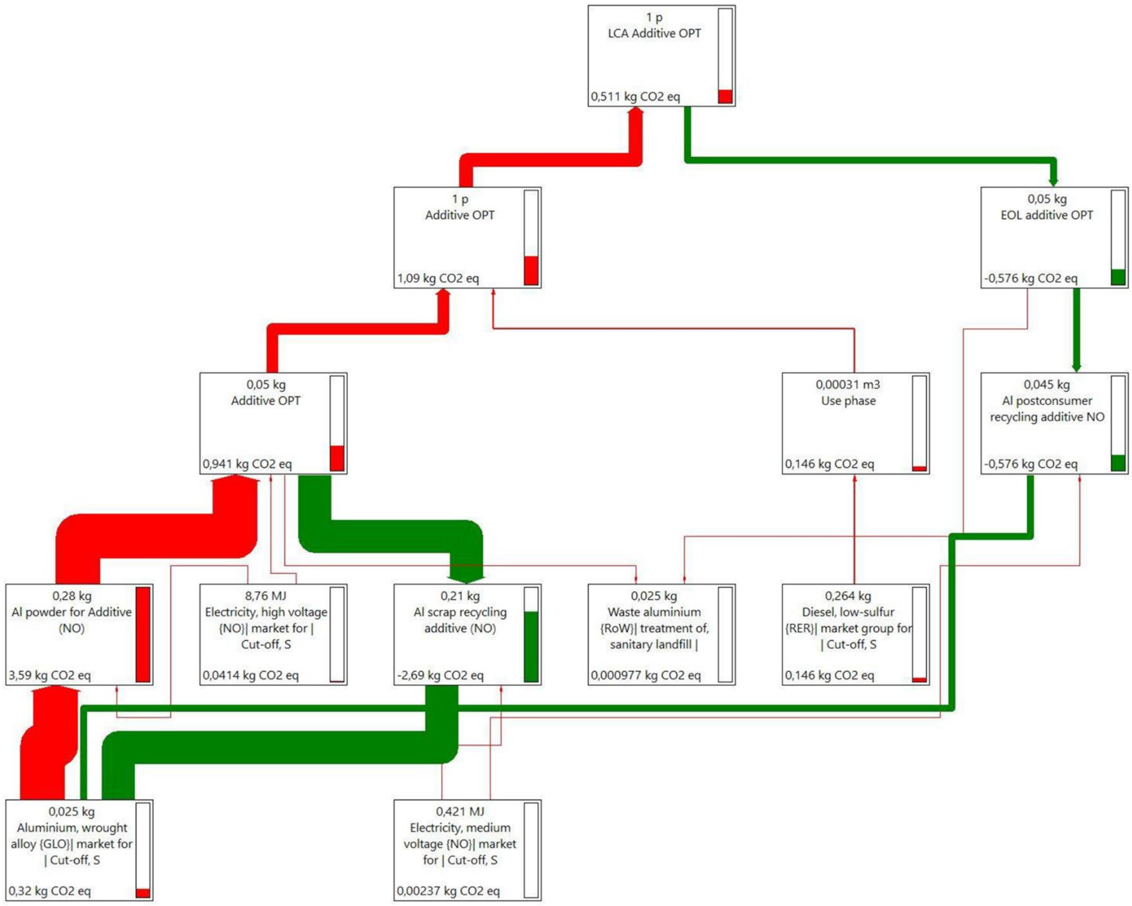


Figure 3.9 GWP network of the optimized shape manufactured by AM

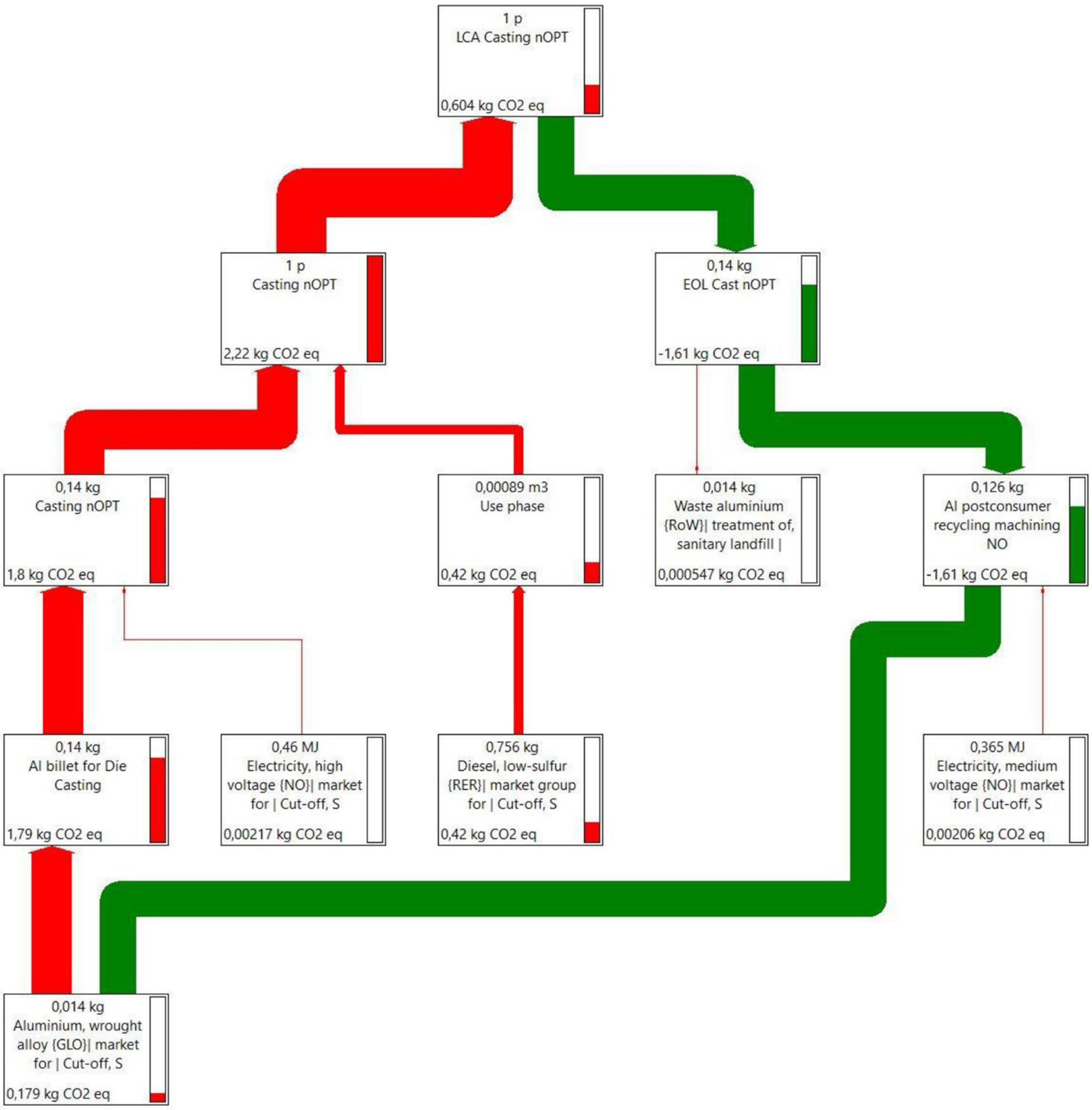


Figure 3.10 GWP network of the initial shape manufactured by CP

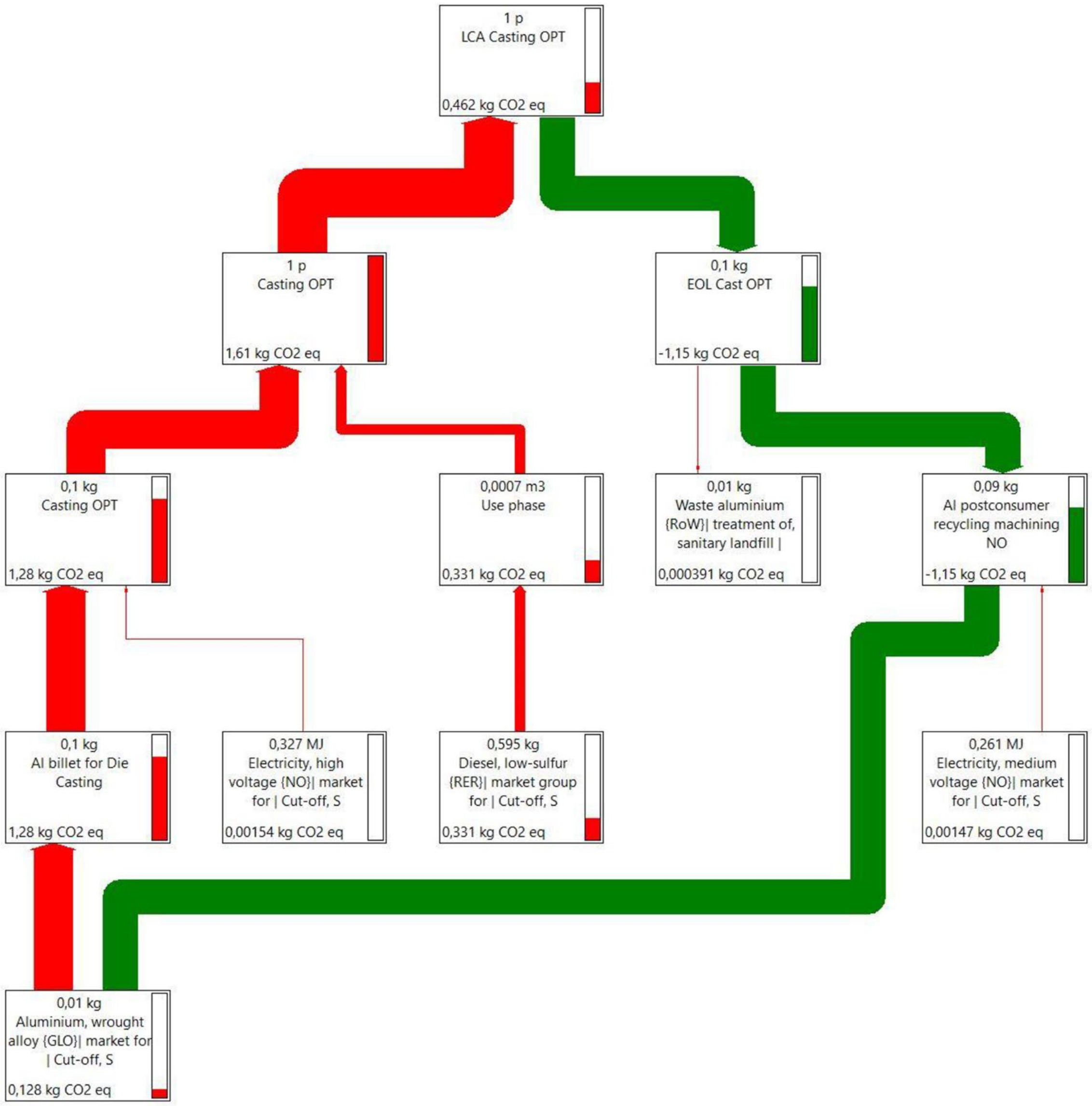


Figure 3.11 GWP network of the optimized shape manufactured by CP

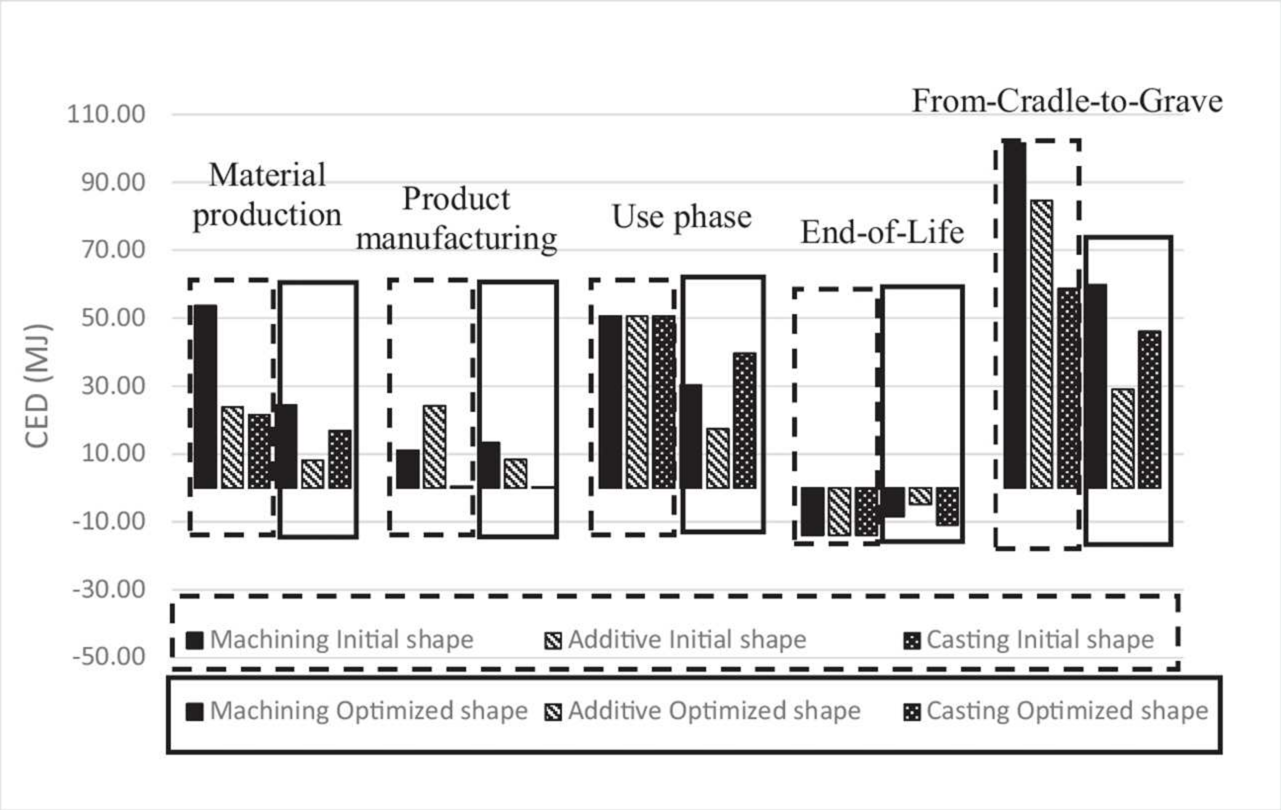


Figure 3.12 The CED weight of the investigated processes for each LCA phase

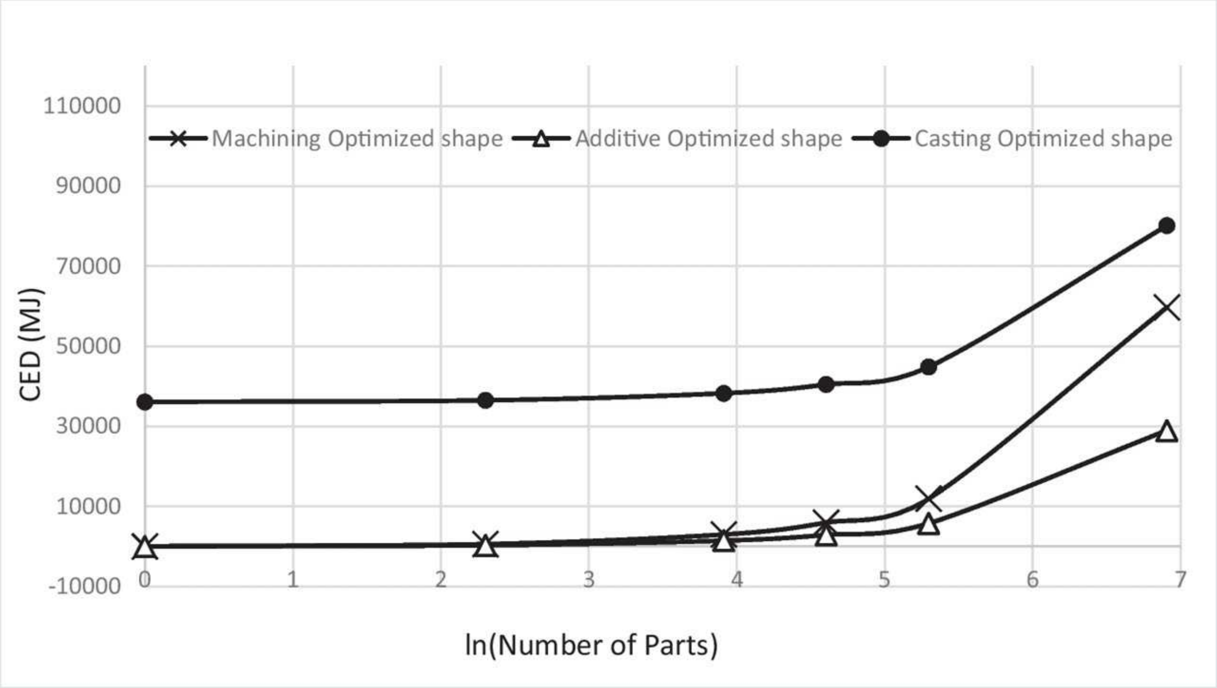


Figure 3.13 CED increment for each manufacturing solution at changing the number of produced parts

Table 3.6. Impact assessment via EF method with comparison of the impact categories for each analysed process

Impact category	**Unit**	**LCA Machining Initial shape**	**LCA Machining shape**	**LCA Additive Initial shape**	**LCA Additive optimized shape**	**LCA Casting Initial shape**	**LCA Casting optimized shape**
Climate change	kg CO2 eq	2.579049476	2.585647153	1.941633738	0.52629137	0.619063064	0.473155794
Ozone depletion	kg CFC11 eq	7.41447E-07	4.92524E-07	7.17216E-07	2.43797E-07	6.59981E-07	5.18529E-07
Ionising radiation, HH	kBq U-235 eq	0.306035533	0.249759515	0.305939718	0.101745289	0.190360081	0.149146588
Photochemical ozone formation, HH	kg NMVOC eq	0.009598695	0.009073313	0.007518974	0.002134282	0.003350317	0.002590919
Respiratory inorganics	Disease inc	1.88495E-07	1.90331E-07	1.3886E-07	3.69175E-08	4.2238E-08	3.21813E-08
Non-cancer human health effects	CTUh	4.43911E-07	4.64105E-07	3.18396E-07	8.20503E-08	6.92705E-08	5.18376E-08
Cancer human health effects	CTUh	1.42211E-07	1.51857E-07	9.8674E-08	2.45083E-08	1.58449E-08	1.15625E-08
Acidification terrestrial and freshwater	Mol H + eq	0.018938434	0.018071602	0.014616743	0.004099588	0.006264067	0.004836632
Eutrophication freshwater	Kg P eq	0.000791338	0.000839284	0.00056668	0.000144782	0.000101727	7.51768E-05
Eutrophication marine	Kg N eq	0.002859192	0.002801937	0.002179413	0.000600285	0.00080773	0.000620812
Eutrophication terrestrial	Mol N eq	0.030162692	0.029435237	0.023102502	0.006393998	0.008764349	0.006742468
Ecotoxicity freshwater	CTUe	2.548639154	2.534190712	1.898979495	0.513912208	0.646118769	0.494684713
Land use	Pt	10.26006613	10.50836728	9.022960549	2.67594735	2.299510617	1.761264263
Water scarcity	m3 depriv	0.419826539	0.461045875	0.363026344	0.10438116	0.0364385	0.02697265
Resource use, energy carriers	MJ	61.1964076	47.15049516	55.37603702	17.86117467	42.03755989	32.9313174
Resource use, mineral and metals	Kg Sb eq	1.07098E-05	1.061E-05	8.28133E-06	2.34858E-06	2.84522E-06	2.18503E-06
Climate change—fossil	Kg CO2 eq	2.563967052	2.569256142	1.929040889	0.52273621	0.617507111	0.472014899
Climate change—biogenic	kg CO2 eq	0.00694136	0.00762969	0.006742247	0.002069138	0.000735008	0.000546032
Climate change – land use and transform	Kg CO2 eq	0.008141064	0.008761321	0.005850602	0.001486021	0.000820945	0.000594864

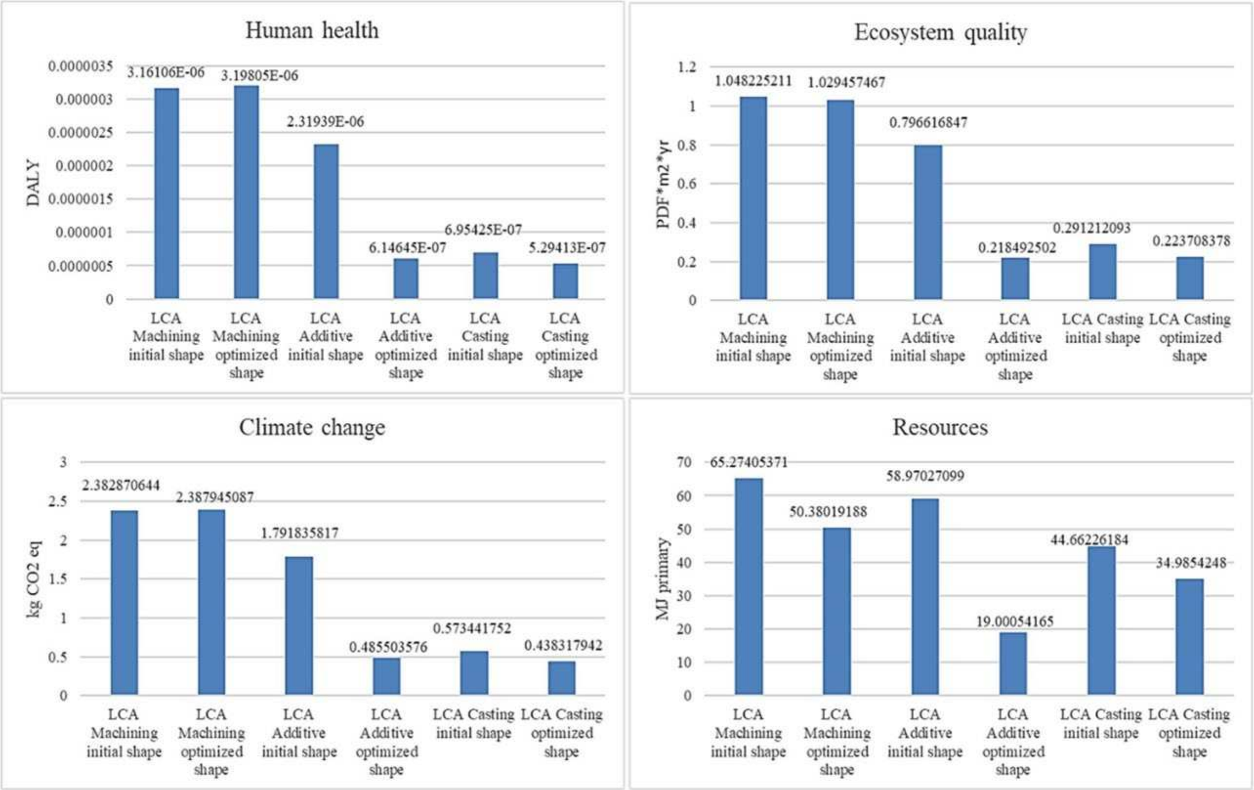


Figure 3.14 Human health, ecosystem quality, climate change and resources categories for each manufacturing solution examined

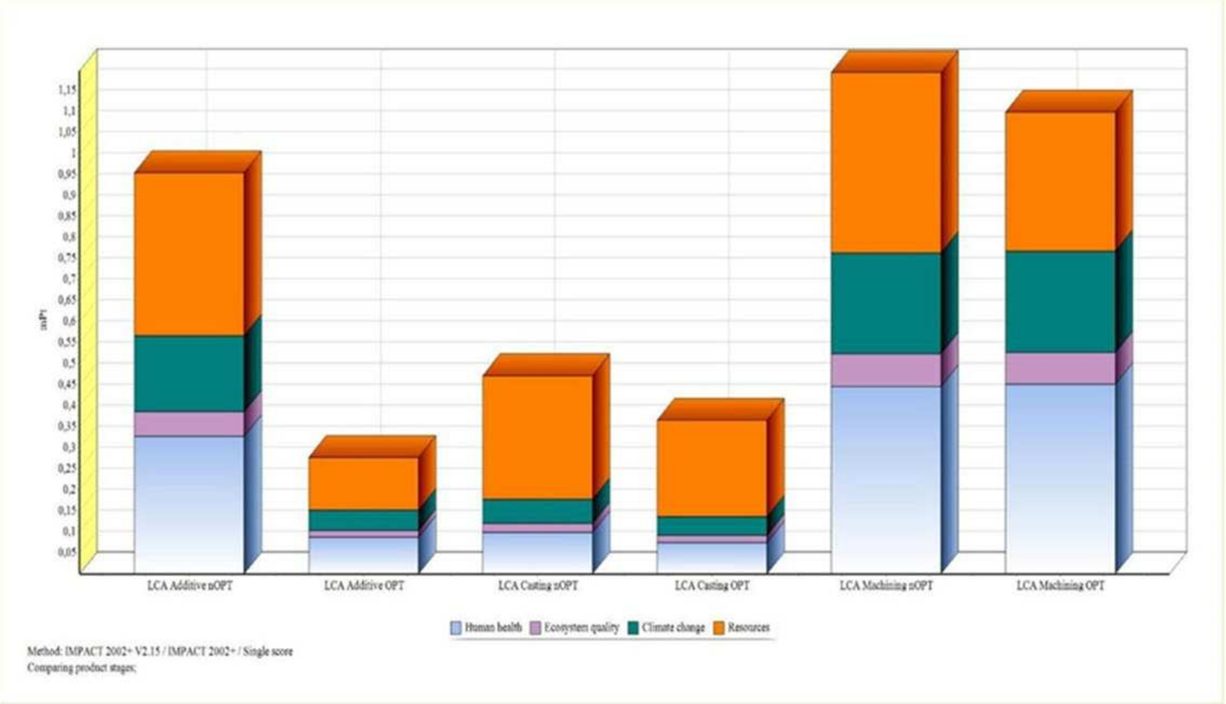


Figure 3.15 Single score graph of the damage categories for each manufacturing solution examined

3.5 Conclusions

This first case study has given a preliminary overview of the environmental performances of a specific component manufactured by different manufacturing processes, i.e. SM, AM, and CP coupled with a topological optimization methodology.

In detail, the impact that the topological optimization methodology can have on the sustainability of a specific component was evaluated by considering different manufacturing strategies. An automotive bracket was studied to minimize its mass while ensuring it met the required minimum strength criteria.

The proposed bracket designs, developed through topology optimization tailored to machining, additive manufacturing, and casting constraints, were evaluated for their environmental impacts across their entire lifecycle. The topology optimization applied to additive manufacturing emphasizes the advantages of this process if compared to machining in terms of sustainability. This consideration is mainly justified by the capability of manufacturing more pronounced topology optimized shapes by AM resulting in a more impacting component lightening and related environmental advantages during its use-phase.

Furthermore, optimized shape for AM means reduction of process time due to the effect on the lengthening of the tool path with a reduction of CED related to product manufacturing phase. This is not applicable to SM, where more material has to be removed from the volume of a standard billet in order to obtain the designed final shape. As far as the casting process is concerned, topology optimisation is slightly advantageous for this solution from an environmental point of view, only having a noticeable effect on the production and material use phase of the LCA. Compared to AM, by the performed analysis, CP performed on an optimized shape resulted to be less eco-friendly regardless the number of parts to be produced showing, anyway, an increasing competitiveness, that has to be evaluated in relation to the type of the shape to be manufactured, for larger batch sizes. This is the production scenario, where casting is often chosen by the power of its more elevated productivity. However, to emphasise this influence and to weigh the contribution of each step, further studies are needed to perform an LCA with different geometries, changing the percentage of volume to be removed from the initial billet before obtaining the desired product. In fact, in general, LCA is competitive with AM if the shape to be produced is simple and, therefore, far from being topologically optimised. In order to investigate the lack of this research in the next chapter 4 a detailed LCA analysis will be performed.

4. Chapter IV: A Comparative LCA of a Component Manufactured by Opposing Manufacturing Strategies.

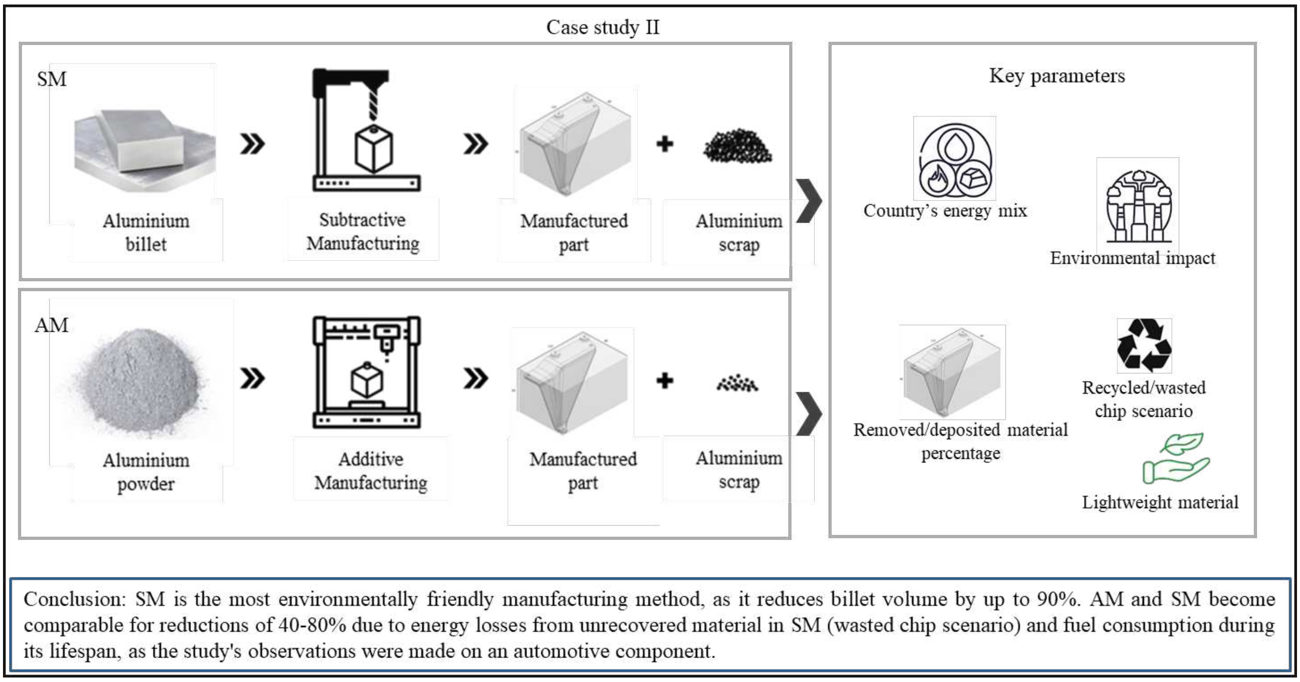
Part of the content of this Chapter was published in:

- Advances in Materials and Processing Technologies

Borda, Francesco, La Rosa, Angela Daniela, Filice, Luigino, Gagliardi, Francesco, 2024. *Environmental comparison of opposing manufacturing strategies at changing of energy sources, EoL approaches and shape peculiarity for an automotive component.*

4.1 Chapter Summary

From outcomes of the research study, discussed in chapter 3, Additive manufacturing (AM) has been considered as an alternative to the conventional manufacturing techniques, such as Subtractive Manufacturing (SM), allowing the production of products characterised by innovative design and performance. On the other hand, sustainability assessments are essential for evaluating the industrial attractiveness of this technology and need to be deepened to better clarify how environmental sustainability parameters affect the investigated processes. Several environmental parameters, such as energy source, EoL scenarios, midpoint and endpoint indicators strictly linked to the cumulative energy demand of the selected processes were quantified in this chapter. This research aimed at performing a life cycle assessment (LCA) of an automotive component manufactured by both the proposed manufacturing techniques at changing the volume ratio between the final shape and the initial enveloping billet. The LCA, performed by a from-cradle-to-grave approach, exploits inventory data associated with impacts categories chosen from those available in literature. Finally, to present a comprehensive overview of the work, the graphical abstract in Figure 4.1 was provided.



Conclusion: SM is the most environmentally friendly manufacturing method, as it reduces billet volume by up to 90%. AM and SM become comparable for reductions of 40-80% due to energy losses from unrecovered material in SM (wasted chip scenario) and fuel consumption during its lifespan, as the study's observations were made on an automotive component.

Figure 4.1 Graphical abstract.

Nowadays, the increasing cost of electricity leads to a more conscious behaviour in the use of this valuable energy source. Furthermore, the energy consumption results in consistent environmental impacts owing to greenhouse gas emission for electricity production. Climate change, such as a global temperature rise, is due to global pollution, being directly connected to the concentration of greenhouse gases in the atmosphere [120]. The climate-neutral economy can be reached if all parties work in symbiosis. Therefore, energy saving has been a focus of global attention for the whole economic sectors that will play a key role by looking at the necessary actions to be performed [121, 122].

Manufacturing is one of these sectors and it must be considered properly. Actually, the energy consumption and carbon dioxide emissions of the manufacturing sector account for more than one-third of the global impact [123].

In 2021, considering the only Italian context, the total energy consumption reached 2,45 thousand tons of standard coal equivalent [124]. Furthermore, the global carbon dioxide emissions from petroleum and industry were 37.12 billion metric tonnes ($GtCO_2$) in 2021.

Since 1990, global CO_2 emissions have increased by more than 60% [125]. Although several policy strategies encourage increasing the amount of electricity generated from renewable resources, nearly 60 percent of electricity in the United States alone is still generated by fossil-fuel power plants [126].

Eco-friendly manufacturing processes have been considered in reducing greenhouse gas emissions [127]. Among these, additive manufacturing (AM), being able to combine materials and to distribute layer by layer the right material in the right place, can be considered as an interesting emerging technology especially for prototype production [128–130]. Furthermore, this material deposition capability, allowing the material to be deposited in any desired position with limited process constraints [131], can be further validated by using topology optimization techniques [132, 133]. Up to now, there has been a growth in the number of AM systems into all areas of industry[134–136]. According to Kanishka et al., 2023, AM plays a key role in remanufacturing, focusing on principles, strategies and applications for repairing and restoring products. Reverse engineering and decision-making frameworks can be also exploited for AM-based remanufacturing [137]. In another study, Kanishka et al., 2023 stated that the AM is making significant progress in the multi-material and large-scale field, with improvements in speed, accuracy and sustainability [138].

The environmental benefits of AM are, however, only explicitly identified under certain conditions, such as when there are energy savings due to the limited material used and, therefore, reduced process time, or when its energy mix comes from more renewable and less carbon-based resources [139].

The AM environmental impact must be properly quantified and compared to other manufacturing routes that could be competitive in production of specific components [37, 140, 141]. In particular, Subtractive Manufacturing (SM), where the shape of the component is obtained gradually by removing material starting with an initial billet, represents a worthy process alternative [142–144]. According to Ramadugu et al., 2023, SM resulted in 14.53% less environmental damage than AM without design optimization. AM with topology optimization reduced environmental damage by 21.31% compared to SM [145].

Faludi et al. pointed out that the AM is not always more sustainable than SM processes [146] even if the ratio of waste in SM can reach values of up to 19:1 compared to the final part [111]. Indeed, although the advantages related to the possibility of customised material distribution, drawbacks, such as time and energy consumed during the manufacturing process, must be evaluated [147]. For that reason, different studies compared both techniques, but just focusing on specific case studies [145, 148, 149].

Process sustainability is a challenge that must be addressed throughout the entire product life cycle [150, 151]. Life cycle assessment (LCA) is a method for estimating the environmental impact of a good, service and technology throughout its life cycle. Several studies have been proposed with the aim of quantifying the transport impact on global warming [152].

In a previous work, the authors performed a LCA analysis quantifying just the Cumulative Energy Demand (CED) of an automotive bracket in its entire life cycle neglecting the transports' impact [148]. In detail, the energy demand for the entire life cycle of this car component was evaluated for different manufacturing processes considering topology optimised shapes constrained by the investigated manufacturing processes' specificities. The results showed that the topology optimization applied to AM emphasises the advantages of this process compared to SM in terms of sustainability. Anyway, this result was mainly justified by the capability of manufacturing more pronounced topology optimised shapes by AM resulting in a more component's lightning.

The novelty of the presented work aims at providing a broader sustainability comparison of the AM and SM processes if employed to produce a general component for the automotive industry. In fact, Lunetto et al., 2021, already compared the environmental impact of a SM and an AM process considering cost, CO_2 emissions and CED as metrics to be evaluated[153]. Anyway, the strength of the work, herein proposed, has to be ascribed to the breadth of a LCA study performed coupling CED and specific environmental impacts' assessments provided by Midpoint and Endpoint indicators. Furthermore, different production scenarios were taken into account starting by the percentages of the removed material to achieve the desired product's shape for being able to generalise the obtained considerations regardless of the components' shape. Indeed, the study was performed fixing the initial billet's volume required to produce the component by machining, and progressively, reducing the component's weight taking, as the final target, the final shape that can be manufactured, considering both the additive and subtractive processes' specificities. Different Country's energy mixes were also considered [110] while the product's End-of-Life (EoL) was assessed by both the recycled content and the substitution method. Finally, the SM's EoL phase was performed examining diverse chips' disposal strategies.

4.3 Material and Methods

The percentage of removed material from an initial billet was changed justifying this choice because the performance of a product can be preserved optimising its shape. The material reductions can result in shapes that were considered for a production of both subtractive and additive techniques. Specifically, the starting weight of the component was defined by a previous study [148]. Gradually, percentages of material were removed from the initial billet mass (m_b), whose volume envelopes the component, completely (Fig. 4.1). The main dimensions of this billet are 135x60x80 mm. The component used in this work is a standard geometry typically manufactured by machining. An aluminium alloy was chosen as the material to be used for the component's production [148]. The different configurations of the whole material removed/deposited, and the weight of the final component are summarised in Table 4.1.

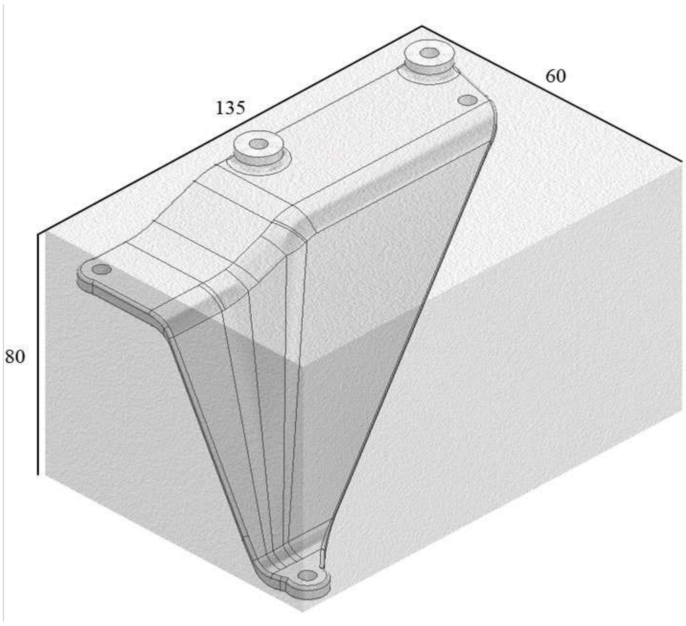


Table 4.1 Weight of the component employed in the manufacturing process.

Manufacturing process	Removed/Deposited material (%)	Component's weight (kg)
Additive	100,00	1,75
	60,00	1,05
	20,00	0,35
	10,00	0,18
Machining	0,00	1,75
	40,00	1,05
	80,00	0,35
	90,00	0,18

A comparative LCA was carried out to assess the environmental impact of AM and SM comparing different component's weights and providing guidance to reduce wasting of the natural assets. The LCA quantifies the environmental potential impacts of a product or service according to a rigorous methodological framework described by ISO 14040 (2006) and ISO 14044 (2006) standards [77]. Specifically, a LCA study must include four main steps: 1) the study's goal and scope definition, 2) the inventory of all process and environmental flows among the life cycle of the product, 3) the environmental impacts calculation and 4) the interpretation of the results. The LCA methodology is often employed to compare several manufacturing processes or design alternatives with the same function and/or to reveal the environmental "hotspots" of a product life cycle.

In the performed analysis, the LCA methodologies were applied looking at different environmental impacts' assessments, considering three different energy mixes. The aim was to compare the influence that hydroelectric, nuclear, petroleum and a mix of them results to have on specific environmental indicators to judge the sustainability of the investigated manufacturing routes. These highlighted energy sources were labelled in the study with the name of countries markedly characterised by each of them. Specifically, Norway for hydroelectric, France for nuclear, The Middle East for petroleum were considered. Furthermore, the World Average energy mix was taken into account [110].

CED was one of the environmental indicators quantified. It must be clarified that the energy consumption is a value that is obtained by converting the wasted energy required to execute a specific process and quantified by the absorbed electric energy (measured in kWh), into MJ oil equivalent (MJoe). This conversion depends on the employed Country's energy mix [110, 154]. For the performed analysis, the absorbed electrical energy, in kWh, was converted into MJoe using a specific parameter for each analysed Country, as ascribed in Table 4.2.

Table 4.2 Country's energy mix [38].

Country's energy mix	Norway	Middle East	France	World Ave.
Petroleum [%] Efficiency [%]	1,00 33,00	97,00 33,00	10,00 40,00	67,00 36,00
Nuclear [%]	0,00	0,00	78,00	15,00
Renewables [%]	99,00	3,00	12,00	18,00
MJoe/kWh	3,67	10,69	4,14	7,89

Moreover, by using the ReCiPe 2016 (H) method, available in SimaPro, specific midpoint indicators (i.e., global warming, ionising radiation, and mineral resource) and endpoint indicators (i.e., human health, ecosystem quality and climate change) were assessed to highlight the impacts of the investigated manufacturing solutions looking at their effects on different moments and environmental categories.

4.3.1 Goal & Scope

The components were manufactured with different percentages of material removed/deposited through subtractive or additive manufacturing processes, as shown in Table 1. A comparative analysis of four different component' shapes was carried out. Goal of this work is to select the right trade-off between removed/deposited material, which results in lower environmental burdens during the entire life cycle of the component. A cradle-to-grave analysis, which includes all unit processes starting from raw materials extraction to product manufacturing, from the product use phase to its EoL. Transports are not included in the system boundary, as represented in Fig. 4.2.

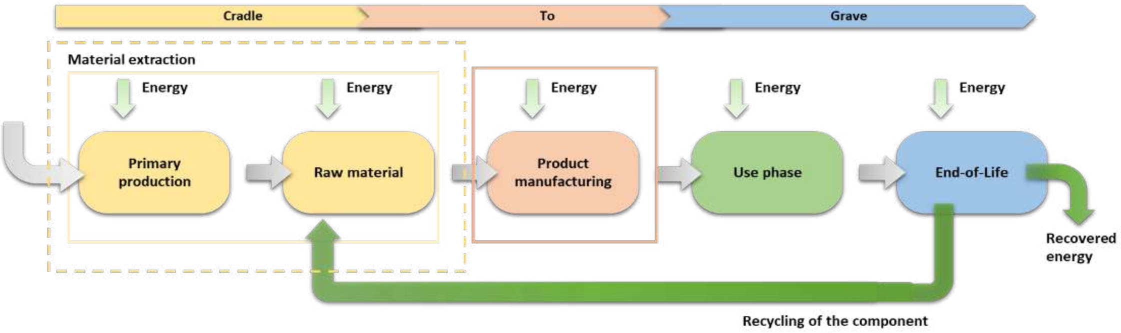


Figure 4.3 System boundary of the performed LCA [148].

4.3.2 Life Cycle Inventory (LCI)

The Ecoinvent V. 4.15 library provided by SimaPro 9.6.0.1 software was used for the inventory data for all the components under investigation [79]. The whole data, used in the analysis, were not available in the Ecoinvent database. For that reason, the energy required for obtaining the raw material employed in each manufacturing process was quantified combining literature data and software database (Table 4.3). The demanded energies for the investigated manufacturing phases were, instead, detected from literature, completely, as described in Table 4.4, where the energies for manufacturing a single component by each of the investigated processes were summarised. In detail, AM employs the Selective Laser Melting 3d printer (SLM) machine model Concept Laser M3 Linear, SM is performed by a Cortini F120/25 CNC. The times of the different printing phases and the required powder were quantified by literature [113]. According to the SLM additive process, the energy impact to operate in a protective inert atmosphere was calculated as 1.58 MJ/kg, with reference to extraction from natural gas [155]. Furthermore, the average flow rate was estimated by literature [40].

The SM energy impact was quantified considering the power of a standard milling machine [148] and the SM working time extracted by literature considering the machined volumes [156]. Finally, the energy impact related to the cutting fluid used in the SM was also taken into account. Specifically, the considered lubricant energy impact and the flow rate were 1.4 MJ/kg and 0.48 kg/h, respectively [155].

Table 4.3 Energy parts required to produce the raw material used in the manufacturing process.

Manufacturing process	Component's weight (kg)		Energy for obtained raw material (kWh/kg)	
Additive	m_c	1,75	h_m	Powder (45,00 [79]1,65 [60])
		1,05		
		0,35		
		0,18		
Machining	m_c	1,75	h_m	45,00 – Billet [79]
		1,05		
		0,35		
		0,18		

Table 4.4 Energy for manufacturing the analysed components considering subtractive and additive processes.

Manufacturing process	Removed/ deposited material (%)	Power (kW)	Working time (h)	Energy (kWh)
Additive	100,00	9,65 [59]	8,75	84,44

	60,00		5,25	50,66
	20,00		1,75	16,89
	10,00		0,87	8,40
Machining	0,00	7,00 [148]	0,00	0,00
	40,00		0,18	1,23
	80,00		0,35	2,47
	90,00		0,39	2,76

The research was performed including the impact of the product's use phase, too. The assumption that each component is mounted in an economy car, which covers 250.000 km in its life [117], was taken into account. The fuel consumption used in the study was obtained by [86, 157]. The fuel considered in the analysis is diesel and its density was taken by [118].

Furthermore, for the component's EoL phase, the percentage of recovered material was derived by [158]. The analysis considered two different methods to assess the product's EoL. The first one is the recycled content (Eq. 2.1), and the second one is the substitution method (Eq. 2.2), as described in the chapter 2. In the performed study, the percentages were considered respectively 95% and 91%, being extracted from literature [158, 159], in order to account the material recyclability (R) and recycling rate (r), respectively. Whereas m_b and m_c represent the initial billet mass and the component mass, respectively; h_m represents the aluminium alloy's material extraction specific energy, which is 45,00 kWh/kg [159]; h_{rc} represents the recycling process's specific energy, which is 2,80 kWh/kg [159]. Finally, h_d denotes the disposal specific energy referring to the landfilling of waste material, and it was quantified in 0,26 MJ/kg [160].

SM generates chips that can be landfilled or recycled [161]. Eq. 2 refers to the case where the chips are landfilled. In this work, both scenarios were evaluated, and Eq. 3 was considered in the case of chip recycling, where a chip recycling rate (r_1) of 88% was set [161].

$$H(net)_{substitution(R)}[MJ] = (m_b) \cdot h_m - r \cdot (m_c) \cdot (h_m - h_{rc}) + (1 - r) \cdot (m_c) \cdot h_d - r_1 \cdot (m_b - m_c) \cdot (h_m - h_{rc}) + (1 - r_1) \cdot (m_b - m_c) \cdot h_d \qquad (3)$$

The material waste for SLM was, instead, not considered owing to the process specificity that results in a really low material waste generation [162].

The life cycle inventory with the detailed values of energy used during each phase of the LCA analysis is summarised in Table 4.5.

Table 4.5 Inventory data employed in the proposed LCA.

Manufacturing process	Removed/ deposited material (%)	Material extraction (kWh/kg)	Product manufacturing (kW/kg)	Use phase (MJ/lt)	EoL (kWh/kg)
AM	100,00 60,00 20,00 10,00	46,65 [60, 79]	9,65 [111]	38,00 [118]	Calculated Eqs. (1-2)
SM	0,00 40,00 80,00 90,00	45,00 [60]	7,00 [148]	38,00 [118]	Calculated Eqs. (1-2)

According to the system boundary discussed in this section, a detailed flow chart for each system unit is summarised in Fig. 4.3.

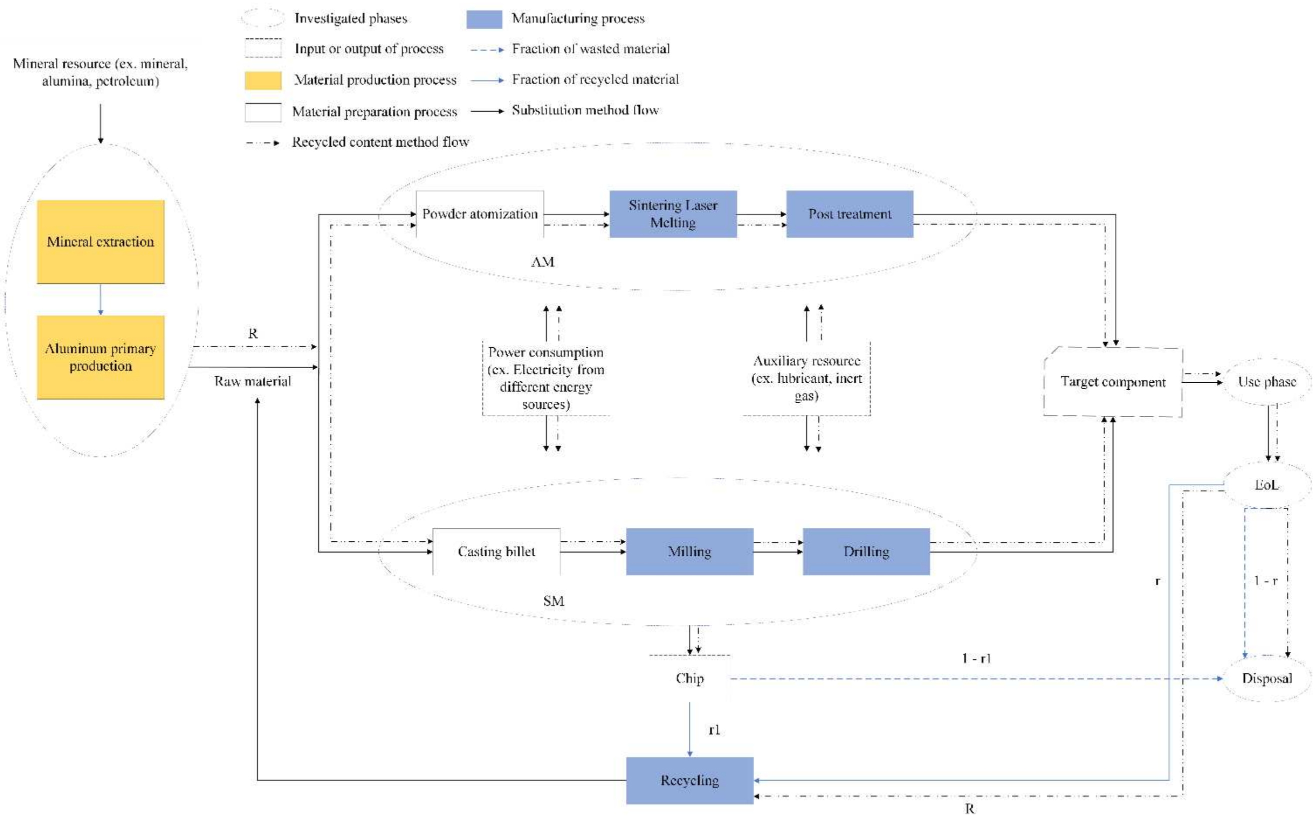


Figure 4.4 System unit of the analysed process.

4.4 Results and Discussion

The data obtained with the inventory analysis form the basis for the impact assessment phase (LCIA), which consists of estimating the environmental effects of the products, generated as a result of the consumption of resources and releases in the environment. Specifically, during this phase, the inventory data are associated with specific impacts categories. The impact categories depend on the evaluation method chosen from those available in the software used to perform the analysis. The selected methods for the impact assessment were the CED, and the ReCiPe 2016 V1.06 method Midpoint and Endpoint, all available in the SimaPro 9.6.0.1 software used for the evaluation [79]. In addition, different electricity sources from the Ecoinvent database were used. Specifically, the CH (Switzerland) database was considered during the analysis.

The results of the CED analysis are illustrated in Figs. 4.4 - 4.5 and synthesised in Table 4.6, where the contributions of the four phases are detailed in order to allow an overview of the analysed scenarios. According to [97, 163, 164] two scenarios were evaluated for the SM’s EoL phase. Specifically, the scenarios with the chip wasted (WCHIP) and with the chip correctly recycled (RCHIP) were taken into account.

Looking at the comparison between AM and SM in terms of CED required for the whole product's life, from its cradle to its grave, at different percentages of billet reduction, the advantage of SM as a process less environmental impacting than AM is evident at least up to a billet mass reduction of 90%, for which the two processes are comparable, essentially. The result is ascribable to the energy of product manufacturing by AM that is too affecting, placing the other contributions secondarily. This achievement can be considered as effective for both the recycling content and the substitution method, but only if the RCHIP scenario (Fig. 4.5 (c)) is taken into account. Indeed, the no management waste (i.e., the WCHIP scenario in Fig. 4.5 (b)) results in an energy incidence of the material extraction more impacting with a break-even point in terms of CED in between 40% and 80% of the billet's material reduction. The highlighted results are valid aside from the used country's energy mix. What changes by the country's choice of the production site is the actual MJoe per piece. Specifically, the Middle East resulted to be the most environmentally impactful both for AM and SM processes. By analysing the AM, in the Middle East the required CED impacts for 1522.97, 913.78, 304.59, 152.30 MJoe at the same part volume, 1.75, 1.05, 0.35 and 0.18 kg, respectively. Quantifying the impact for SM, instead, looking firstly at the recycling content method in Fig. 4.5 (a), the required CED per piece in the Middle East is equal to 622.20, 416.81, 211.14 and 159.87 MJoe considering respectively 0%, 40%, 80% and 90% of material reduction. Finally, the CED percentages of the other country's production sites with respect to the Middle East, are reported in Table 4.7.

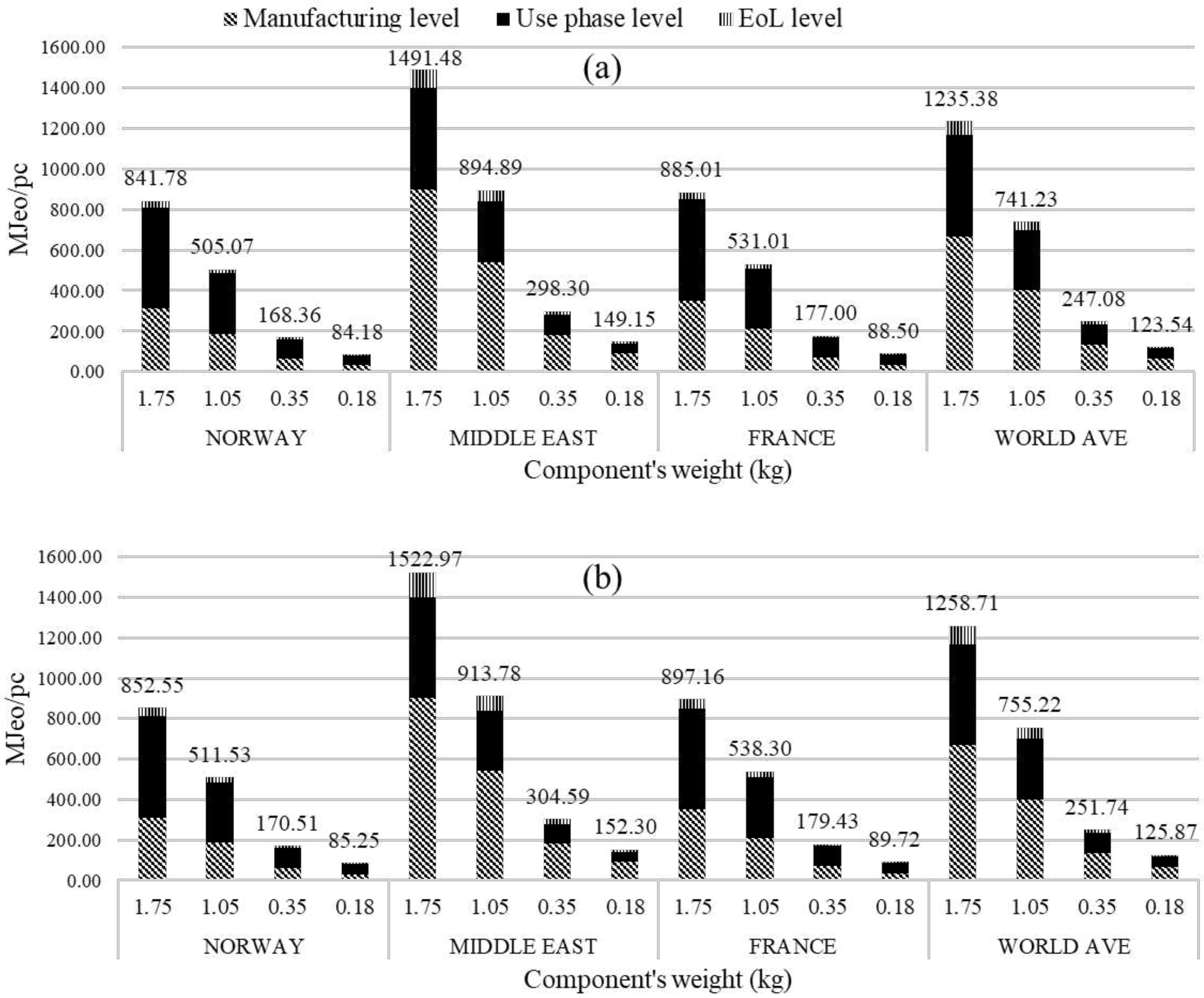


Figure 4.5 Assessment of CED in AM according to the recycled content method (a) and the substitution method (b).

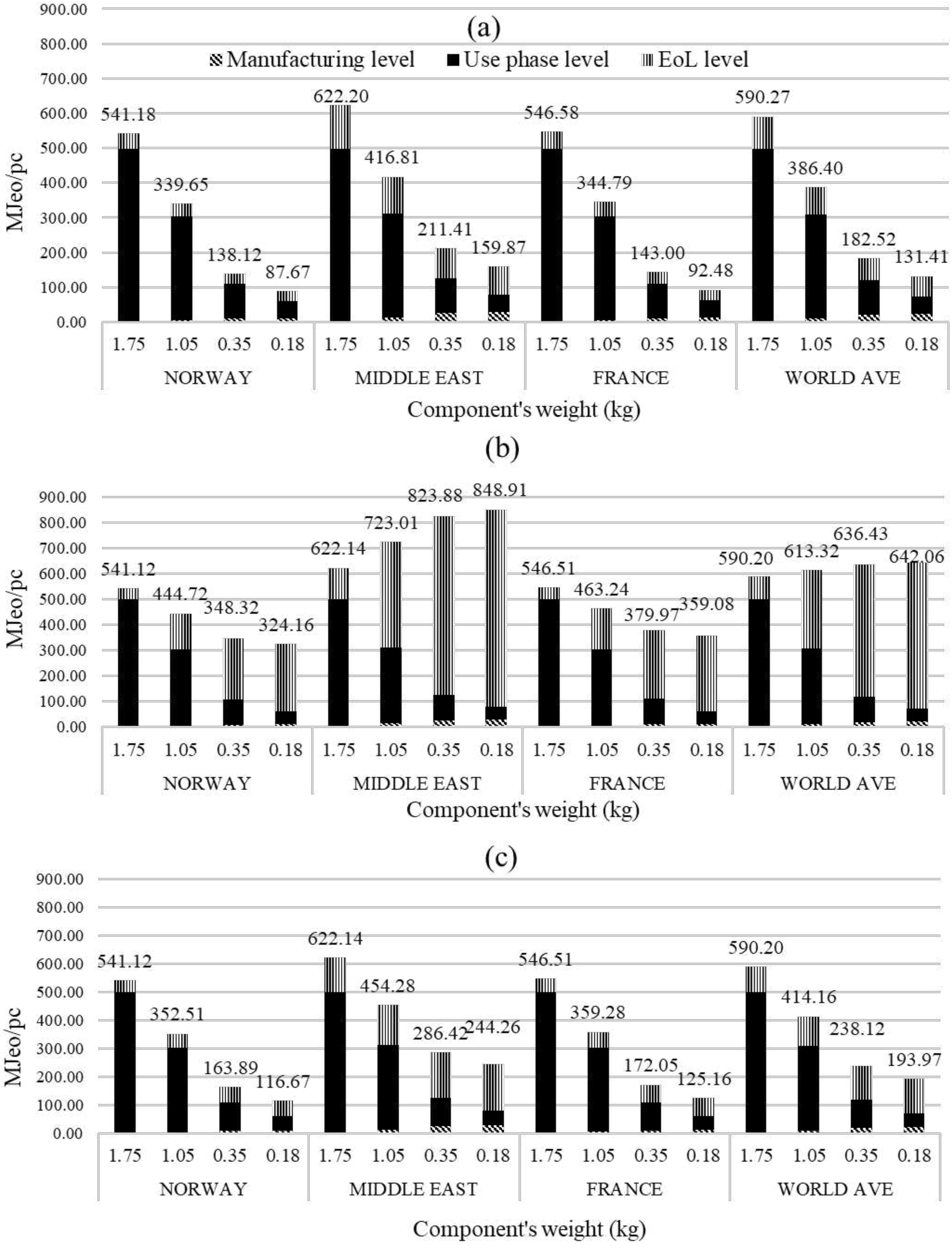


Figure 4.6 Assessment of CED in SM according to the recycled content method (a), the substitution method with wasted chip (WCHIP) (b) and the substitution method with recycled chip (RCHIP) (c).

Table 4.6 CED for each phase of the LCA for the process solutions and methods investigated.

CED [MJ]		Material Production				Product Manufacturing				Use Phase	Recycled content method							
											End-of-Life				from cradle-to-grave			
		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave
AM	100% deposited	289.26	841.82	326.03	624.02	311.43	900.83	350.65	668.50	498.75	31.60	91.89	35.61	68.13	841.78	1491.48	885.01	1235.38
	40% deposited	173.55	505.09	195.62	374.41	186.86	540.50	210.39	401.10	299.25	18.96	55.14	21.37	40.88	505.07	894.89	531.01	741.23
	80% deposited	57.85	168.36	65.21	124.80	62.29	180.17	70.13	133.70	99.75	6.32	18.38	7.12	13.63	168.36	298.30	177.00	247.08
	90% deposited	28.93	84.18	32.60	62.40	31.14	90.08	35.06	66.85	49.88	3.16	9.19	3.56	6.81	84.18	149.15	88.50	123.54

		Material Production				Product Manufacturing				Use Phase	Substitution method							
											End-of-Life				from cradle-to-grave			
		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave
AM	100% deposited	289.26	841.82	326.03	624.02	311.43	900.83	350.65	668.50	498.75	42.37	123.39	47.76	91.45	852.55	1522.97	897.16	1258.71
	40% deposited	173.55	505.09	195.62	374.41	186.86	540.50	210.39	401.10	299.25	25.42	74.03	28.66	54.87	511.53	913.78	538.30	755.22
	80% deposited	57.85	168.36	65.21	124.80	62.29	180.17	70.13	133.70	99.75	8.47	24.68	9.55	18.29	170.51	304.59	179.43	251.74
	90% deposited	28.93	84.18	32.60	62.40	31.14	90.08	35.06	66.85	49.88	4.24	12.34	4.78	9.15	85.25	152.30	89.72	125.87

		Material Production				Product Manufacturing				Use Phase	Recycled content method							
											End-of-Life				from cradle-to-grave			
		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave
SM	No reduction	289.26	841.82	326.03	624.02	0.00	0.00	0.00	0.00	498.75	42.43	123.45	47.83	91.52	541.18	622.20	546.58	590.27
	40% reduction	173.55	505.09	195.62	374.41	4.53	13.18	5.10	9.77	299.25	35.87	104.38	40.43	77.37	339.65	416.81	344.79	386.40
	80% reduction	57.85	168.36	65.21	124.80	9.06	26.36	10.21	19.54	99.75	29.31	85.30	33.04	63.23	138.12	211.41	143.00	182.52
	90% reduction	28.93	84.18	32.60	62.40	10.12	29.46	11.41	21.84	49.88	27.67	80.53	31.19	59.70	87.67	159.87	92.48	131.41

		Material Production				Product Manufacturing				Use Phase	Substitution method															
											End-of-Life								from cradle-to-grave							
		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave		Norway		Middle East		France		World Ave		Norway		Middle East		France		World Ave	
											WCHIP	RCHIP	WCHIP	RCHIP	WCHIP	RCHIP	WCHIP	RCHIP	WCHIP	RCHIP	WCHIP	RCHIP	WCHIP	RCHIP	WCHIP	RCHIP
SM	No reduction	289.26	841.82	326.03	624.02	0.00	0.00	0.00	0.00	498.75	42.37	42.37	123.39	123.39	47.76	47.76	91.45	91.45	541.12	541.12	622.14	622.14	546.51	546.51	590.20	590.20
	40% reduction	173.55	505.09	195.62	374.41	4.53	13.18	5.10	9.77	299.25	140.94	48.73	410.58	141.85	158.88	54.92	304.30	105.14	444.72	352.51	723.01	454.28	463.24	359.28	613.32	414.16
	80% reduction	57.85	168.36	65.21	124.80	9.06	26.36	10.21	19.54	99.75	239.51	55.08	697.77	160.31	270.01	62.09	517.14	118.83	348.32	163.89	823.88	286.42	379.97	172.05	636.43	238.12
	90% reduction	28.93	84.18	32.60	62.40	10.12	29.46	11.41	21.84	49.88	264.16	56.67	769.57	164.92	297.79	63.88	570.35	122.25	324.16	116.67	848.91	244.26	359.08	125.16	642.06	193.97

Table 4.7 CED percentage due the country's choice of the production sites for both SM and AM with respect to the Middle East.

Manufacturing process	Component's weight (kg)	Norway (%)	France (%)	World Ave. (%)
SM	1.75	86.9	87.8	94.8
	1.05	81.5	82.7	92.7
	0.35	65.3	67.6	86.3
	0.18	54.8	57.8	82.2
AM	1.75	55.9	58.8	82.6
	1.05	55.9	58.8	82.6
	0.35	55.9	58.8	82.6
	0.18	55.9	58.8	82.6

The CED trend is similar for Norway and France, except for a couple of percentage points for Norway. The World Ave., instead, is generally more environmentally impactful than Norway for more than the half difference between this country and The Middle East. This difference slightly increases for SM, at increasing the working time, and for AM. The comparison among the different production sites is homogeneous for AM without consideration of the part's weight. For SM, instead, the environmental impacts in percentage vary depending on the production site at changing of the part's weight because the effect of manufacturing phase is characterised by a countertrend respect of both Use-Phase and End-of-Life. For this countertrend, furthermore, the effect of the Use-Phase, more consistent for heavier parts, makes less, in percentage, the environmental benefits attributable to the strong employment of hydroelectric (Norway) or nuclear (France) energy with respect to petroleum (The Middle East).

As written above, these trends and related observations are valid even if SM and AM are compared by using the substitution method to assess the product's EoL if the chips produced in machining are recovered properly. The considerations on the environmental impacts change if the chips are totally wasted and not recycled. For this configuration (WCHIP scenario in Fig. 4.5 (b)), the energy necessary for the material extraction, not compensated by the chip recycling, results to be impactful for the SM sustainability. Quantifying the impact for this case, the required CED per piece in the Middle East, still the most affecting production site, is equal to 622.14, 723.01, 823.88 and 848.91 MJoe considering respectively 0%, 40%, 80% and 90% of material reduction.

The first evidence is that the CED grows progressively at increment of the percentage of the billet to be machined. This is due to the impact of a lack of proper material recovery that affects MJoe saving more than the weight reduction of the part and more than the related reduction of fuel consumption. In Table 4.8, the CED percentages of the other country's production sites are reported with respect to the Middle East, just for the WCHIP configuration.

Table 4.8 CED percentages of the production sites with respect to the Middle East for WCHIP.

Manufacturing process	Component's weight (kg)	Norway (%)	France (%)	World Ave. (%)
SM (WCHIP)	1.75	86.9	87.8	94.8
	1.05	61.5	64.0	84.3
	0.35	42.3	46.2	77.2
	0.18	38.2	42.3	75.6

Specifically, for a component that is produced without machining and, therefore, without considering the effects of chips wasting on CED, the different production sites are characterised by a comparable MJoe request owing to the influence of the Use-Phase of the product. But, if the component's shape needs a secondary production phase to be finished, the environmental advantages arisen by the choice of the production site grow at the increment of the removed material being the percentage weight of the material extraction and production more relevant.

Synthesising the facts resulting from CED analysis, nuclear and hydroelectric energy mixes are characterised by similar behaviour in terms of environmental impact with their undeniable advantages in comparison to petroleum. Among the impact categories provided by the ReCiPe

2016 (H) method, available in SimaPro v 9.6.0.1 [79], used for the LCA analysis, three midpoint and three damage indicators (endpoint) were, moreover, selected assessing the environmental effects of the process routes in relation to the chosen energy mix from other perspectives. These midpoint and endpoint impact categories are reported in Tables 4.9 - 4.10, respectively.

Table 4.9 Impact assessments via ReCiPe 2016 midpoint (H) method V1.06 with comparison of the midpoint impact categories for the different electricity sources from the Ecoinvent database for each analysed process from-cradle-to-grave approach.

MIDPOINT CATEGORIES	**Removed/Deposited material**	**AM**							
		Recycled content				**Substitution method**			
		Norway	**Middle East**	**France**	**World Ave**	**Norway**	**Middle East**	**France**	**World Ave**
Global warming [kgCO2eq]	No reduction/ 100% deposited	12.76	2080.36	22.69	966.94	12.92	2124.29	23.00	985.20
	40% reduction/deposited	7.66	1248.22	13.61	580.16	7.75	1274.58	13.80	591.12
	80% reduction/deposited	2.55	416.07	4.54	193.39	2.58	424.86	4.60	197.04
	90% reduction/deposited	1.28	208.04	2.27	96.69	1.29	212.43	2.30	98.52
Ionizing radiation [kBqCO-60eq]	No reduction/ 100% deposited	0.71	174.19	2641.49	1134.16	0.72	177.87	2677.74	1155.57
	40% reduction/deposited	0.43	104.51	1584.89	680.50	0.43	106.72	1606.65	693.34
	80% reduction/deposited	0.14	34.84	528.30	226.83	0.14	35.57	535.55	231.11
	90% reduction/deposited	0.07	17.42	264.15	113.42	0.07	17.79	267.77	115.56
Mineral resource [kgCueq]	No reduction/ 100% deposited	0.25	3.62	2.68	2.81	0.26	3.70	2.72	2.86
	40% reduction/deposited	0.15	2.17	1.61	1.69	0.15	2.22	1.63	1.72
	80% reduction/deposited	0.05	0.72	0.54	0.56	0.05	0.74	0.54	0.57
	90% reduction/deposited	0.03	0.36	0.27	0.28	0.03	0.37	0.27	0.29

		SM											
		Recycled content method				**Substitution method (WCHIP)**				**Substitution method (RCHIP)**			
		Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave	Norway	Middle East	France	World Ave
Global warming [kgCO2eq]	No reduction/ 100% deposited	8.20	867.87	14.01	462.00	8.20	867.78	14.01	461.95	8.20	867.78	14.01	461.95
	40% reduction/deposited	5.15	581.38	8.84	302.43	6.74	1008.48	11.88	480.05	5.34	633.64	9.21	324.17
	80% reduction/deposited	2.09	294.89	3.67	142.86	5.28	1149.18	9.74	498.14	2.48	399.51	4.41	186.38
	90% reduction/deposited	1.33	222.99	2.37	102.86	4.91	1184.09	9.20	502.55	1.77	340.71	3.21	151.82
Ionizing radiation [kBqCO-60eq]	No reduction/ 100% deposited	0.46	72.67	1631.36	541.90	0.46	72.66	1631.17	541.84	0.46	72.66	1631.17	541.84
	40% reduction/deposited	0.29	48.68	1029.08	354.74	0.38	84.44	1382.63	563.06	0.30	53.06	1072.34	380.23
	80% reduction/deposited	0.12	24.69	426.80	167.57	0.29	96.22	1134.09	584.28	0.14	33.45	513.50	218.61
	90% reduction/deposited	0.07	18.67	276.01	120.65	0.27	99.14	1071.73	589.46	0.10	28.53	373.57	178.08
	No reduction/ 100% deposited	0.16	1.51	1.66	1.34	0.16	1.51	1.66	1.34	0.16	1.51	1.66	1.34

Mineral resource [kgCueq]	40% reduction/deposited	0.10	1.01	1.04	0.88	0.13	1.76	1.40	1.40	0.11	1.10	1.09	0.94
	80% reduction/deposited	0.04	0.51	0.43	0.42	0.11	2.00	1.15	1.45	0.05	0.70	0.52	0.54
	90% reduction/deposited	0.03	0.39	0.28	0.30	0.10	2.06	1.09	1.46	0.04	0.59	0.38	0.44

Table 4.10 Impact assessment via ReCiPe 2016 (H) Endpoint method V1.06 with comparison of the endpoint impact categories for the different electricity sources from the Ecoinvent database for each analysed process from cradle-to-grave approach.

ENDPOINT CATEGORIES	**Removed/Deposited material**	**AM**							
		Recycled content method				**Substitution method**			
		Norway	**Middle East**	**France**	**World Ave**	**Norway**	**Middle East**	**France**	**World Ave**
Human Health [DALY]	No reduction/ 100% deposited	3.39E-05	2.34E-03	1.35E-04	1.14E-03	3.43E-05	2.39E-03	1.37E-04	1.16E-03
	40% reduction/deposited	2.03E-05	1.40E-03	8.11E-05	6.81E-04	2.06E-05	1.43E-03	8.22E-05	6.94E-04
	80% reduction/deposited	6.77E-06	4.67E-04	2.70E-05	2.27E-04	6.86E-06	4.77E-04	2.74E-05	2.31E-04
	90% reduction/deposited	3.39E-06	2.34E-04	1.35E-05	1.14E-04	3.43E-06	2.39E-04	1.37E-05	1.16E-04
Ecosystem quality [species.yr]	No reduction/ 100% deposited	6.01E-08	1.46E-05	1.69E-07	6.76E-06	6.08E-08	1.49E-05	1.71E-07	6.89E-06
	40% reduction/deposited	3.60E-08	8.74E-06	1.01E-07	4.06E-06	3.65E-08	8.92E-06	1.03E-07	4.13E-06
	80% reduction/deposited	1.20E-08	2.91E-06	3.37E-08	1.35E-06	1.22E-08	2.97E-06	3.42E-08	1.38E-06
	90% reduction/deposited	6.01E-09	1.46E-06	1.69E-08	6.76E-07	6.08E-09	1.49E-06	1.71E-08	6.89E-07
Climate change [DALY]	No reduction/ 100% deposited	1.63E-05	3.50E-03	6.14E-05	1.64E-03	1.65E-05	3.58E-03	6.22E-05	1.67E-03
	40% reduction/deposited	9.79E-06	2.10E-03	3.68E-05	9.82E-04	9.92E-06	2.15E-03	3.73E-05	1.00E-03
	80% reduction/deposited	3.26E-06	7.01E-04	1.23E-05	3.27E-04	3.31E-06	7.16E-04	1.24E-05	3.33E-04
	90% reduction/deposited	1.63E-06	3.50E-04	6.14E-06	1.64E-04	1.65E-06	3.58E-04	6.22E-06	1.67E-04

		SM											
		Recycled content method				**Substitution method (WCHIP)**				**Substitution method (RCHIP)**			
		Norway	**Middle East**	**France**	**World Ave**	**Norway**	**Middle East**	**France**	**World Ave**	**Norway**	**Middle East**	**France**	**World Ave**
Human Health [DALY]	No reduction/ 100% deposited	2.18E-05	9.74E-04	8.35E-05	5.43E-04	2.18E-05	9.74E-04	8.35E-05	5.43E-04	2.18E-05	9.74E-04	8.35E-05	5.43E-04

	40% reduction/deposited	1.37E-05	6.53E-04	5.27E-05	3.55E-04	1.79E-05	1.13E-03	7.08E-05	5.64E-04	1.42E-05	7.11E-04	5.49E-05	3.81E-04
	80% reduction/deposited	5.56E-06	3.31E-04	2.18E-05	1.68E-04	1.40E-05	1.29E-03	5.80E-05	5.85E-04	6.59E-06	4.49E-04	2.63E-05	2.19E-04
	90% reduction/deposited	3.53E-06	2.50E-04	1.41E-05	1.21E-04	1.30E-05	1.33E-03	5.48E-05	5.90E-04	4.69E-06	3.83E-04	1.91E-05	1.78E-04
Ecosystem quality [species.yr]	No reduction/ 100% deposited	3.86E-08	6.08E-06	1.04E-07	3.23E-06	3.86E-08	6.07E-06	1.04E-07	3.23E-06	3.86E-08	6.07E-06	1.04E-07	3.23E-06
	40% reduction/deposited	2.42E-08	4.07E-06	6.57E-08	2.12E-06	3.17E-08	7.06E-06	8.83E-08	3.36E-06	2.52E-08	4.44E-06	6.85E-08	2.27E-06
	80% reduction/deposited	9.86E-09	2.06E-06	2.72E-08	9.99E-07	2.49E-08	8.04E-06	7.24E-08	3.48E-06	1.17E-08	2.80E-06	3.28E-08	1.30E-06
	90% reduction/deposited	6.26E-09	1.56E-06	1.76E-08	7.19E-07	2.31E-08	8.29E-06	6.84E-08	3.52E-06	8.33E-09	2.38E-06	2.38E-08	1.06E-06
Climate change [DALY]	No reduction/ 100% deposited	1.05E-05	1.46E-03	3.79E-05	7.82E-04	1.05E-05	1.46E-03	3.79E-05	7.82E-04	1.05E-05	1.46E-03	3.79E-05	7.82E-04
	40% reduction/deposited	6.58E-06	9.79E-04	2.39E-05	5.12E-04	8.62E-06	1.70E-03	3.21E-05	8.12E-04	6.83E-06	1.07E-03	2.49E-05	5.49E-04
	80% reduction/deposited	2.68E-06	4.97E-04	9.92E-06	2.42E-04	6.75E-06	1.94E-03	2.64E-05	8.43E-04	3.18E-06	6.73E-04	1.19E-05	3.15E-04
	90% reduction/deposited	1.70E-06	3.76E-04	6.42E-06	1.74E-04	6.28E-06	1.99E-03	2.49E-05	8.50E-04	2.26E-06	5.74E-04	8.68E-06	2.57E-04

Both midpoint and endpoint indicators confirm the trends highlighted by CED analysis considering the comparison between SM and AM at changing of the percentage of the component respect of the initial billet volume for the different End-of-Life strategies. Specifically, looking at Global warming and Climate change, the last one was quantified taking into account ozone layer depletion and fine particulate matter formation, the advantages of using hydroelectric and/or nuclear energy sources are consistent with respect to petroleum. Anyway, the comparability of environmental impacts of Norway and France ends if the other midpoint and endpoint indicators are analysed. Indeed, both ionising radiation and mineral resource (midpoint) and human health and ecosystem quality (endpoint) result to be markedly affected by the nuclear energy that is the more environmentally impacting, losing its competitiveness not just in respect of hydroelectric but also if compared to petroleum energy source.

4.5 Conclusions

In this chapter, the two additive and subtractive process techniques are studied extensively from the point of view of environmental analysis. Indeed, the processes were analysed considering different scenarios and environmental parameters to provide a valid tool for process selection based on the geographical positioning and consequently the energy mix of the country of reference.

Therefore, a life cycle assessment coupled by two framework and scenarios was reported. The LCA study was carried out to assess the environmental impact of AM and SM at different component's shapes, obtainable by a fixed volume of an enveloping billet. The LCA analysis was performed evaluating the CED of the manufacturing processes, quantified considering the influence owing to different energy sources, and other environmental assessments, extracted by Midpoint and Endpoint impact categories. Furthermore, concerning the SM process, two End-of-Life scenarios were analysed, namely WCHIP and RCHIP.

In general terms and in a perspective of reducing the environmental impacts for the entire product's life, the results showed that AM and SM have to be compared considering the percentage of the enveloping billet's volume to be reduced and looking also at the material waste management. Specifically, if the CED is the parameter to be considered, SM resulted to be the most environmental manufacturing route up to a strong billet's volume reduction (around 90% of its initial volume) because the manufacturing energy required for AM overshadows the other contributions. But, if waste is not properly managed (i.e., the WCHIP scenario), AM and SM became comparable for lower billet's volume reduction (between 40% and 80%) because of the energy related to the material lost and not recovered in SM. The countries' energy mix does not influence the highlighted CED trends.

But, considering the WCHIP recycling scenario, the different impacts due to a lack of proper material recovery and to the fuel consumption modify the trend of the MJoe consumption at changing of the component's weight depending on the energy mix is more or less based on petroleum sources.

Looking, instead, at specific Midpoint and Endpoint indicators, such as, respectively, actual MJoe per piece and climate change or global warming, petroleum was the most environmentally impacting energy while hydroelectric and nuclear energies are almost comparable and the most sustainable energy sources. However, their environmental comparability ended if other Midpoint and Endpoint indicators were taken into account. For example, both ionising radiation and mineral resources (Midpoint) and both human health and ecosystem quality (Endpoint) resulted to be markedly affected by the nuclear energy that was more environmentally impacting not just on respect of hydroelectric, but also if compared to petroleum sources.

On the other hand, it should be emphasised that the assessments made in this chapter could be influenced by the type of material used in the process. Indeed, since in the automotive field it is essential to use lightweight materials in order to reduce the weight to be transported and consequently reduce emissions, as described above. At the same time, it is also necessary to guarantee the durability and mechanical resistance of the components, hence, the behaviour of multi-material components will be examined in the next chapter.

5. Chapter V: Cumulative Energy Demand Analysis of Commercial and Hybrid Metal-Composite Gears at Different End-of-Life Strategies

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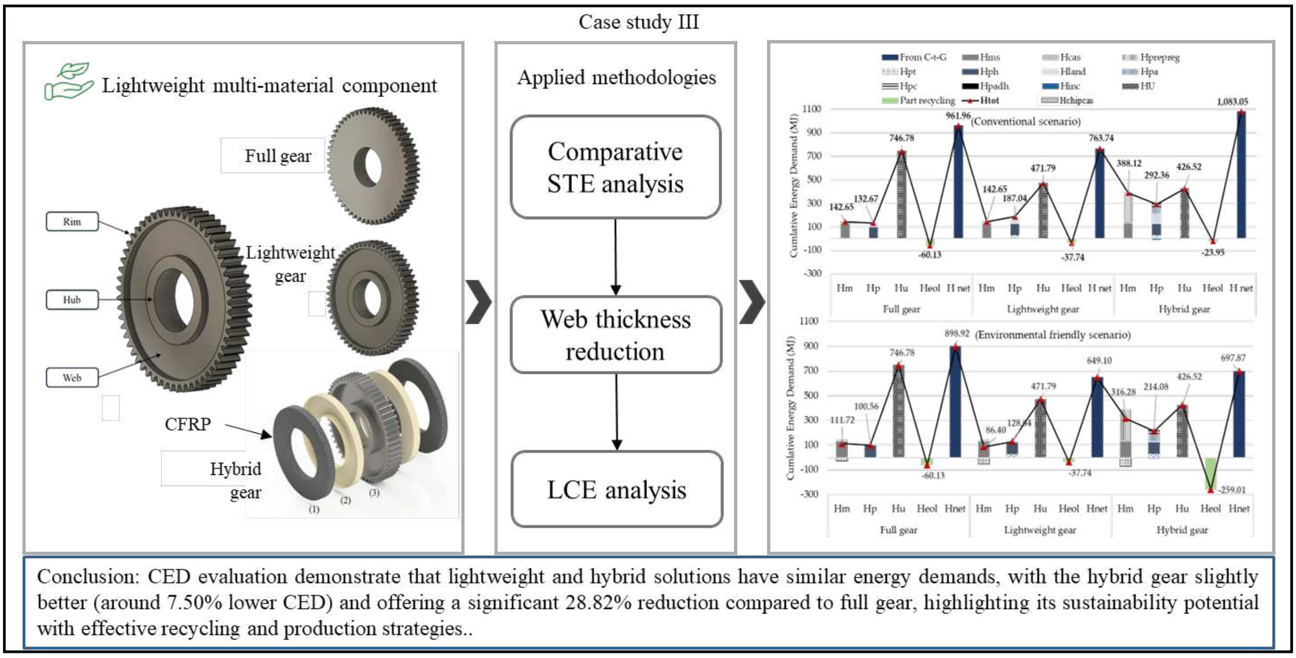
5.1 Chapter Summary

In this chapter, the aims of the research area moved towards the use of the joining of different materials such as common steel and innovative material such as continuous fibre reinforced polymers (CFRP) used in the automotive sector in order to optimise the component's weight. In this perspective, the study is focused on a hybrid gear manufactured with the joining of steel and composite material. On the other hand, nowadays, gears remain a fundamental component in mechanical power transmission, with ongoing research focused on enhancing performance and sustainability. This chapter addresses the process of gear lightweighting, a key factor for efficiency improvements in automotive and aerospace sectors. Traditionally, material removal from gear bodies results in weight reduction, but at the cost of increased noise and vibration. A novel approach using hybrid gears, which combine a metal rim and hub with a composite material web, offers a promising solution. This research proposes a comparative environmental analysis among a conventional full steel, a lightweight and a hybrid gear using a life cycle energy quantification. The study herein proposed, considers two End-of-Life (EoL) scenarios: a conventional open loop scenario with partial recycling and a closed loop scenario with comprehensive recycling, including a thermal recycling for carbon fibre reinforced plastics. The Cumulative Energy Demand (CED) has been conducted by applying a from cradle-to-grave approach. The CED has been evaluated for each gear configuration quantifying the impact of each unit process involved in the production of the gear, from raw materials extraction to product manufacturing and from use phase to different EoL scenarios. Finally, to present a comprehensive overview of the work, the graphical abstract in Figure 5.1 was provided.



Conclusion: CED evaluation demonstrate that lightweight and hybrid solutions have similar energy demands, with the hybrid gear slightly better (around 7.50% lower CED) and offering a significant 28.82% reduction compared to full gear, highlighting its sustainability potential with effective recycling and production strategies..

Figure 5.1 Graphical abstract.

5.2 Introduction

After millennia of technological advancements, nowadays gears are still the preferred technology for mechanical power transmission in machines. In spite of their large diffusion, gears are still a relevant research topic for academic as well as industrial researchers, whose efforts aim at enabling the full satisfaction of increased performance demands, while meeting the general paradigm of sustainability enhancement.

System lightweighting for efficiency enhancement is one of the main innovation drivers in industrial sectors, such as automotive and aerospace. In the last sector, the concept of lightweight gears originated to satisfy the demand of payload reduction, considering that gearboxes can account for up to 15% of the total weight [165]. The concept extended to the automotive area, in which manufacturers have in mass reduction an instrument to face the challenges coming from increasingly stricter regulations on fuel efficiency and emissions [166–168].

Conventionally, gear lightweighting is achieved by removing material from the gear body. However, the increased flexibility of gears with a thin rim or with holes in the blank has an impact on the noise and vibration (N&V) performance of the transmission [169].

Recently, a novel approach for weight reduction of gears was proposed by exploiting the favourable weight-to-stiffness ratio of composite materials [170, 171]. An innovative concept of hybrid gear originates whereby the metal rim and hub are connected by a web made of triaxial braided composite material. The proposed material distribution enables a weight reduction of about 20% with respect to the steel gear with the same macro-geometry web. The concept of hybrid gears will be also exploited for the design and manufacturing of a full-scale bull gear by LaBerge et al. in [172], while in [173] experimental tests are illustrated for a bull gear with variable thickness of the composite body.

Catera et al. used the Finite Element Method (FEM) to analyse the meshing behaviour of transmissions incorporating hybrid gears, while two joining technologies for metal-composite gear manufacturing [174–177], namely adhesive bonding and interference fitting, were compared in [178] by FEM and by experimental tests at component level. Instead, with the aim of analysing the N&V behaviour of hybrid gears, numerical and experimental investigations are reported in [179] to illustrate the Static Transmission Error (STE) curves.

Yılmaz et al., studied the effect of rim thickness on the root and joint stress, tooth stiffness, natural frequency and dynamic behaviour of hybrid gears assembled by adhesive bonding, showing the great potential of proposed technology to enable lightweighting in geared mechanical power transmissions[180]. FEM analyses, in combination with experimental material characterisation, allowed, Gauntt and Campbell, to study the modal behaviour of a hybrid gear with different composite materials and various layup sequences[181].

To the best of our knowledge, no research efforts aimed at assessing the sustainability of hybrid gears by a Life Cycle Energy (LCE) demand methodology are reported in literature. In order to fill this knowledge gap, the environmental performance of gears in the automotive sector was investigated in this study. The focus of the analysis is, therefore, to quantify the LCE demand of different gear typologies to reduce carbon dioxide (CO_2) emissions meeting the limits imposed by the European council [182]. Specifically, energy consumption is strictly linked to CO_2 emissions. A Cumulative Energy Demand (CED) analysis was performed for this reason in the herein research.

Worldwide, industrial emissions have increased by around 60% between 1990 and 2022 due to the growing global demand for industrial goods [183, 184]. By 2022, emissions have decreased approximately 2%, mainly due to the reduction of industrial activities during the pandemic crisis. On the other hand, it is imperative to focus efforts on reducing the impact of pollutant emissions, considering the consequences for both the environment and human health. Indeed, industrial activities generate emissions of substances with a toxic impact on humans and the environment. According to 2017 estimates, industrial and transport emissions damage human health and the environment by EUR 277- 433 billion per year [182].

In this context, the European Commission presented proposals in 2022 to modernise the standards 2010/75/EU and 1999/31/EC for industrial emissions and waste landfill respectively, with the goal of achieving climate neutrality by 2050 [182]. Specifically, in 2022, the distribution of CO_2 emissions in the European Union, indicates that almost 50% of pollution is from the transport and industry sector. In this context, the European Commission has projected a reduction in global emissions of about 3% each year until 2050 to meet the Net Zero Emission (NZE) target. Specifically, a reduction of carbon dioxide per km was set from 93,6 g in 2025 to 0 g in 2050 [184].

Several studies claim that the lightening of components results in environmental emissions reduction [86, 90, 185, 186]. But, to assess the Greenhouse gas (GHG) benefits of lightweighting, the entire life cycle must be considered, as demonstrated by Kirchain Jr et al. [187]. In detail, a from cradle to grave approach should be applied to quantify the overall impact that considers the material production, product manufacturing, use phase and different EoL scenarios. For example, a Life Cycle Assessment (LCA) coupled with component lightening by topological optimization, allowed Borda et al. to quantify and to optimise the CED [148, 188]. Therefore, just a conscious choice of materials according to the required mechanical requirements, of the manufacturing process, based on the shape peculiarities of the components, and of their EoL allows providing a strategic decision guidance for the minimization of the environmental impact, as also demonstrated by [189]. Considering the aforementioned matters, the purpose of the present paper is to perform a comparative environmental analysis among a conventional full steel, a lightweight and a hybrid gear using a comparative Cumulative Energy Demand (CED) analysis from cradle–to–grave with different End-of-Life (EoL) scenarios. In detail, the first EoL scenario describes a more usual recycling process, where the metal chips and composite scraps from the manufacturing processes are landfilled and incinerated, respectively, whereas the gears body at the EoL are remelted. The second EoL scenario involves a more environmentally friendly recycling strategy of all employed materials, as detailed in the following paragraphs. Both scenarios were investigated in the analysis resulting in guidelines for selecting the proper scenario in gear production according to the imposed constraints.

5.3 Material and Methods

The model was designed specifying the gear dimension analysed in [179]. The main characteristics of the analysed gear are listed in Table 5.1.

Table 5.1 Main dimensions of the analysed gear [174].

Parameter	**Value**
Teeth number	59
Module	2.5 mm
Pressure angle	20°
Face width	24 mm
Tip diameter	154 mm
Root diameter	142.75 mm
Theoretical pitch diameter	147.50 mm
Base diameter	138.60 mm

For completeness, Figure 5.1 (a) shows the different parts in which a gear is usually divided, i.e., the rim, the web and the hub section [174]. In the proposed research, a full gear (Figure 5.1 (b)), made of case-hardened 18NiCrMo5 alloy steel with a density of 7,85E-05 kg/mm^3, a lightweight gear, made with the same alloy steel (Figure 5.1 (c)) with a reduced web thickness, and a hybrid gear, made with the same alloy steel and carbon fibre reinforced plastic (CFRP) to fill the web (Figure 5.1 (d)), were analysed. Indeed, as highlighted by a literature review [190], the CFRP provides performance advantages not only in terms of mechanical performance, but also in terms of component lightening. Figure 5.1 (d) also provides an exploded view of the hybrid gear manufactured by using pre-impregnated composite plies. The pre-impregnated layers are composed of an epoxy resin matrix and M40J carbon fibres. The mechanical properties of the matrix and reinforcement material are listed in Table 5.2. The reinforcement materials, i.e. carbon fibres (CFs), are combined with the epoxy matrix in a ply with a fibre mass fraction percentage of 43.2%. A quasi-isotropic configuration, $[0/30/60/90/120/150]_{3s}$, was taken into account. In addition, an adhesive layer is used, to join the metal and composite part.

Table 5.2 Main properties of the composite material.

Property	**Fiber**	**Matrix**
Material type	Carbon M40J	Epoxy
Longitudinal Modulus [GPa]	377	2.7
Transverse Modulus [GPa]	15	2.7
Shear Modulus [GPa]	24.7 Long./ 5.0 Transverse	1
Poisson's ratio [-]	0.41	0.35
Density [g/cm^3]	1.77	1.2

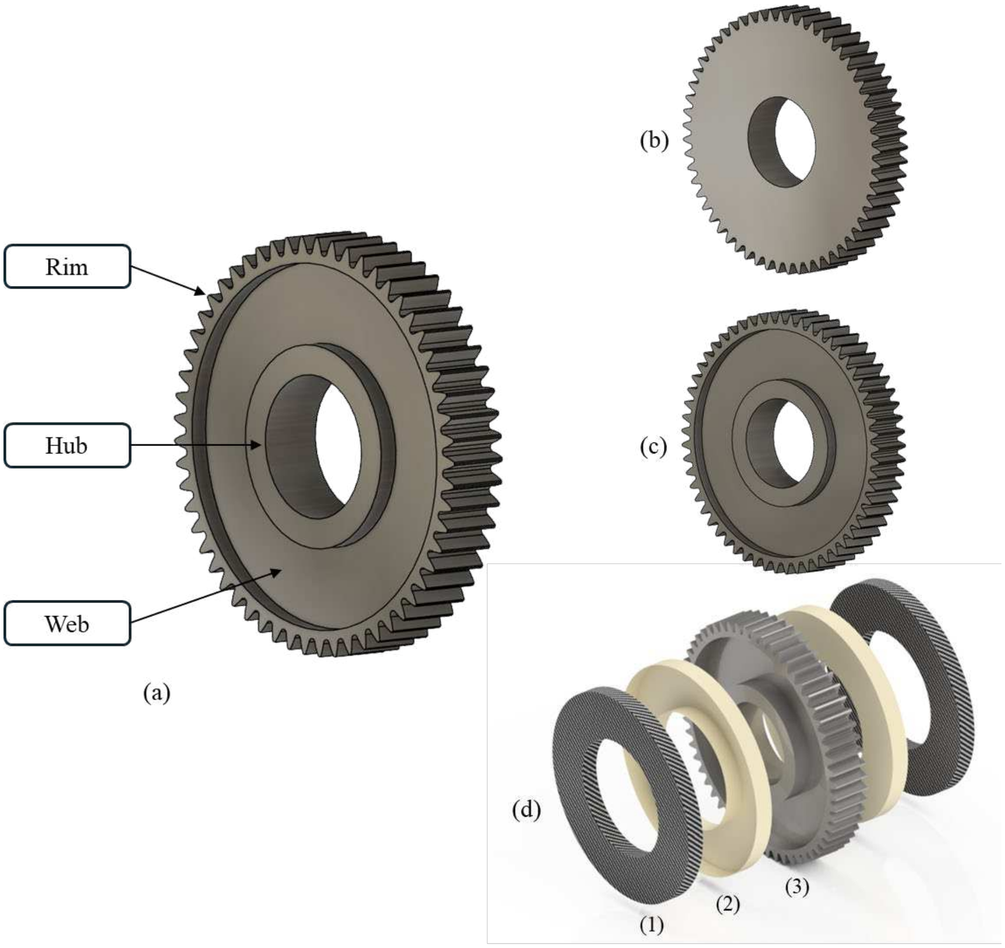


Figure 5.2 On the left side: (a) detail of each conventional gear section; on the right the detail of the analysed gears: (b) full, (c) lightweight and (d) detail of hybrid composite gear; (1) composite web, (2) adhesive layer, (3) metal gear body.

The three different gears are sized performing numerical analysis as detailed in the next 5.3.1 subsection.

5.3.1 Numerical Model

Geared transmissions are complex mechanical systems that enable the power flow between input and output shafts. To this end, gears are often designed to find the best trade-off between different operational metrics such as (i) energy efficiency and (ii) dynamic performances[191]:

i. Mass reduction is one of the key drivers of performance enhancement in automotive as well as aerospace sectors to satisfy the increasingly stricter regulations on combustion engine emission and fuel efficiency [166, 191, 192]. Current design solutions rely either on material removal from the gear blank [169, 193] or on the combination of lightweight materials with high-performance steel [178] to decrease the gear mass. In both cases, the optimal design choice must prevent the deterioration of N&V performance [169], while preserving the structural integrity of the geared transmission.
ii. Despite gears are designed to be perfectly conjugate, the lightweighting process introduces additional gear body flexibilities that induce deviations from the ideal kinematic conditions producing unwanted self-induced vibrations. These are often traced back to the static transmission error (STE) of two meshing gears [169]. It is the defined as the degree of offset between conjugate and actual behaviour of the meshing gears:

$$TE = \frac{1}{\tau} \mathit{\Delta}\theta_2 - \mathit{\Delta}\theta_1, \tag{1}$$

where τ is the transmission ratio of the gear pair, while $\mathit{\Delta}\theta_1$and $\mathit{\Delta}\theta_2$ are the rotations of the driving and driven gears, respectively. Due to the variability of the TE over the meshing cycle and the harmonic nature of the rotating gears, internal induced vibrations are generated which highly affect the N&V performance of a geared transmission. In order to assess the severity of parametric excitation at different load and velocity levels, the pick-to-pick (PtP) value of the TE has been demonstrated in [194] to be a valuable and synthetic metric.

In this work, in order to access the overall EoL performances of different design choices, the PtP STE metric of the innovative hybrid lightweight design described in the previous section is considered as target to define a mono-material but lightweight design starting from a full gear body. This was achieved varying the web thickness parameters of the lightweight gear in a discrete manner until the target was approximatively matched. Once the design of experiments was well defined the PtP STE performances were virtually evaluated by means of an advanced MultiBody (MB) simulation platform, Simcenter Motion ("Siemens. White Paper: Boosting Productivity in Gearbox Engineering," 2019), where both varying contact stiffness and gear body flexibility were accounted for as described in [195]. Figure 5.2 shows the MB model of a generic gear pair where a reference motion of 10 rpm is given in input to the full gear design and transmitted to the parametric lightweight gear on which a constant resistant torque of 100 Nm is applied [178].

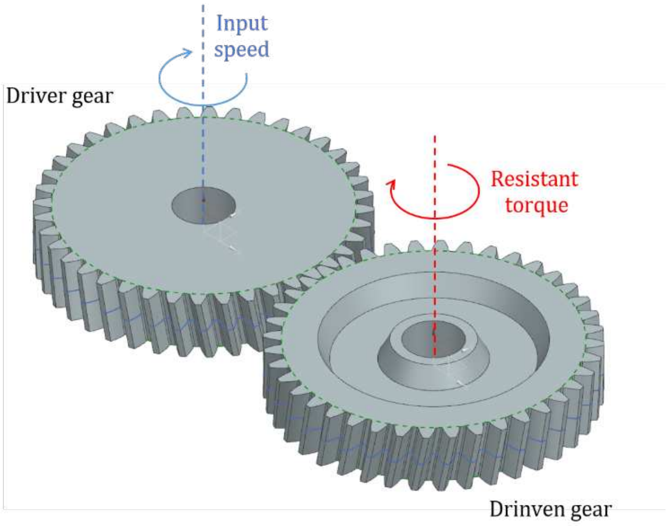


Figure 5.3 MB model of the considered lightweight gear transmission: the driver gear design is fixed and full while the driven gear is parametric and lightweight.

Finally, Table 3 summarizes the PtP STE metric for the evaluated gear designs. Moreover, it is highlighted in red that the lightweight gear design with a web thickness τ of 10 mm is the closest to the reference hybrid gear with an overall PtP STE Error of 0.014 µm. For completeness the mass of the evaluated designs is also reported in Table 5.3 and will be considered in the next section for performing the environmental analysis.

Table 5.3 Summary of the evaluated gear designs in terms of PtP STE and mass of the driven gear.

Component	**Web thickness τ [mm]**	**PtP STE [µm]**	**PtP STE difference [µm]**	**Mass [kg]**
Hybrid gear	-	1,963	reference	1,539
Full gear	23	1,706	0,257	2,674
Lightweight gear	15	1,849	0,114	2,148
	12,5	1,907	0,056	1,954
	10	**1,977**	**0,014**	**1,761**

	7,5	2,072	0,109	1,567
	5	2,193	0,230	1,373

The designed variable τ, whose variation ensures the desired PtP STE, allows to compare the analysed gears. The τ quantification, assuming a Static Transmission Error (STE) calculated by simulation, results in calculating the volume and, consequently, the mass (M_{gear}), for each analysed gear, as detailed in Table 3.

5.3.2 Goal & Scope

The LCE quantification allows assessing the environmental impacts of a product by using its life cycle. If the production process is considered, environmental impacts are assessed from the raw material processing. This phase is also called “Cradle”, which is part of the term “Cradle-to-Grave”. The term “grave” is derived from the last piece of material processing, when materials are recycled, disposed of, or lost.

The comparison of different masses and/or joining strategies of different materials can help decision-makers to reduce environmental impact, and the LCE quantification is a valuable tool that can be used to compare different products or different design alternatives with the same function and to highlight the useful phases in the product life cycle. The present LCE work describes a comparative environmental assessment of three different gear configurations with two different EoL scenarios, in order to select the proper configuration able to reduce the environmental impact during its entire life cycle. The analysis involves three different system products made with different materials as described in Figure 5.1. The functional unit (f.u.) is represented by the gears that were sized to have the same PtP STE with a different web thickness (τ), as described in the previous subsection 5.3.1. The main goal of the work is to evaluate the best scenario to reduce the overall environmental impact during the entire life cycle of the gear, from a CED point of view.

This CED study is conducted by applying a from cradle-to-grave approach, which includes all the unit processes involved in the production of the gear, from raw materials extraction to product manufacturing and from use phase to different EoL scenarios. The work was performed according to the system boundaries as reported in Figure 5.3. Furthermore, the transport phase between the process units is excluded from the analysis, as it is assumed to be the same between process units and between the analysed scenarios. The electricity production used in industrial processes is obtained from the combustion of natural resources, as shown in literature [189]. Considering the electric energy demand of the process, it was converted into primary energy source consumption by taking into account an average efficiency of 36% in order to consider the energy generation and transmission losses [110]. In order to assess the cumulative energy demand according to the Country's energy mix, the factor 7,85 MJoe/kWh was used to convert the electricity of the manufacturing process into energy consumption [110]. For the performed analysis, the energy consumption refers to the European average energy mix.

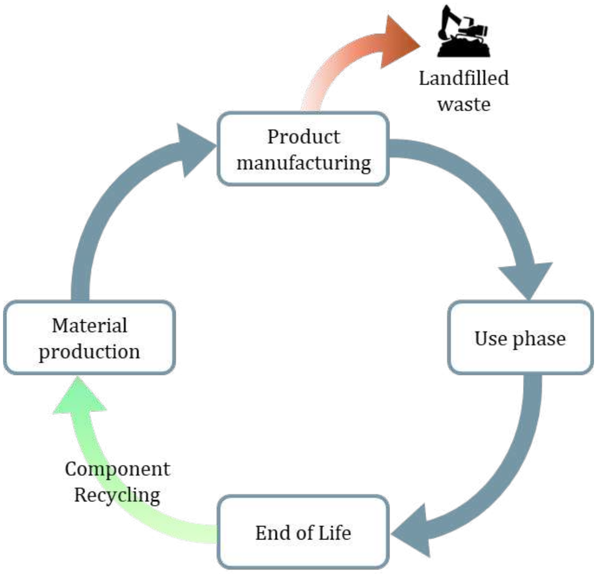


Figure 5.4 System boundaries.

Looking at EoL phase of the investigated gears, the benchmark EoL scenario is the so-called conventional open loop scenario, allowing a CED assessment of a component that is processed by combustion and where the metal and composite scraps produced during the manufacturing processes are disposed of by landfill and incinerator, respectively. Indeed, considering this open loop process, the gear body is remelted to obtain the raw material. The second scenario analysed in the study, the so-called closed loop, involves the recycling of the entire component with a remelting of the gear body and the metal scraps. In addition, in this case, the composite gear part is recycled by a pyrolysis process (thermal recycling). Specifically, the Carbon Fibres (CFs) are fully recovered by the pyrolysis process while the epoxy matrix is burned [196]. Pyrolysis was chosen because several studies claim that if the decomposition process is carried out at a temperature range from 350° C to 700° C, this recycling process is the most efficient and reliable in terms of energy and material recovery [197–200]. Lastly, a cleaning step is required during the CF recycling. The cleaning phase is necessary to purify the reinforcement (CF) to make it ready for a new life cycle. The two different EoL scenarios, i.e., the conventional open-loop scenario and closed-loop scenario, are summarised in Figure 5.4. These EoL routes are considered as the "more usual" and the "more environmentally friendly" scenario, respectively.

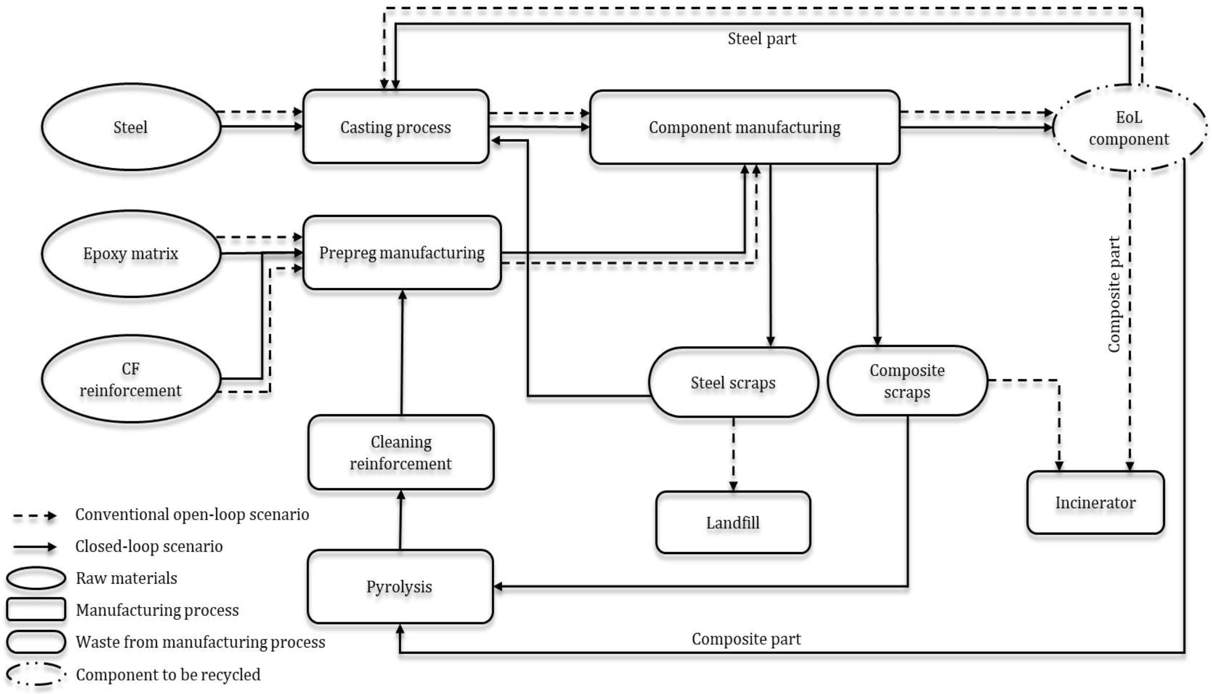


Figure 5.5 Detail of the “more usual” and “more environmentally friendly” analysed EoL scenarios.

5.3.3 Life Cycle Inventory (LCI)

LCI data were generated by using different approaches. Data from scientific literature and technical reports were used. In detail, according to previous work [189], a great variability of data was reported. For this reason, in order to reduce the variance, an average value was used when a variability in data was encountered.

To evaluate the environmental impact of both metal and CFRP gear body, the material energies are considered. In detail, the energy aliquots linked to mineral extraction and to casting billet were considered for the alloy steel. The embodied energies of the reinforcements (CFs) and of the polymeric matrices, raised up by the energy needed to perform sub-processes to combine fibres in yarns and to process these yarns to achieve the CFs prepregs, were taken into account for the CFRPs. These energy rates of the materials are represented by H_m, as detailed in Table 5.4.

Table 5.4 Embodied and manufacturing energy of investigated material for each analysed gear.

Nomenclature	**Material energy**	**Energy consumption [MJ/kg]**	**References**
	Steel embodied energy (H_{ms})	32.00	[110]

H_m	Steel casting energy (H_{cas})	4.15	[110]
	CFs embodied energy (H_{mCFs})	722.39	[189]
	Epoxy embodied energy (H_{mEpoxy})	117.50	[110]
	Prepreg manufacturing ($H_{prepreg}$)	132.63	[189]

At the end of the material energy quantification, a metallic billet and a pre-impregnated CFRP blank (prepregs) were analysed. To consider the environmental impact of the manufacturing processes, the process energy rates were specified for each analysed gear. Specifically, the starting cylindrical billet and prepregs are characterised by a volume of 5,03E+05 mm^3 and 3,83E+05 mm^3, respectively. The turning process, comprising the other sub-operation, i.e. roughing, finishing, drilling, and trimming, was considered to obtain the hub and the web section. The full and lightweight gears were manufactured by turning the manufacturing process regarding the web and hub sections, and by the hobbing process regarding the rim section. The turning process time was estimated by setting a simulation via CAD/CAM software [201]. Specifically, the process time was estimated as 0.045 h, 0.503 h, and 0.533 h, for full, lightweight and hybrid gears, respectively. A standard CNC turning machine was used, and the estimated value of energy consumption was 7 kW, as reported in literature [148, 202]. Whereas, considering the rim section, the hobbing process was selected as being the most efficient and precise process. To determine the process parameters, a mathematical calculation was performed according to Wang et al. allowing the hobbing process time to be calculated [203]. In detail, the hobbing process time to obtain the selected gears was estimated as 1.72 h. The energy consumption value was estimated by a scientific technical report [204]. For what concerns the lightweight gear, the web thickness, and consequently the turning process time, was defined by the performed numerical simulations, as described in the previous section 5.3.1.

Furthermore, during the analysis, the impact of consumables was considered. The quantity of cutting fluid used during a standard machining process and the embodied energy of the cutting fluid were estimated from literature. Specifically, according to [204], in a standard manufacturing process the cutting fluid was accounted for 2.24 ml/s, and according to [28] the environmental impact, from an energy point of view, was accounted for 380.00 MJ/kg.

On the other side, the hybrid gear (Figure 5.1 (d)) was manufactured by following a multi-step process approach as detailed in [179]. Rim and hub, linked by a 2mm-thick metal layer, were manufactured by using the same material and manufacturing process of the full and lightweight gears. In the web, the 2mm-thick layer was left to ensure axiality between the rim part and the hub, as demonstrated by

Rezayat et al.[179]. Simultaneously, the axial direction gap was left to allow the housing of a 10.50mm-thick layer of composite laminate material on each side of the web section of the gear. In detail, overlapping of pre-impregnated layers were considered, characterised by homogeneous in-plane properties and cured in an autoclave process to consolidate the different plies.

Furthermore, an abrasive water jet (AWJ) process is used to size the composite blank to the correct web section [205]. In addition, an adhesive layer is used for joining the metal and laminate part. The amount of energy related to the used adhesive layer was taken from the literature [110]. The overall energy portions considered during the gear manufacturing processes, grouped in H_p, are detailed in Table 5.5.

Table 5.5 Energy consumption during product manufacturing process for each analysed gear.

Nomenclature	Manufacturing processes	Energy consumption			Unit	References
		full	lightweight	hybrid		
H_p	Turning (H_{pt})	0.31	3.52	3.73	kWh/pc	Calculated
	Hobbing (H_{ph})	12.04	12.04	12.04	kWh/pc	Calculated
	Autoclave (H_{pa})	-	-	152.34	MJ/kg	[110]
	Adhesive (H_{padh})	-	-	117.50	MJ/kg	[110]
	AWJ (H_{pc})	-	-	3.46	kWh/pc	[205]

In order to evaluate the use phase for each analysed gear, it was taken into account that each gear was mounted on an economy diesel car, which covers 250.000 km in its life with a vehicle weight of 1400 kg [206]. The fuel consumption is accounted for 0.30 l for each km and for each travelled kg and its density was accounted as 0.85 kg/l [86, 207]. According to [110], the energy intensity of diesel accounted for 44.00 MJ/kg. The energy consumption used in the whole use phase for each gear is represented by H_U and is estimated to be 746.77 MJ, 471.79 MJ, 426.51 MJ for full, lightweight and hybrid, respectively.

Finally, different EoL scenarios for the gear were assumed, strictly linked to the employed materials. Considering the metallic material, i.e. steel, the mass fraction of steel that could be recycled was recovered by a casting process. On the other side, the steel scrap was disposed of in landfill. The energy for both above processes was obtained from the literature [86, 110] and accounted for 4.15 MJ/kg and 3.68 kWh/kg, respectively.

Considering the prepregs, the CFRP material was recycled by pyrolysis according to the recycling route first proposed by Pimenta et al. [196, 208]. After the pyrolysis process, a cleaning step is required to obtain the recycled CFs. In detail, the energy required by the pyrolysis and cleaning process of the prepreg CFRP was extracted by [189] and accounted for 43.50 MJ/kg and 8.73 MJ/kg, respectively.

5.3.4 Life Cycle Energy Demand Assessment

The methodology proposed in [209] was applied to quantify the CED to perform a comparative analysis of the environmental impact in the case study described in the previous section. The life cycle energy demand assessment was performed using Eqs. (5.2) – (5.7).

The CED quantification of the target component assesses the environmental impact during its life cycle. The method considers the energy of the raw components production (H_m) based on the weight of the gear strictly linked to the initial steel billet and, if it is present, to the employed composite prepregs as summarised in Eq. (5.2). Specifically, a H_m portion of the component is calculated as the mass fraction of the used steel (mf_s) and, if it is present, of the composite prepregs, made by carbon fibres (mf_{CFs}) and polymeric resins (mf_{Epoxy}) multiplied, respectively, by the embodied energy of the steel (H_{ms}), of the fibres (H_{mCFs}) and of the epoxy resins (H_{mEpoxy}). The mass of the prepreg ($mf_{prepreg}$) employed in the gear body is the sum of mf_{CFs} and mf_{Epoxy}. H_m considers also the contributions of the casting process required to achieve the initial metallic billet (H_{cas}) and all the specific sub-processes required to combine fibre and polymeric matrix to obtain the prepregs ($H_{prepreg}$). The energy of the gear manufacturing is taken into account by H_p in Eq. (5.3). This energy aliquot (H_p) is calculated taking into account the manufacturing phases to process the metallic billet achieving the final shape of the gear, i.e., turning (H_{pt}) and hobbing processes (H_{ph}), and, if present, the all-manufacturing phases to work the prepregs to obtain the laminate utilised in the hybrid gear, i.e., autoclave moulding (H_{pa}) and cutting process (H_{pc}). Subsequently, considering the hybrid gear, the joining phase (H_{padh}) to assemble the metal and the laminate parts by an adhesive layer was considered. The energy related to the use phase (H_U) was calculated for each analysed gear multiplying the mass fraction of consumed fuel (mf_f) by the energy intensity of fuel ($H_{u\_specific}$), as described in Eq. (5.4). The overall energy for each target component is summed up by H_{gear} in Eq. (5.5).

$$H_m = mf_s \cdot (H_{ms} + H_{cas}) + (mf_{CFs} \cdot H_{mCFs}) + (mf_{Epoxy} \cdot H_{mEpoxy}) \tag{5.2}$$

$$H_P = H_{pt} + H_{ph} + H_{pa} + H_{pc} + H_{padh} \tag{5.3}$$

$$H_U = mf_f \cdot H_{u\_specific} \tag{5.4}$$

$$H_{gear} = H_m + H_P + H_U \tag{5.5}$$

Eq. (5.5) can be used to quantify the CED of each target component without considering the EoL scenario and the scrap material produced during the gear manufacturing.

For what concerns the EoL, the substitution method was considered. Specifically, the EoL contribution (H_{EoL}) and the scrap material contribution (H_{Scrap}) to the cumulative energy of the gear (H_{net}) can be evaluated by considering two different approaches, named "more usual" and "more environmentally friendly" depending on the implemented recycling scenario. If the more usual approach is taken into account, just the metallic part of the gear is recycled ($mf_{s_{Gear}}$) at its EoL, while the epoxy resin of the CFRP is burned recovering the heat (H_{inc}) and the wasted material in manufacturing, for both steel ($mfs - mf_{s_{Gear}}$) and CFRP ($scrap_{Prepreg}$) are addressed to the landfill (H_{land}). For this approach, H_{EoL} and H_{Scrap} are calculated by Eq. (5.6). If the more environmentally friendly approach is executed, H_{EoL} and H_{Scrap} are quantified considering that the whole gear is properly recycled. In detail, pyrolysis, a thermal strategy [40] is employed to recycle the CFRP laminate (H_{pyro}). Furthermore, the wasted material is properly recovered by melting the metallic chips and burning the sheet scrap derived from the overlapping composite plies ($scrap_{Prepreg}$) (Eq. (5.7)). Eqs. (5.6) and (5.7) are below made explicit:

$$H_{Usual} = -\left(R_s \cdot mf_{s_{Gear}} \cdot (H_{ms} - H_{cas})\right) + (1 - R_s) \cdot mf_{s_{Gear}} \cdot H_{land} - mf_{Prepreg} \cdot (H_{inc}) + (mf_s - mf_{s_{Gear}}) \cdot H_{land} + scrap_{Prepreg} \cdot H_{land} \tag{5.6}$$

$$H_{Envir.} = -\left(R_s \cdot mf_s \cdot (H_{ms} - H_{cas})\right) - (mf_{CFs}) \cdot (H_{mCFs} - H_{pyro}) - (R_s \cdot (mf_s - mf_{s_{Gear}}) \cdot (H_{ms} - H_{cas})) - (scrap_{Prepreg} \cdot H_{inc}) + (1 - R_s) \cdot mf_s \cdot H_{land} \tag{5.7}$$

where, R_s is the fraction of the steel that can be recovered by remelting it ($R_s = 90\%$) [210].

5.4 Results and Discussion

The CED values for the three different gears, listed as full, lightweight and hybrid gears for the two different recycling approaches (i.e., the "more usual" and the "more environmentally friendly"), are reported in Figure 5.5. The CED results shown in Figure 5.5 (a) were calculated for the entire life cycle of the analysed gears for the "more usual" approach. Specifically, this EoL configuration was evaluated to provide an upper threshold value. In detail, the metallic gear body was recycled by remelting the part, the epoxy resin of the CFRP plies employed in the hybrid gear were burned to recover the heat, whereas all the other involved materials, i.e. the oxidised metallic part due to the casting process, the chip derived by the machining process and the scrap of composite laminate owing to the specific size of the gear web, were disposed of in landfill. In this scenario, the process impact related to metallic chip and to the overall composite laminate (scrap and web section of the hybrid gear) are accounted for in the (H_p) for each analysed gear. The energy of the raw components production (H_m) has an impact of 142.65 MJ $(H_{ms} + H_{cas})$ for the gears made just of steel, both for the full and the lightweight gear. Whereas, for the hybrid gear, (H_m) increases of about 175% owing to the CFRP production ($H_{prepreg}$=245.47), resulting in a cumulative impact of 388.12 MJ. Looking at the gear manufacturing (H_p), an opposite trend can be observed. Indeed, in this phase, the full gear is characterised by a reduced impact of 96.98 MJ being necessary a short machining phase $(H_{pt} = 2.47, H_{ph} = 94.51)$ to achieve the final gear shape. In addition, a value of 35.68 MJ (H_{land}) from the landfilling of metal scrap generated during the manufacturing process was taken into account. Specifically, the (H_p) value increases by 40.98% and 120.37% for lightweight and hybrid gear, respectively. For the lightweight configuration, the machining phase increases to dig the web $(H_{pt} = 27.64)$ and consequently for the increase in metallic scrap $(H_{land} = 64.89)$. The (H_p) increment for the hybrid variant takes into account the manufacturing of the prepregs $(H_{pa} = 53.11)$, the impact related to landfilling of metallic and composite waste $(H_{land} = 89.92)$, the recovered heat due to the incineration of the CFRP laminate derived from gear web section $(H_{inc} = -11.16)$ and the impact of the adhesive bonding $(H_{padh} = 9.50)$ and cutting phase $(H_{pc} = 27.17)$.

The use phase (H_u), being related to the weight of the components that consume fuel for their movement, sees the heavier full gear with the more significant impact of 746.78 MJ. This CED aliquot is 75.08% and 58.29% higher than the lightweight (471.79) and hybrid gear (426.52), respectively.

The EoL phase of the gear was taken into account applying the conventional open-loop scenario described in Eq. (5). Specifically, the considered aliquots for the EoL phase are: 60.13 MJ, 37.74 MJ, and 23.95 MJ for the full, lightweight, and hybrid gear, respectively. Finally, considering the whole life cycle with a cradle-to-grave approach (H_{net}), the hybrid gear resulted to be comparable to the full gear, with an increase of 12.58% in CED. On the other hand, in this scenario, the lightweight gear allows an advantage, in terms of CED recovery, of 41.81% over the hybrid gear.

On the other hand, the results of the "more environmentally friendly" approach are shown in Figure 5.5 (b), which provides lower threshold values. In detail, the closed-loop scenario was considered for the EoL of the gear and of the materials wasted during the manufacturing phases. In this approach, for the full gear, H_m takes into account the metallic chip recovered by a casting process and quantified by $(H_{chipcas} = -30.93)$. $H_{chipcas}$ results to be of -56.25 and -71.84 for lightweight and hybrid gear, respectively, considering the different quantity of removed material from the initial casting billet.

For what concerns H_p, the H_{land} related to the metallic chip is not considered because it is properly recycled. Actually, just the oxidised chip portion is landfilled impacting for 3.57, 6.49 and 8.29 in the full, lightweight and hybrid gear, respectively. Furthermore, for the hybrid gear, the thermal energy of prepregs scraps is recovered $(H_{inc.} = -7.80)$. Nothing changes for the use-phase as compared to the first approach.

Finally, considering the EoL, the hybrid gear, which includes the metallic gear body recycled by remelting process and composite prepreg web section recycled by pyrolysis process, enables a CED recovery of 259.01 MJ allowing a recovery of 331% and 586% respect to lightweight and full gear, respectively, that do not change their EoL phase. The higher recovered energy rate is mainly due to the high impact of the production of virgin CFs.

The overall CED assessment (H_{net}) for the "more environmentally friendly" approach results in the values of 898.92 MJ, 649.10 MJ, 697.87 MJ considering the full, lightweight and hybrid gear, respectively. In this scenario, the lightweight and hybrid solutions result to be comparable, with a CED difference around 7.50%. On the other hand, the hybrid gear reaches a CED saving of 28.82% if compared to the full gear.

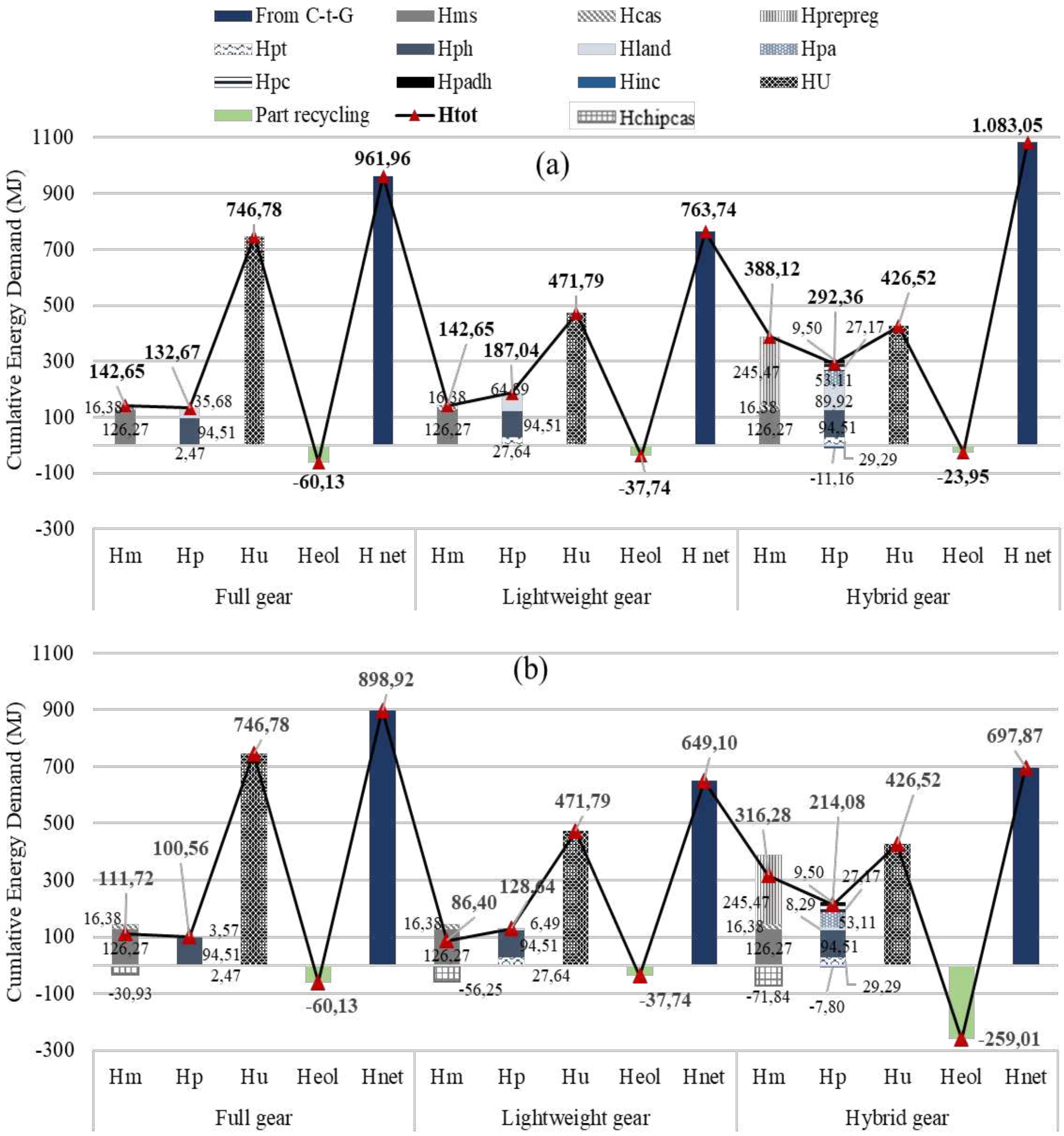


Figure 5.6 Energy impacts of the different steps in the whole from-cradle-to-grave product's life for (a) conventional open loop scenario and (b) closed loop scenario.

5.5 Conclusions

The herein proposed study, from a CED point of view, provides useful elements for practitioners in the environmental impact study considering the entire gear life cycle. In detail, based on the performed analysis, different gears, but with similar mechanical performance, were compared considering diverse EoL strategies based on an open and a closed loop scenario. Synthesising, a gear full-steel gear was compared to a lightweight gear, characterised by a reduced web thickness, and a hybrid gear, where the web is made of a polymeric matrix composite reinforced by continuous CFs.

The possible EoL scenarios were studied, from a theoretical point of view, collecting the required energy quantification of each phase in the product life from its cradle to its grave.

Assuming that the best environmental choice can be more or less convenient depending on the scenarios analysed, the hybrid gear proved its competitiveness with respect to the full gear not just in terms of performance enabled by the reduced weight that is guaranteed.

The following evidence was extracted: the high environmental impact from the energy point of view, mainly due to the LCE related to the CFRP laminate, cannot allow the hybrid gear to be environmentally friendly if a proper EoL strategy is not followed, especially if this is compared to the lightweight solution. Conversely, operating with appropriate recycling strategies, the CED required to process hybrid gears could be reduced resulting in a competitiveness of the solution not just for the use-phase, where it exploits the low weight, but also in a whole cradle-to-grave analysis.

On the other hand, in order to make a comprehensive assessment of the sustainability of multi-material products, it is necessary to choose a correct trade-off between environmental and economic sustainability. In this context, a multi-objective model has been set up that considers the entire production cycle of a component in the automotive field that can be made of metal material and/or with the joining of metal and composite material. The proposed optimisation model aims to minimise carbon dioxide emissions and production costs based on design constraints. Preliminary results of the proposed model were presented at a sector conference. Further studies are needed to integrate other manufacturing processes and materials with the aim of implementing a comprehensive tool to make the proper strategic choices in the design phase while minimising the environmental and economic impact of the product, in perfect accordance with the circular economy pillars proposed by the European Union.

6. Chapter VI: Cumulative Energy Demand Analysis in the Current Manufacturing and End-of-Life Strategies for a Polymeric Composite.

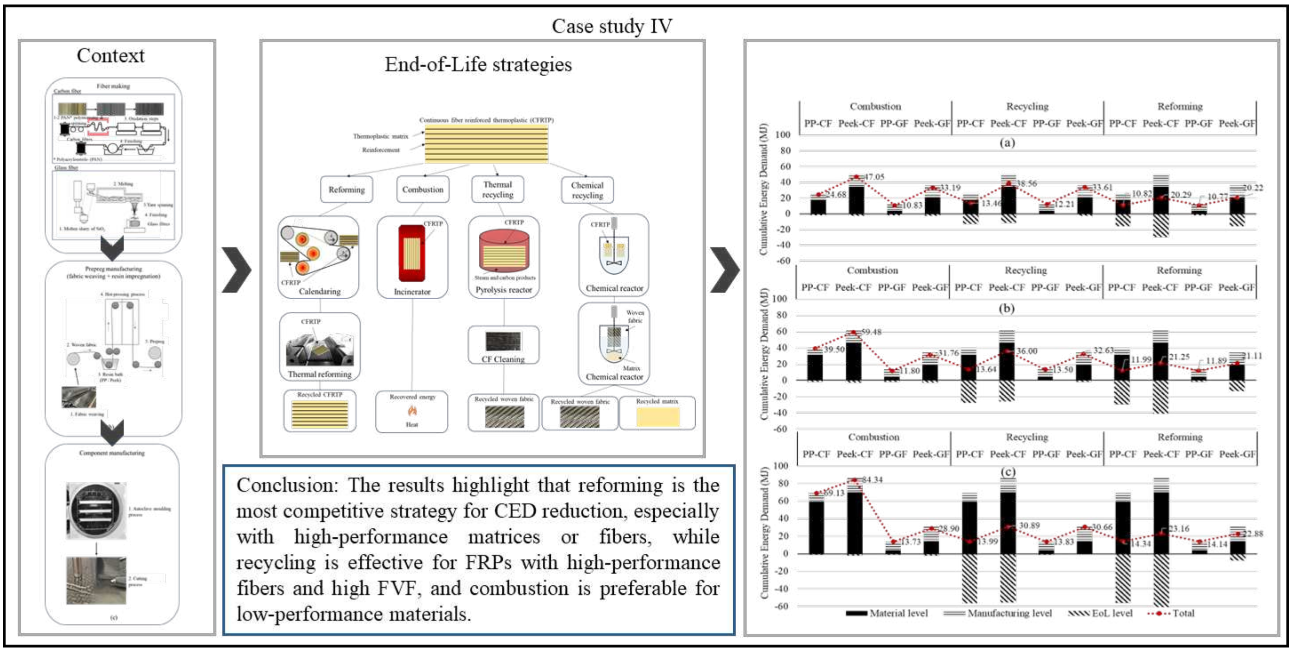
Part of the content of this Chapter was published in:

- Journal of Cleaner Production

Borda, Francesco, Ingarao, Giuseppe, Ambrogio, Giuseppina, Gagliardi, Francesco, 2024. *Cumulative energy demand analysis in the current manufacturing and end-of-life strategies for a polymeric composite at different fibre-matrix combinations.*

6.1 Chapter Summary

In this chapter, a scientific study of composite materials is proposed. The study was focused on this type of material because, as can be seen from the previous chapter, innovative materials have a high potential for lightening components, but at the same time the impact on the environment must be considered. Taking these assumptions into consideration, the following study was set up with the aim of investigating in depth the manufacturing process of composite materials with a specific focus on end-of-life strategies. In this context, the case study analysed is a generic component that does not belong to the automotive sector, the aim of the work is in fact to provide a clear guide for practitioners of LCA studies. Indeed, by making strategic choices during the design phase, it is possible to select the correct materials and optimise the environmental impact, therefore operating an eco-design. Finally, to present a comprehensive overview of the work, the graphical abstract in Figure 6.1 was provided.



Conclusion: The results highlight that reforming is the most competitive strategy for CED reduction, especially with high-performance matrices or fibers, while recycling is effective for FRPs with high-performance fibers and high FVF, and combustion is preferable for low-performance materials.

Figure 6.1 Graphical abstract.

6.2 Introduction

Continuous fibre-reinforced polymers (CFRPs) are innovative materials that combine high strength and stiffness with low density, making them attractive for a wide range of applications. The continuous fibres, if compared to short fibres, provide the material with high mechanical properties, making them stronger and stiffer [211]. CFRPs are also highly resistant to fatigue and corrosion and have excellent thermal and electrical properties [212].

The unique properties of composites have made them popular in industries such as aerospace, automotive, construction and sporting goods [213]. In aerospace, CFRPs are used in aircraft structures and components to reduce weight and fuel consumption. The reduction in fuel and maintenance costs can help to balance out the higher initial cost [214]. In the automotive sector, numerous studies claim that replacing various vehicle components with lightweight materials, such as composites, reduces CO_2 emissions [215–217].

While CFRPs offer many advantages, there are also some drawbacks to be faced. Firstly, CFRPs are more costly to produce [218]. Advancements in production methods and increasing demand have, however, resulted in a decrease in costs, making CFRPs more accessible for a wider range of applications [219]. Indeed, the production of CFRPs components has increased significantly [220].

The global CFRPs market size reached US$ 2.55 Billion in 2022 expecting the market to reach US$ 3.62 Billion by 2028, exhibiting a growth rate (CAGR) of 5.90% during 2023-2028 [221].

A second drawback is related to environmental challenges. The production of these materials uses about one-fifth of global energy demand [222] and, furthermore, increased volumes of CFRPs in today's applications will result in the creation of waste tomorrow. All this waste will have to be managed. In this context, the Circular Economy (CE) paradigm allows the industrial system to be restorative and regenerative from product idea to design in line with the European Union's (EU) 2050 climate neutrality target as part of the Green Deal [223].

In this perspective, the use of CFRPs is a challenge for their EoL treatments[224]. In detail, the separation of matrix and fibre is problematic, due to the covalent bonds created in the polymer's chemical structure. Moreover, fillers and additives, added to provide additional properties, increase this difficulty further [225–227]. The types of fibre and matrix affect the EoL treatments to be used. Looking at used matrices, CFRPs can be made either by thermosetting or by thermoplastic polymers. The advantages of composite materials based on thermoplastics matrix is the process reversibility [228–231]. These matrices are reinforced mainly by continuous Glass, Carbon and Other fibres [232, 233].

The present work focuses on CE approaches of continuous fibre-reinforced thermoplastics (CFRTPs). CFRTPs estimated at US$948.9 Million in the year 2022, is projected to reach a size of US$1.5 Billion by 2030, growing at a CAGR of 6% over the analysis period 2022-2030 [234].

Specifically, exploiting the hot re-formability of thermoplastics, three different EoL routes were analysed: combustion, recycling and reforming. These strategies were investigated for different matrices and fibres combinations. The analysis was performed using a methodology available in literature [235, 236] quantifying the primary energy demand, i.e., the Cumulative Energy Demand (CED), of the different CFRTPs from cradle-to-grave. In detail, the impacts of two reinforcing materials such as carbon fibres (CFs) and glass fibres (GFs) and two types of thermoplastic matrices such as polypropylene (PP) and polyether ether ketone (PEEK) were evaluated. The materials were combined to obtain four different composite configurations. Specifically, CFs and GFs were analysed because they are the more and the less valuable reinforcements, respectively. In addition, CFs are worth considering the high cost of the raw material, the technology involved in their development and the expected highest growth in the next few years [221]. These aspects deserve attention in a closed-loop economy perspective [237]. GFs, instead, allow manufacturing the most common composites that constitute more than 95% of production mainly for the transport industry (automobile, railway) and for the electrical construction [238]. Simultaneously, PEEK and PP were chosen as performing and poor matrices, respectively. In particular, PEEK exhibits a distinctive combination of mechanical and electrical properties at elevated temperatures allowing promising applications in different fields. Furthermore, these applications can further evolve by incorporating functional fillers and fibres [239]. On the other side, polyolefins, whose PP belongs to, are widely used for fabricating reinforced composites [240]. Finally, three fibre volume ratios were analysed.

The variables were selected considering the differences in their impact in terms of Embodied Energy (EE). The EE of raw materials refers to the energy required to extract, process and transport the raw materials used in the manufacturing of a product or system. It represents the energy, measured in MJ/kg, consumed from the initial extraction of the resources from the earth to their arrival at the manufacturing site [110]. Furthermore, a detailed inventory analysis was carried out, as, at present, the study of the energy impacts of the composite materials is still too limited and uncertain [241].

The objective of this study is, therefore, twofold. On the one hand, it aims to provide a comprehensive data record useful for composite partitioners, and on the other hand, more importantly, to present a CED analysis of the three highlighted different EoL routes. These two objectives can be considered interconnected, as the dataset obtained in the former was used to achieve the latter. Owing to that, section 2 provides an overview on the production and recycling processes of CFRTPs pointing out the ranges for each energy aliquot. To be more specific, the literature review was developed in order to provide the energy demand of each step of CFRTPs component life cycle. Section 3, instead, describes the definition of goal and scope, functional unit, boundary conditions and methodology used for the case study analysis, whose results and future developments were discussed in sections 4 and 5 according to the standard ISO 14040 [77].

6.2.1 Investigated manufacturing and EoL strategies

CFRTPs manufacturing involves different technologies and process routes. In the field of thermoplastic composites, the typical manufacturing processes could be autoclave, compression moulding, cold press moulding, automated tape laying, while in the case of thermosets there are spay-up, pressure bagging, microwave curing, vacuum-assisted resin transfer moulding, as stated by [153]. In this work, the autoclave manufacturing process was considered. The use of an autoclave is a common method in the manufacturing process of composite thermoplastics [242]. The autoclave process for composite thermoplastics offers advantages such as uniform compaction, improved consolidation and enhanced fibre impregnation [243]. The specific autoclave parameters and process conditions may vary depending on the composite material, part design, and manufacturing requirements [244]. Regarding the impact of autoclave manufacturing, looking at the quantification of the energy, lack of information was evidenced by several articles [153, 245, 246].

As regards the EoL of CFRTPs, landfill is still the most widely used disposal method worldwide [247]. Anyway, the EU's waste Directive introduced restrictions on landfilling of all waste suitable for recycling from 2030 [223]. These results are needed to develop more sustainable routes for a CE of CFRTPs, which can be disposed of, recycled or reformed, through different methods. Commonly, composite wastes are disposed via combustion, such as an incinerator, generating ash and creating, in any case, an environmental impact. This ash can only be landfilled as inert waste, which is detrimental to the CE progress. Another disadvantage is that when heat is converted into electricity, an efficiency of only 35% can be achieved. However, burning coal in the furnace is a much better option than burning CFRP [247].

Recycling of CFRTPs can be performed without separating the fibres from the matrix. Indeed, mechanical recycling processes are based on shredding composites resulting in a negative effect on mechanical properties of the fibres with the main part of CFRTPs' value being lost because of length reduction and a loss of fibre architecture [248]. In this case, the recycled fibres are filamentous and unorganised. This EoL route, often proposed owing to its low-cost technologies [249, 250], results in components characterised by reduced mechanical properties if a direct impregnation of these fibres is executed [220].

If the fibres are not broken during the recycling phases, the CFs can, instead, maintain their tensile strength, with only a few percentage points less than virgin CFs [251]. Several studies claim that the reduction in CFs mechanical properties depends on the type of carbon fibre and on the recycling process parameters [252, 253]. Furthermore, woven recycled CFs exhibit a similar tensile modulus in the principal directions than virgin woven CFs [196]. On the other hand, tensile strength and failure strain of recycled GFs decrease up to 70% in comparison with virgin GFs [254].

Chemical or thermal recycling processes allow the fibres to be separated by the matrix preserving the fibre length. Specifically, the chemical process, the so called solvolysis, allows the polymer matrix to be degraded by a solution of acids, bases, and solvents, whose composition must be fine-tuned to the matrix [208, 255]. After the process, the recycled fibres are cleaned to remove decomposed polymeric composites and solvent residues and reoriented. On the other side, the thermal process, the so-called pyrolysis, decomposes thermally the polymer removing the pyrolytic char on the carbon fibres by an oxidation process permitting the reinforcing materials to be recovered and reused [247, 256]. Several studies have shown that the decomposition process is performed at a temperature range from 350 °C to 700 °C [197–199]. Witik et al., 2013, claim that the pyrolysis process has emerged as more efficient and reliable than solvolysis in terms of energy and material recovery [200].

Recapitulating, before performing one of the recycling processes, above detailed, different preprocessing solutions have to be evaluated obtaining different levels of retaining of the initial fibres architecture and, consequently, of recovering fibre values [74, 220]. Anyway, even after the recycling step, several post-processing stages can be explored to improve the quality of the recycled fibres. For example, wet paper-making [257] or realignment techniques, such as HiPerDif process [258] or different spinning variants [185, 259–261] have been proposed.

Pre-processing, processing and post-processing stages, therefore, have to be considered together to judge the most promising recycling route of CFs or GFs-reinforced polymers. Currently, at least for the authors' knowledge, few studies have taken into account the whole stages [220]. In particular, He et al., 2020, following the LCA methodology, assessed five different recycling routes taking into account pre-processing, processing and post-processing stages proving that a less impactful solution in terms of energy demand is the route, where the woven fibre architecture is not shredded during the pre-processing stage. More in detail, the less demanding energy route was the one in which the retained architecture was obtained by pyrolysis, subsequently, impregnated with resin, without requiring a post-processing stage and directly reusing the woven in production of a new product. This recycling route, first proposed by Pimenta and Pinho was, therefore, considered in the research herein presented[196].

Finally, a perfect CE can be achieved, if the polymer matrix is thermoplastic, by reforming the product providing a new life cycle to it. In this context, owing to the thermoplastic matrix fusibility, CFs or GFs-reinforced thermoplastics (GF/CF-RTP) are considered reformable [250]. Kiss et al. 2020 in their study, revealed that the reverse forming, so-called reforming, is a viable route for CFRTPs. They showed that this method can be also applied to correcting any forming mistake or to reform the product at the EoL. Von Freeden et al., 2023, focused the attention on the reforming process and its effect on composite sheets. They stated that lifespan of CFRTPs could be extended up to 5 processing cycles compared to alternative materials [231].

6.2.2 Embodied & manufacturing Energy

The analysis of the available scientific literature has shown a great variability in EE values of the raw materials. In Table 6.1, the embodied energies of the reinforcements and the thermoplastic matrices, analysed in the proposed study, are summarised. The values marked with a star symbol (*) indicate that the level of energy form was not specified in the literature data. Therefore, data reliability could be threatened. Anyway, the risk in the data consistency was already taken into account referring to embodied energies of materials that have a brief scientific history and that are characterised by high variability as also stated by [110]. To mitigate this weakness, the study was performed considering the whole ranges of the detected values.

Table 6.1 Embodied energy of the investigated raw materials.

	Material	Embodied energy (MJ/kg)	Reference(s)
Polymer matrix	PP	72.00-112.00	[262]
		24.00	[263]
		66.00-80.00	[263]
		11.00-27.00	[153]
	PEEK	286.00-315.00	[263]
Reinforcement	CF	183.00-286.00 *	[252]
		272.00-300.00	[263]
		280.00 *	[252]
		1000.00	[200, 264]
		704.00	[200]
		1468.00 *	[265]
		286.00-478.00	[153]
		190.00-870.00 *	[266]

		521.00-1563.00 *	[252]
		855.00	[200]
	GF	49.00-54.00	[153, 263]
		13.00-32.00 *	[252]
		7.00-16.00 *	[266]

The fibres need to be produced by specific sub-processes to be combined in yarns, which can be considered as the base unit for the woven construction. In Table 6.2, these sub-processes are detailed for both CFs and GFs yarns summarising the energy consumption for each phase. Specifically, CFs are obtained by the polymerization of Polyacrylonitrile (PAN) while GFs are produced starting by a molten SiO_2 slurry. In Fig. 6.1(a), these different sub-processes are illustrated. According to that, it has to be clarified that the energy consumption is a value that is obtained by converting the wasted energy required to execute a specific process, and quantified by the absorbed electric energy, measured in MJ, into MJ oil equivalent, which depends on the employed country's energy mix. For the performed analysis, the energy consumption refers to the European average energy mix [110].

Table 6.2 Sub-processes used to weave the yarns.

Fibres	Sub-processes	Energy consumption (MJ/kg)	Reference(s)
CF	1.PAN Polymerising	0.00-156.00	[266, 267]
	2.PAN spinning	2.60	
	3.Oxidation	142.00-427.00	
	4.Finishing	35.00-75.00	

GF	1.Molten slurry of SiO_2	1.30-2.50	
	2.Melting	3.40-9.10	
	3.Yarn Spinning	2.60	
	4.Finishing	0.90-1.90	

Once the yarns are obtained, these have to be weaved to achieve the fabrics. Therefore, the yarns are wrapped and oriented by specific crimp angles to create the desired woven fabric. This can be performed using techniques such as weaving, knitting, or braiding methods. The energy used in this manufacturing phase was estimated by [267]. Specifically, this energy consumption was quantified at 2.90 MJ/kg. The woven fabric, subsequently, has to be impregnated with the thermoplastic resin to obtain the prepregs by applying heat and pressure to soften the matrix, allowing it to impregnate and bond with the reinforcement. This can be executed using techniques like hot pressing, hot melt infusion, or thermoforming (Fig. 6.1(b)). For the impregnation, the energy required for the PP and the PEEK matrices was quantified in the range of 20.80 – 23.00 MJ/kg and 25.30 – 27.90 MJ/kg, respectively [267]. The prepregs must be finally manufactured by the autoclave moulding process. Also, for this working step, the energy consumption values vary depending on the characteristics of the polymer matrix and its melting temperature. Furthermore, the production volume must be considered in the assessment of energy consumption [235]. Considering the investigated thermoplastics, the process energy values were found in literature and listed in Table 6.3.

Table 6.3 Energy consumption required for the autoclave moulding process.

Thermoplastic matrix	Melting temperature (°C)	Energy consumption (MJ/kg)	Reference(s)
PP	160	141.00	[265]
		111.36 -141.00	[268]

PEEK	340	163.68	[265]

Finally, the cutting phase necessary to finish the demoulded parts obtained after autoclaving requires energy ranging from 0.10 to 1.40 MJ/kg as detected in the literature [245] (Fig.6.1(c)).

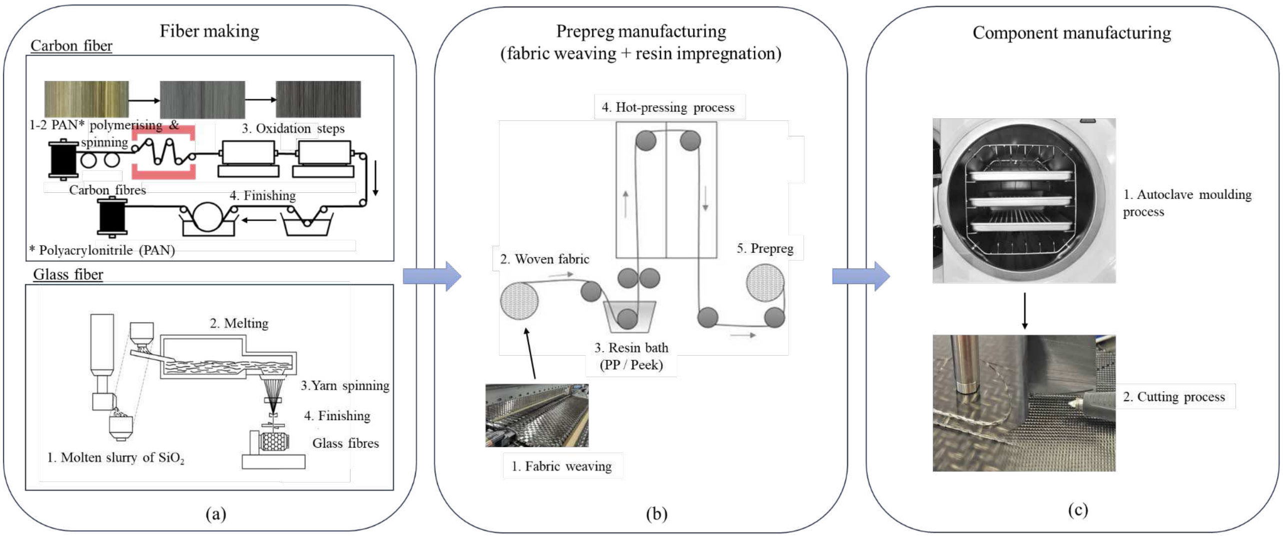


Figure 6.2 The whole production phases of the target component made of CFRTPs: (a) Yarn, (b) prepreg and (c) component manufacturing.

6.2.3 EoL considerations

As already mentioned, the increasing use of composite materials in several sectors results in problems of waste management [269, 270]. When a material is recycled, it often requires less energy than extracting and processing the raw material from scratch. For this reason, different recycling methods have been proposed [160, 198, 219, 252, 253, 271–273]. In this work, combustion, recycling (thermal/chemical) and reforming were analysed. Specifically, about the recycling process, (Table 4), the solvolysis (chemical recycling) consists in the removal of the thermoplastic matrix by dissolution in a proper solvent. The advantages of chemical recycling over thermal recycling, is that lower temperatures are generally required to degrade the polymeric matrices [252] reducing possible damages on the recovered fibres allowing recovery of both the polymer matrix and the full-length fibres [274]. Anyway, a limited number of studies is still available in the scientific literature on the chemical recycling of CFRTPs [249], which can be performed by using a wide spectrum of solvents and catalysts that significantly affect the environmental impact of the EoL phase. For this variability and data solidity, the solvolysis was not further explored leaving its analysis to a following research step.

In detail, the process energy of three different EoL phases was outlined in Table 6.4. Combustion, where both matrix and fibres are wasted, recycling by pyrolysis conserving the full architecture of the woven fabric, and reforming, where the whole materials are saved for a new manufacturing phase, were considered in the executed study. The impact of solvolysis was reported just for further data information deserving, as above highlighted, a specific in-depth analysis looking not just at this EoL's energy consumption, but also at the impacts of employed solvents and catalysts.

Table 6.4 Energy consumption of the investigated EoL routes.

EoL phase	Method	Material	Energy consumption (MJ/kg)	Reference(s)
Combustion	Incinerator	PP/PEEK	30.50-32.00	[160]
			32.00-33.60	[263]
Recycling	Pyrolysis	PP	2.80-30.00	[160]
		PEEK	23.98-63.00	[265]
	Solvolysis	PP	15.00-64.00	[160]
		PEEK	61.00-93.00	
Reforming	Thermo-forming	PP	3.23	[275]
		PEEK	3.82	
		PP	28.68	
		PEEK	45.29	

The values used in Table 4 were extracted from literature and Cambridge Engineering Selector Edupack database (CES) [263]. In addition, a cleaning step and a reorientation phase are required in the recycling phase. For what concerns the cleaning step, the energy consumption is 8.73 MJ/kg [276]. The cleaning phase is necessary to purify the reinforcement (GF/CF) to make it ready for a new life cycle. In the reforming route, instead, the reforming process consists of a thermal forming phase that consists of heating the component and a consolidation phase known as calendaring. Considering the polymer matrix of PP (melting temperature 160°C) and PEEK (melting temperature 340°C), a heat-assisted forming tool step is required during thermal re-forming. The energy consumption for these reforming phases is 6.882 MJ/kg for PP and 15.122 MJ/kg for PEEK [275]. Finally, a heat treatment is required during the calendering process. The energy consumption for this process step is 3.354 MJ/kg and 6.215 MJ/kg if the composite is made, respectively of PP or PEEK [275]. The different EoL routes are described in Fig. 6.2.

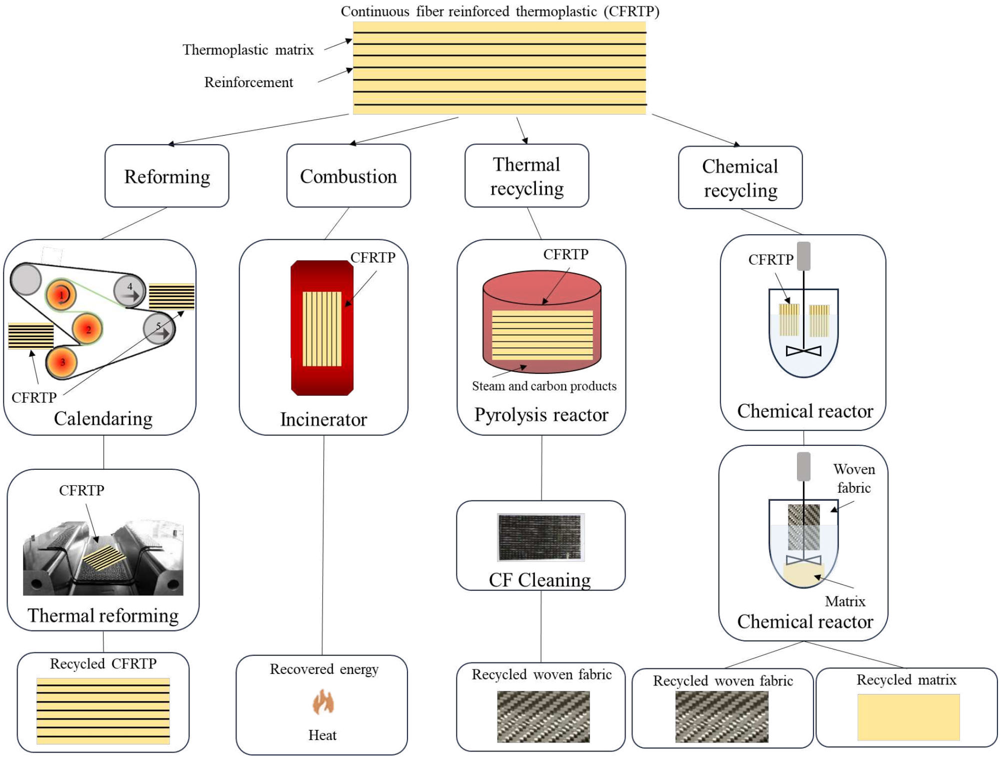


Figure 6.3 Main steps to move from the initial composite/scrap to the final recycled product for reforming, combustion, and thermal and chemical recycling.

6.3 Material and methods

Four different material combinations were analysed using GFs and CFs reinforcement fabrics, 2/2 twill balanced weave [277], and PP and PEEK polymeric matrices. A low performing polymer matrix (PP) and one with high-performance (PEEK) were taken into account. The same consideration was made for the fibres' selection, being GF and CF known as a low and a high-performance reinforcement, respectively. Furthermore, different percentages of reinforcement were analysed. Specifically, the investigated Fibre Volume Percentages (FVF) are: 45% (FVF 1), 23% (FVF 2) and 11% (FVF 3). These reinforcement percentages were considered because 45% is close to the upper limit of reinforcement that can be achieved in a composite while 11% is close to the lower limit (below which reinforcement fails to improve the performance of the composite [278]). Finally, 23%, besides being a typical value for reinforcements within composites, was chosen as this is a volume percentage that is almost double of 11% and half of 45%. The CED impact of the various composite sheets was evaluated considering three different EoL routes. The research was performed without considering the changing of performance between virgin and recycled or remanufactured materials. According to Von Freeden et al., 2023, longer and multiple use of the composite material in high quality condition was proved[231]. However, the demonstration was performed at laboratory level and needs further studies to be evaluated considering additional phenomena [279]. Hence, a CED analysis of the materials and processes was carried out, according to the type of reinforcement, matrix, and their percentage in the composite materials. The product system is a component made of CFRTPs, the so-called target component, which is characterised by a volume of 78.4 mm^3. Specifically, composite sheet blanks with dimensions of 280mmx280mmx1mm were considered. The densities of the matrices and of the reinforcements are summarised in Table 6.5.

Table 6.5 Density of the investigated materials.

	Polymer matrix		**Reinforcement**	
	PP	PEEK	CF	GF
Material density (kg/m^3)	912.50	1320.00	1900.00	1857.00
Reference(s)	[280]	[281]	[282]	[283]

The target components' configurations analysed, namely PP-CF, PEEK-CF, PP-GF, PEEK-GF are summarised in Table 6.6.

Table 6.6 Component features expressed in kg at the three investigated FVF.

PP-CF	**FVF 1**	**FVF 2**	**FVF 3**
Fibre mass	0.067	0.034	0.017
Matrix mass	0.039	0.055	0.063
Component weight	0.106	0.089	0.080
PEEK-CF			
Fibre mass	0.067	0.034	0.017
Matrix mass	0.057	0.080	0.092
Component weight	0.124	0.114	0.108
PP-GF			
Fibre mass	0.065	0.032	0.016
Matrix mass	0.039	0.055	0.063
Component weight	0.104	0.088	0.079
PEEK-GF			
Fibre mass	0.065	0.032	0.016
Matrix mass	0.057	0.080	0.092
Component weight	0.122	0.113	0.108

6.3.1 Goal and Scope

The aim of the study is to characterise the environmental impact, from a CED point of view, of one target component manufactured by each EoL route. The results can be used to compare the CED of EoL routes analysed in the study. The aim is to analyse these impacts for each route to provide guidance for the selection of the most energetically friendly EoL strategy with varying production scenarios. The functional unit chosen for this study is the EoL processing of one unit of the target component (composite sheet blank with dimension 280mmx280mmx1mm). Indeed, the general idea is to compare the EoL processing, looking at the primary energy used from cradle to grave for each of the highlighted EoL scenarios. The benchmark EoL scenario was the so-called conventional open loop process allowing a CED assessment of a component that is processed by combustion. The second scenario is a partially closed loop because the woven fabric, thermally recycled, once cleaned and reoriented, needs, subsequently, to be impregnated with the virgin thermoplastic resin to obtain the prepregs. The third scenario envisages a whole closed loop involving the recovery of the entire component, with the possibility of changing its original shape for a new use. The three detailed manufacturing scenarios are summarised in Fig. 6.3.

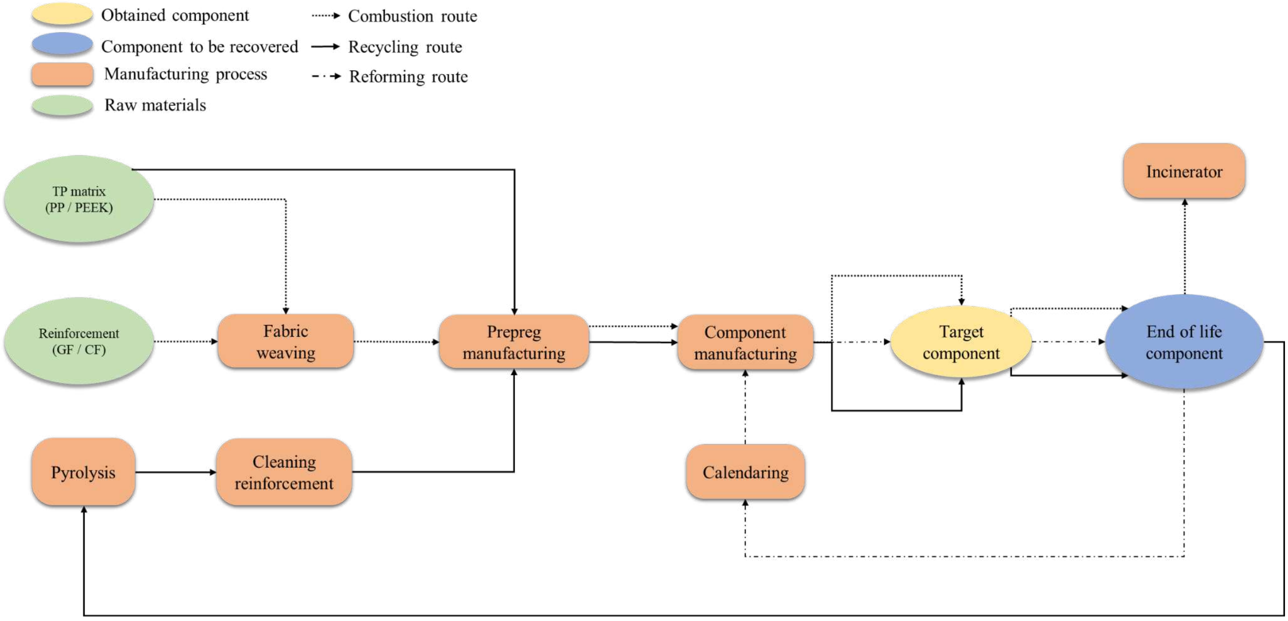


Figure 6.4 Detail of the analysed EoL routes.

In the study, a recycled content approach was applied. This approach, also called the 100:0 or the recycled content, considers that the environmental impacts of the production phase for a product are attributed to the first use of this product and follows the “polluter pays” principle [284]. The second use of the product only bears the environmental impact of collection and the preparation of the product for its subsequent use. In some cases, the collection is also attributed to the first use of the product. However, the materials used for the second time bear no environmental burden from the primary production process [109, 285].

6.3.2 System boundary and main assumptions

Concerning the metric for the comparison of the environmental impact, CED (MJ) was used. Indeed, since the first LCA studies, CED has been one of the considered key indicators [285]. The adopted system boundary includes raw material extraction, product manufacture and EOL, as schematised in Fig. 6.4. The analysis does not include the use phase's contributions. Indeed, the use phase was neglected, being common to the three processes examined. Furthermore, the impact of transport between process units was not taken into account, as it is assumed to be the same between process units and between the analysed scenarios. In the following paragraph, some details about assumptions made to deal with electrical energy demand and material scraps, if present, were specified. Regarding the process's electric energy demand, it was converted into primary energy source consumption by considering an average efficiency of 36% to account for the energy generation and the transmission losses [110].

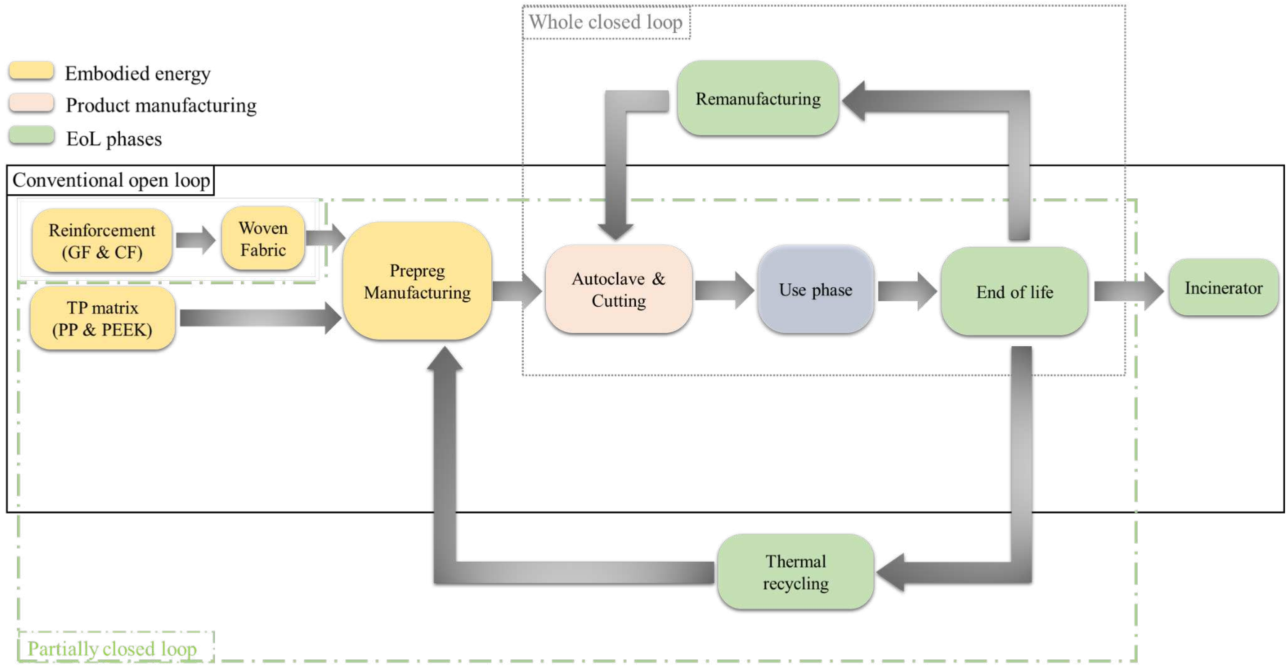


Figure 6.5 The adopted system boundaries.

As far as material waste is concerned, all the material creates an environmental impact for the conventional open loop process because the whole component at the end of its life is processed via incinerator. Whereas for the partially closed loop approach, all the fibres were considered without any degradation due to the thermal recycling phase while the matrices become waste and a new quantity of thermoplastic, PP or PEEK, must be added in the process. Finally, for the whole closed loop, on the other hand, there was no material's environmental impact, as all material is reused and reformed. Furthermore, in this case the mechanical performances of the material remain unchanged [231].

6.3.3 Life cycle inventory

LCI data were generated using different approaches. Data from scientific literature and CES Edupack database [263] were used. A great variability in the parameters of EE was found in the scientific data, as previously shown in Table 6.1 - 6.2. Therefore, the analysis was conducted considering the lower, the average and the higher values as described in Table 6.7, where the various energy contributions were organised. In detail, H_{mc} gathers the EE values necessary to obtain both matrices and fibres and the sub-processes energy required to combine fibres in yarns. H_{ppc} collects the energy for weaving the yarns, achieving the fabrics and the energy for their impregnation to get the prepregs. H_{pc} lists the energy required to form the prepregs, i.e., the manufacturing energy, including the cutting phase. According to this aliquot, the autoclave manufacturing process assumes two energy values depending on the different process temperatures of PP and PEEK (Table 3). Indeed, the process temperature is closely related to the process energy [265, 268]. Finally, H_{rc} reports the EoL energy taking into account all the routes analysed. As already written, the data related to solvolysis were reported to provide a complete inventory data, even if pyrolysis was the only considered in the study, being the most energy efficient recycling process from a CED's point of view [286] and considering the lack of data for chemical recycling of CFRTPs. Furthermore, the processes of reforming and reconsolidation were, instead, obtained by the energy absorption of the employed machines considering the composite's reprocessing temperature [231].

Table 6.7 Life cycle inventory data.

	Processes	Energy consumption (MJ/kg)		
		Low	Ave	High
H_{mc}	CF embodied energy	608.78	722.39	836.00
	GF embodied energy	23.00	28.50	34.00

	PP embodied energy	43.25	52.00	60.75
	PEEK embodied energy	283.01	290.26	297.51
	CF manufacturing	47.75	132.63	217.50
	GF manufacturing	1.75	2.90	4.05
H_{ppc}	PP manufacturing	20.80	21.90	23.00
	PEEK manufacturing	25.30	26.60	27.90
	Fabric manufacturing	2.54	2.60	2.67
H_{pc}	Autoclave (PP)	55.68	90.93	126.18
	Autoclave (PEEK)	65.60	114.64	163.68
	Cutting phase	0.05	1.76	3.47
H_{rc}	Incinerator	30.50	31.25	32.00
	Pyrolysis (PP)	3.00	16.50	30.00
	Pyrolysis (PEEK)	23.98	43.50	63.00
	Cleaning	0.00	1.76	8.73
	Re-forming (PP)	10.11	10.11	10.11
	Re-consolidation (PP)	32.03	32.03	32.03
	Re-forming (PEEK)	18.94	18.94	18.94
	Re-consolidation (PEEK)	51.51	51.51	51.51

6.3.4 Life Cycle Energy Demand Quantification

The methodology proposed by Suzuki and Takahashi [235] to quantify the CED was applied to perform a comparative analysis of the case study's environmental impact, described in Section 6.3. The life cycle primary energy demand quantification analysis was performed using Eqs. 6.1-6.5. The CED analysis of the target component assesses the environmental impact during its life cycle. The method considers the EE of the composite material (H_{mc}) based on the weight of the polymer matrix fraction and of the reinforcement as summarised in Eq.1. The EE of the component is calculated as the mass fraction of the matrix (mf_m) and of the fibres (mf_f) multiplied by the EE of the matrix (H_{mm}) and of the fibres (H_{mf}), respectively. The contributions of the processes used in pre-manufacturing and manufacturing are included through the energy consumption parameters (H_{pp} and H_p) (Eqs.6.2-6.3). The overall energy of the formed composite product is quantified by H_c (Eq.6.4).

$$H_{mc} = mf_m \cdot H_{mm} + mf_f \cdot H_{mf} \tag{6.1}$$

$$H_{ppc} = mf_m \cdot H_{pp1} + m_c \cdot H_{pp2} \tag{6.2}$$

$$H_{pc} = m_c \cdot (H_{p1} + H_{p2} + \ldots + H_{pn}) \tag{6.3}$$

$$H_c = H_{mc} + H_{ppc} + H_{pc} \tag{6.4}$$

Eq.4 can be used to quantify the CED of the target component for the combustion route (conventional open loop) adding just the contribution of H_{rc}. Being the developed analysis based on the recycling content approach, Eq.6.5 was instead used to calculate the component's CED in the recycling and reforming routes (respectively, partially and whole closed loops):

$$H_{Recycling\ content\ approach} = R \cdot \left[(H_c - (H_{rc} \cdot mf_m + H_{rc} \cdot mf_f)\right] \tag{6.5}$$

where, R is the fraction of the recycled material. R value is equal to 100% for the reforming route while, in the recycling strategy just the fibres are completely recycled.

6.4 Results and discussions

The CED values for the four material configurations, listed as: PP-CF, PEEK-CF, PP-GF, PEEK-GF, for each FVF and EoL strategy are reported in Fig. 6.5.

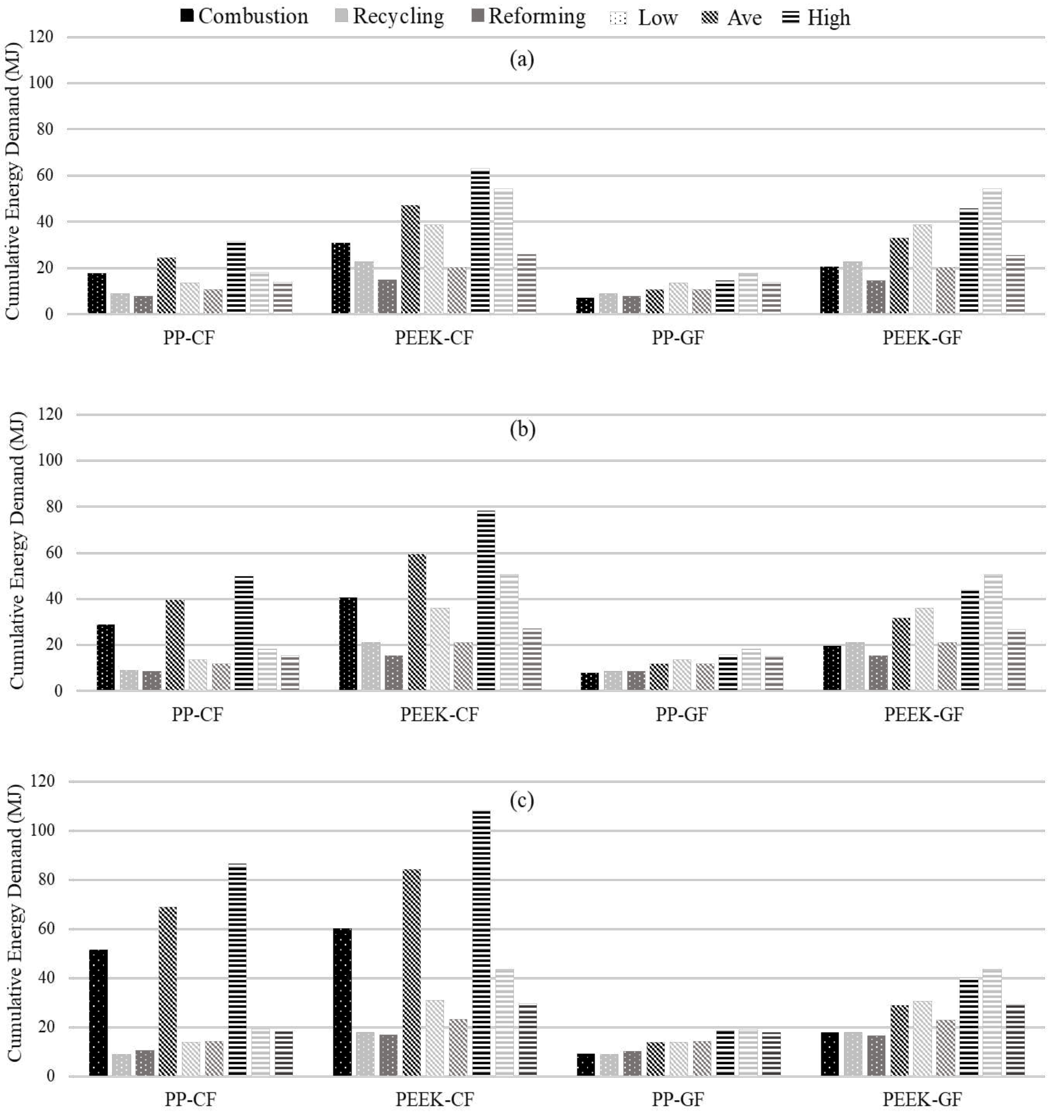


Figure 6.6 CED required for each investigated FRPs and EoL routes at changing of (a) 11%, (b) 23%, (c) 45% FVF percentage.

The impact of the different EoL strategies on CED depending on the type of composite material to be processed can be deduced from Fig. 6.5. The analysis of Fig. 6.5 resulted in different evidence that could be useful to consider for CED minimization of a specific CFRTPs component. In detail, the PP-CF scenario is with a low performance polymer matrix and a high-performance reinforcement fibre. For the PP-CF scenario, the recycling and reforming EoL strategies are always comparable. Both processes are more advantageous than the combustion process. This advantage is even more evident as the percentage of reinforcement increases. For example, when considering the composite with 45% of reinforcement, the average values of the three EoL processes are 69.13MJ, 13.99MJ and 14.34MJ, respectively. The PEEK-CF configuration is the one with the composite made of both high-performance polymeric matrix and fibre. The most competitive product's EoL is reforming, which has an energy impact that depends slightly on the fibre volume fraction percentage. The recycling process, instead, starts to become competitive just for the configuration with a high fibre percentage. Indeed, being the pyrolysis a recycling route that recovers the fibres, if the amount of reinforcement in the composite increases, the impact of the recycling process decreases. Conversely, if the matrix increases its prevalence, the pyrolysis wastes a higher quantity of high-performance matrix resulting in an increment of the energy impact close to the one ascribed to the combustion. Looking at the average values of the 3 processes, the values are respectively of 84.34, 30.89, 23.16 MJ for combustion, recycling, and reforming for a fibre percentage of 45% while if this percentage passes to 11% the values change to 47.05, 38.56, 20.29 MJ, respectively. Looking at PP-GF, the composite material is made of both low-performance polymeric matrix and fibre. The EoL routes, i.e., combustion, recycling, and reforming processes, are comparable. The trend remains unchanged as the percentage of composite's reinforcement changes. Therefore, in this scenario, the combustion, being the simplest to be performed, is to be preferred, if CED is the index to be considered. Looking at the average values of the 3 processes, the values are respectively of 13.73, 13.83, 14.14 MJ for combustion, recycling, and reforming for a fibre percentage of 45% while if this percentage decreases to 11% the values remain comparable respectively to 10.83, 13.42, 10.77 MJ. The last consideration has to be, instead, reassessed, if specific midpoint or endpoint LCA indicators on use of raw materials are taken into account (Mio & Fermeglia, 2022). Considering the PEEK-GF, the composite material made from high-performance polymer matrix and low-performance fibre shows that the reforming process is the most promising process, especially if the configuration with low fibre volume percentage is taken into account. Furthermore, for this scenario, combustion is always preferred when compared to the recycling route. Looking at the average values of the 3 processes, the values are respectively of 28.90, 30.70, 22.88 MJ for combustion, recycling, and reforming for a fibre percentage of 45% while if this percentage decreases to 11% the values change respectively to 33.19, 38.52, 20.22 MJ.

Furthermore, the energy impacts of the different steps in the whole from-cradle-to-grave product's life were shown in Fig. 6.6, where the CED average values, for each considered FVF percentage, were reported. The weights of the recovered energies owing to the chosen EoL strategy are relevant, affecting the performances of the selected route, if products made by CFs are processed. Indeed, recovering CFs by recycling or reforming allows to reduce the energy impact of the products, markedly. For these configurations, reforming is, gradually, more promising than recycling at FVF's reduction if a performing polymer, i.e. PEEK, is processed. On the other side, if less valuable fibres are treated, i.e., GFs, the EoL routes, lose their weight on CED of the composite products, especially if GFs are combined to poor matrices.

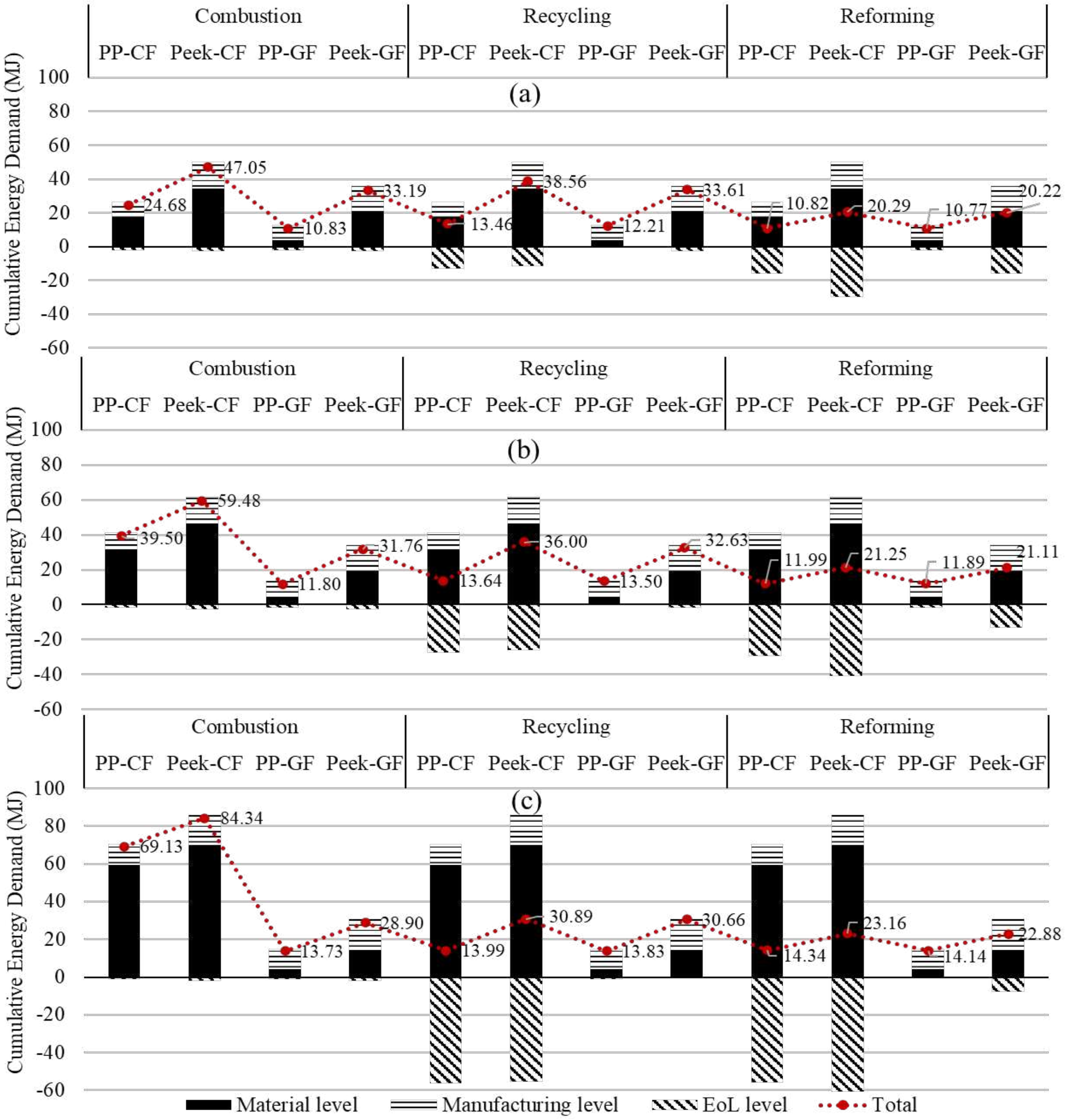


Figure 6.7 Energy impacts of the different steps in the whole from-cradle-to-grave product's life for (a) 11%, (b) 23%, (c) 45% of the analysed FVF percentage.

6.5 Conclusions

A CED analysis was carried out by evaluating a target component made by the combination of two types of fibres, GF and CF, and matrices, PP and PEEK and considering also three FVF (11%, 23% and 45%). A life cycle energy analysis was performed evaluating three EoL routes. Specifically, applying the recycling content method approach, the CED of a specific product's life cycle was evaluated by using the data collected by a literature review. From this point of view, the possible EoL strategies were identified modelling, theoretically, the processing steps and gathering the information required for a proper CED quantification for each of them. The achieved LCI data are characterised by a huge dispersion in terms of embodied energies and energy consumption for both materials and manufacturing processes. In this respect, low, average and high values were reported, and used in the analysis to evaluate the products' CED with different material combinations.

The obtained results highlighted how, in a perspective of reducing the energy impact, the reforming EoL strategy is always a valuable solution to be taken into account. The choice can be more or less convenient depending on the type of composite processed looking at the utilised fibres and matrices and at the percentage of their employment in the composite construction. This research aimed at providing guidance for the selection of the most suitable EoL strategies, taking into account the CFRTPs material properties, as a decision support tool that, practically, can be employed in choosing the most energetically convenient path. The following recommendations can be extracted:

- if the composite is made of a low-value matrix and a high-value fibre, both reforming and recycling EoL routes can be used to minimise the energy impact;
- if the composite is made of a high value of both matrix and fibre, it is definitely worthwhile to use the reforming process, especially for low FVF of the FRPs;
- if the composite is made of a low value of both matrix and fibre, the energy impact of the three investigated EoL routes is comparable. Therefore, the choice of combustion, being the simplest solution, via incineration, should be preferable if CED is the only indicators to be considered;
- if the composite is made of a high-value matrix and a low-value fibre, reforming is more energetically convenient even if its advantages are more evident for low FVF;
- recycling is not always more advisable than combustion. Actually, if the composite is made by low-value fibres, combustion is to be preferred.
- the FVF can change the advantages of one EoL route with respect to another one. Specifically, particularly if high-value fibres are processed, recycling and reforming processes become increasingly comparable if the percentage of reinforcement increases and, at the same time, the combustion process becomes increasingly impactful.

7. Discussion

Over the years, the development and evolution of LCA has revealed the usefulness of the methodology for assessing the sustainability of production processes with the aim of measuring and thus contributing to the reduction of the environmental impact of a given system.

However, from the literature, it has not always been possible to analyse and compare the different processes, environmental parameters and end-of-life scenarios of the product and the respective material. In response to this shortcoming, new approaches to LCA have been and are currently being developed that are able to provide the knowledge of the environmental impact that a specific process may have under varying construction constraints. Following these premises, it will be possible to anticipate the future impact and define strategies and intervention points in order to optimise the development of a product and correct the trajectory in time.

With regard to the objectives of this work, Objective 1 was defined as a literature review of the main production processes analysed in terms of sustainability and to identify knowledge gaps and provide possible solutions. Despite the various sustainability reviews examined, there is a lack of comparative studies in the literature regarding the study of different end-of-life scenarios and strategies for the main production processes. On the other hand, a lack of robustness of life cycle inventory data was noted.

Therefore, considering Objective 2, a framework was applied to evaluate the different end-of-life scenarios; this framework was coupled with the LCA methodology in order to quantify the entire production cycle as the end-of-life scenario and the type of material used vary. This framework makes it possible to make assessments of the energy quantified when obtaining the raw material that enters the production cycle under study. On the other hand, it is possible to quantify the end-of-life phase in the different scenarios in order to obtain a comparative evaluation of the processes, thus estimating the best scenario from an environmental point of view. Thus, by applying the proposed framework coupled with the LCA methodology, it is possible to evaluate a conventional technology with an innovative one. At the same time, it is possible to integrate the recycled content of the first-use material into the analysed system. In this way, assessments can be made based on the impact the material has on the entire life cycle of a component.

Therefore, after defining the methodology for the comparative assessment of the analysed processes, the latter was applied to four case studies. The case studies cover different fields of application from conventional production processes involving multi-material products to the production processes of unconventional materials applied in the automotive industry.

Objective 3 focuses on the application of the proposed methodology for the evaluation of the selected case study, which involves the comparative analysis of three production processes such as the machining, additive and casting process of a lightweight aluminium component with and without topological optimisation. The latter is constrained by the construction constraints and the material chosen. The component selected for the environmental sustainability benchmarking is a bracket used in the automotive industry. Considering the parameter representing the total energy required by the process, the analysis revealed that topological optimisation significantly reduces the CED, especially for AM (-65%) and SM (-55%), while CP benefits less (-24%) considering the material production phase; at the same time, AM has a great advantage due to its ability to reduce volume, from 23.72 MJ to 8.14 MJ.

Considering the product manufacturing phase, as far as the SM is concerned, the CED increases with the optimised shape (13.35 MJ vs. 11.08 MJ) due to the removal of more material. While AM reduces the energy required (from 24.19 MJ to 8.29 MJ), the impact of CP remains marginal (0.46 MJ vs. 0.37 MJ).

In the use phase, the energy required is directly related to mass. The AM obtains the greatest benefit (-17.32 MJ), while the SM and CP require 30.31 MJ and 39.30 MJ, respectively.

Considering the end-of-life phase, however, the recovered energy is proportional to the mass: -13.85 MJ (initial SM), -8.33 MJ (optimised SM), -4.76 MJ (optimised AM), -11.89 MJ (CP).

Concerning the whole Life Cycle (from Cradle-to-Grave), the optimisation leads to an overall reduction of the CED: AM: -65%, SM: -41%, CP: -25%. On the other hand, CP is not sustainable for limited production runs, given the impact of moulds.

In detail, AM is the most efficient and sustainable process due to its ability to optimise shape and volume, considering geometrically complex shapes.

Objective 4, on the other hand, provides a further evaluation framework to the LCA analysis and also analyses specific indicators as the energy mix studied changes, comparing the two techniques that proved to be comparable in the first analysis phase. It then extends the considerations to multi-material products and processes to include non-conventional materials such as thermoplastic matrix composites in the sustainability analysis.

Specifically, two scenarios for the end-of-life (EoL) phase of the subtractive process (SM) were investigated using the framework applied to LCA analysis. WCHIP (discarded chips) in which processing chips are not recovered; RCHIP (recycled chips) in which chips are properly recycled.

A comparison between additive manufacturing (AM) and subtractive manufacturing (SM), considering the CED throughout the entire product life cycle (from cradle to grave), shows that the SM process is less impactful up to a 90 per cent reduction of the initial block mass. At this level of reduction, the two processes become broadly comparable. This result is due to the high incidence of energy required for production in the case of AM, which outweighs the other contributions. These conclusions are valid both in the case of chip recycling (RCHIP) and by applying the substitution method for the evaluation of EoL. In the case of WCHIP, however, the energy required to extract the material (not compensated by recycling) has a greater impact on the sustainability of the MS, leading to a CED break-even point of between 40% and 80% reduction of the initial block material.

The results are valid regardless of the energy mix of the country of production, but the total environmental impact (MJoe per piece) varies by production site: The Middle East turns out to be the most impactful for AM and SM. For AM, the required CED in the Middle East is 1522.97, 913.78, 304.59 and 152.30 MJoe for volumes of 1.75, 1.05, 0.35 and 0.18 kg respectively. For SM (RCHIP), the CED is 622.20, 416.81, 211.14 and 159.87 MJoe for material reductions of 0%, 40%, 80% and 90%.

Norway and France show similar behaviour through the use of hydropower and nuclear energy respectively, with substantial advantages over oil (Middle East). The impact of the World Average is generally intermediate, but closer to the Middle East than to Norway or France, with more marked differences for AM and MS with longer processing times.

On the other hand, in the case of no chip recovery (WCHIP), the energy required for material extraction becomes significant, with the CED increasing as the percentage of block reduction increases. In the Middle East, the CED values for SM are 622.14, 723.01, 823.88 and 848.91

MJoe for material reductions of 0%, 40%, 80% and 90% respectively. This progressive growth is due to the lack of material recovery, which weighs more than the reduction in part weight or fuel savings in the use phase.

The Global Warming and Climate Change categories confirm the advantages of hydropower and nuclear energy. For other impact categories (e.g. radiation, human health), nuclear power loses competitiveness compared to other energy sources.

The data reinforce the need for efficient materials management and the importance of choosing a sustainable energy mix to minimise the overall environmental impact.

On the other hand, in order to extend the analysis to products and processes that also require the use of non-conventional processes, a multi-material case study used in the automotive field was investigated. In fact, with a view to a lightening that guarantees both high mechanical performance and high durability of the component, a comparative analysis of several types of gear wheels was carried out. The analysis showed that the evaluation of the CED (cumulative energy required) for the three types of gears analysed (full, lightweight and hybrid) showed distinct results for the two recycling scenarios analysed:

“Most common” approach: metal and composite waste is mainly disposed of in landfills or incinerated to recover energy. Full gear has the lowest production impact, but the higher weight generates the highest energy consumption in the use phase. The lightweight gear reduces the overall CED by 41.81% compared to the hybrid. The hybrid gear, while having a higher CED, is comparable to the full gear (+12.58%).

“More sustainable” approach: metal scrap is remelted and composite (hybrid) laminates recycled through pyrolysis. Energy recovery improves significantly, with the hybrid gear having the highest recovery in the EoL phase (259.01 MJ), saving 28.82% CED compared to full. Lightweight and hybrid are energetically comparable, with only a 7.5 per cent difference.

The sustainable approach reduces the overall impact. The lightweight gear is the most efficient in the total life cycle, while the hybrid excels in the recycling phase due to its high energy recovery.

Finally, the last case study analysed involves the analysis of a composite component with different end-of-life strategies. The work adds clarity to the composite material processes and provides guidance on design choices based on the required product performance specifications. The analysis of the impact of different end-of-life (EoL) strategies on the CED (cumulative energy required), depending on the type of composite material processed, provides useful indications for minimising the energy impact of components made of CFRTP (fibre-reinforced thermoplastic composites). Below are the scenarios analysed.

As for PP-CF, i.e. low performance polymer matrix, high performance reinforcement fibres):

Recycling and reforming strategies are always comparable and more advantageous than combustion, especially with increasing percentage of reinforcement fibres. For example, with 45% reinforcement, the average CED values are 69.13 MJ (combustion), 13.99 MJ (recycling) and 14.34 MJ (reforming), respectively.

Considering PEEK-CF (polymer matrix and fibres both high performance): reforming is the most advantageous option, with the energy impact varying little with fibre percentage. Recycling becomes competitive only with a high percentage of fibres, due to their recovery by pyrolysis. If the matrix prevails, the energy impact of recycling approaches that of combustion. Considering 45% reinforcement, the average CED values are 84.34 MJ (combustion), 30.89 MJ (recycling) and 23.16 MJ (reforming). With 11% fibre, the values change to 47.05 MJ, 38.56 MJ and 20.29 MJ respectively.

On the other hand, PP-GF (low-performance matrix and fibres): the three strategies (combustion, recycling, reforming) have comparable energy impacts, regardless of the percentage of reinforcement. Combustion, being the simplest process, is preferable if CED is the only indicator considered. Indeed, investigating 45% reinforcement, the average values are 13.73 MJ (combustion), 13.83 MJ (recycling) and 14.14 MJ (reforming). While considering 11%, the values are similar: 10.83 MJ, 13.42 MJ and 10.77 MJ.

Considering the PEEK-GF scenario (high performance matrix, low performance fibres): reforming is the most promising strategy, especially with low fibre percentages. Burning is always preferable to recycling. Considering 45% reinforcement, the average values are 28.90 MJ (combustion), 30.70 MJ (recycling) and 22.88 MJ (reforming). With 11%, the values become 33.19 MJ, 38.52 MJ and 20.22 MJ.

Generally, recovery by recycling or reforming significantly reduces the energy impact. Reforming is progressively more advantageous with a high-performance matrix (PEEK) and reduced fibre content. The impact of EoL strategies on CED decreases, especially if glass fibres are combined with low-value matrices. In this case, combustion remains a preferable option for simplicity and efficiency.

8. Conclusions

As part of the doctoral project, this thesis work addressed the challenges and knowledge gaps that emerged from the literature analysis and explored the possibility of evaluating and comparing the different processes in order to provide guides for LCA practitioners to anticipate decision-making choices with a view to optimising future environmental impacts.

Starting from these premises, the thesis began with an analysis of the literature, described in chapter 1, which made it possible to highlight the critical points in the existing literature, laying the foundations for a research that set out to fill the knowledge gaps regarding a lack of robustness in the inventory data present, an analysis of the end-of-life scenarios that in chapter 2, through a specific framework, were coupled with the analysis of sustainability in order to carry out extensive evaluations capable of comparing different scenarios and suggest sustainable practices to reduce the environmental impact of the processes investigated.

To this end, the LCA methodology applied to topological optimisation processes of the main manufacturing processes, such as machining, additive manufacturing and casting, was studied in Chapter 3. Specifically, the application of topological optimisation to additive manufacturing highlights the significant advantages of this process over machining in terms of sustainability. These advantages derive primarily from the ability of additive manufacturing to produce more complex optimised geometries, which allow for substantial component lightening and, consequently, environmental benefits during the use phase.

A further strength of optimised shapes for additive manufacturing is the reduction in process time, made possible by the simplification of the tool path, resulting in lower energy consumption in the production phase. In contrast, in machining by chip removal, more material must be removed from the initial semi-finished product to obtain the desired shape, resulting in a greater environmental impact in the production phase.

Shifting to the casting process, topological optimisation offers lower environmental benefits, mainly influencing the production of the material and the utilisation phase of the life cycle. The analysis conducted showed that, compared to additive manufacturing, the casting process applied to optimised shapes is less sustainable, regardless of the number of parts produced. However, as batch sizes increase, the casting process becomes increasingly competitive, especially for less complex shapes. This makes casting a preferred choice in production contexts where high productivity is a key requirement.

The results from Chapter 2 show that the comparable processes are the additive process and machining, therefore, a more extensive LCA analysis was the subject of the first part of Chapter 4.

The LCA study was conducted to assess the environmental impact of the additive manufacturing (AM) and machining (SM) processes on components with different shapes, which can be obtained from a fixed volume of semi-finished coil. The analysis considered the CED (Direct Energy Consumption) of the production processes, evaluating the influence of the different energy sources, and other environmental parameters derived from the Midpoint and Endpoint impact categories. In addition, two end-of-life scenarios were analysed for the SM process: WCHIP (waste without recovery) and RCHIP (waste with recovery).

The results show that, in order to reduce the environmental impact over the entire product life cycle, it is essential to compare AM and SM both on the basis of the percentage of the volume of the semi-finished product to be removed and considering material waste management. If CED is taken as the main parameter, SM is more sustainable up to high reductions in the volume of the semi-finished product (around 90% of the initial volume), as the energy required for production with AM outweighs the other factors. However, in the absence of proper waste management (WCHIP scenario), AM and SM become comparable for intermediate volume reductions (between 40% and 80%), due to the energy associated with the material lost and not recovered in the SM process.

The national energy mix does not significantly alter these CED trends. However, in the WCHIP scenario, the absence of adequate material recovery and the consumption of fossil fuels alter the primary energy consumption (MJoe) as a function of component weight, with variations related to the dependence of the energy mix on oil sources.

With reference to specific midpoint and endpoint indicators, such as MJoe per piece and impact on climate change or global warming, oil emerges as the most impactful energy source, while hydropower and nuclear energy are the most sustainable and nearly equivalent. However, this comparability breaks down when considering other indicators. For example, factors such as ionising radiation and the use of mineral resources (Midpoint), as well as human health and ecosystem quality (Endpoint), show a higher environmental impact of nuclear energy not only compared to hydropower, but also compared to oil sources.

At this point, not only conventional processes and materials were comprehensively evaluated in Chapter 5 but also processes that allow ultralight materials such as composite materials to be processed. And at the same time, what the production of hybrid components entails in terms of environmental impact.

In detail, the presented LCE study offers valuable insights into the analysis of the environmental impact of gears throughout their life cycle, with a focus on EoL. The analysis compared different types of gears with the same mechanical performance, considering end-of-life (EoL) strategies based on open and closed loop scenarios. Three cases were examined: an all-steel gear, a lightened gear with reduced flange thickness and a hybrid gear with a flange made of continuous carbon fibre reinforced polymer matrix composite (CFRP). The EoL scenarios were analysed theoretically, quantifying the energy required at each stage of the product life cycle, from initial production to final disposal.

The results showed that the optimal environmental choice varies depending on the scenarios considered. The hybrid gear proved to be competitive with the all-steel gear not only in terms of weight reduction performance, but also in an overall life cycle view.

In particular, it was found that CFRP laminate, while offering weight advantages, has a high energy impact during production, penalising the environmental sustainability of the hybrid gear if an effective EoL strategy is not adopted. This is particularly evident when comparing with the lightweight steel solution. However, by implementing appropriate recycling strategies, the EoL required to run the hybrid gear can be significantly reduced, making this solution not only advantageous in the use phase due to its reduced weight, but also competitive in a full cradle-to-grave analysis.

Finally, in Chapter 6, the focus was on composite materials and the impact that different end-of-life processes can have on the environment.

Thus, a CED analysis was conducted on a component made by combining two types of fibres, GF and CF, and two matrices, PP and PEEK, considering three different fibre volume percentages (FVF: 11%, 23% and 45%). Life cycle energy analysis was performed by evaluating three EoL strategies. In particular, by applying the recycling content method, the life cycle EoL of a product was estimated using data collected from a literature review.

From this perspective, possible EoL strategies were identified by modelling, theoretically, the processing steps and collecting the necessary information for a correct quantification of the CED for each of them.

The LCI data collected show a great dispersion in terms of embodied energy and energy consumption for both materials and production processes. In this respect, minimum, average and maximum values were reported and used in the analysis to assess the CED of products with different material combinations.

The results showed that, from an energy impact reduction perspective, the EoL strategy of reforming is always a valid solution to consider. However, the most cost-effective choice depends on the type of composite examined, in particular the combination of fibres and matrices used and the percentage of use in the composite construction.

Therefore, the objective is to provide guidelines for selecting the most suitable EoL strategies, considering the properties of CFRP materials, as a decision-support tool to identify the most energy-efficient route.

9. Further development

Future work could focus on expanding the reach of the thesis and extend the application of the proposed approach to other processes from academic and industrial R&D.

As far as future developments, different coolants for SM and the biomaterials for the AM techniques, as a function of the type of shape to be manufactured and of the process typology taken into account, can be process variables to be considered. The increasing of these key variables that potentially influences the LCA outcomes, will result in the need of a sensitivity analysis implementation to detect the most environmentally impactful and their possible interactions.

On the other hand, considering multi-material and composite components, as far as future developments are concerned, experimental tests need to be considered to assess the mechanical performance of the investigated composite product at different EoL routes. Loss in performance of the recycled fibres due to recycling phase or limitations in reforming owing to critical areas, such as bend angles and wrinkles onset, must be also considered, and evaluated as a future step for the development of the executed analysis. Furthermore, to be able to properly consider in the analysis also the solvolysis, namely the chemical recycling EoL route for CFRTPs, and its impacts due to the different solvents and catalysts used in recovering of both the polymer matrix and the full-length fibres. By doing so, specific midpoint indicators, i.e., global warming, ionising radiation, and mineral resources, and endpoint indicators, i.e., human health, ecosystem quality and climate change, can be assessed to highlight the impacts of the investigated EoL solutions looking at their effects on different moments and environmental categories and providing a different point of view able to develop the results arisen by the CED analysis.

Finally, the application of the LCA methodology in the manufacturing and deposition of a composite filament has to be considered. In order to quantify, firstly, the environmental impact of glass/Kevlar reinforcement, and PLA/PEEK matrix during the production of composite filament and, secondly, the environmental impact of deposition during a 3D printing process. Considering this emerging technology, i.e. 3D printing of CFRP, a predictive LCA is required to quantify the environmental impact in the early development stages and to optimise the environmental impact before marketing. on the other hand, the traditional design flow must be modified to obtain a circular process in which the design phase interfaces with the LCA analysis phase to make trade-off choices between the development of a sustainable and an appropriately mechanical performing component.

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