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# Life Cycle Assessment

# applied to the case study
# of a lawn mower tractor

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# SOMMARIO

La valutazione del ciclo di vita, definita anche con l’acronimo LCA derivato dalla terminologia inglese Life Cycle Assessment, è una metodologia di estrema efficacia che viene utilizzata per studiare e valutare la performance ambientale di un determinato prodotto o servizio durante tutte le fasi del suo ciclo di vita. Essa, infatti, analizza l’interazione tra il prodotto (o il servizio) e l’ambiente prendendo in considerazione tutti i processi che vanno dall’estrazione delle materie prime impiegate per la sua realizzazione, fino al suo smaltimento finale, al fine di quantificarne gli impatti ambientali.

In questo modo, l’LCA consente di mettere in evidenza eventuali punti di debolezza presenti all’interno del sistema produttivo come l’impiego di tecniche con un forte impatto ambientale o l’utilizzo di apparecchiature che richiedono notevoli quantità di energia. Questa metodologia permette così agli esperti di analizzare e identificare alternative di processo migliori che portino ad una ottimizzazione del processo di produzione, sia a livello ambientale sia economico.

Tuttavia, per poter applicare questa metodologia con lo scopo di ottenere dei risultati accurati, è necessario avere a disposizione una notevole quantità di dati (primari o secondari) che non sempre è possibile ottenere o reperire. È per questo motivo, e talvolta anche per semplificare la complessità dell’analisi, che si ricorre a delle assunzioni, sempre cercando di mantenere un buon bilanciamento tra il livello di precisione raggiungibile e il grado di soggettività dell’analisi.

In questo contesto, l’obiettivo del lavoro di tesi è stato quello di mettere in luce i punti di forza e di debolezza della procedura di LCA attraverso la sua applicazione, dalla culla alla tomba, ad un caso di studio reale: un trattore taglia erba.

Il software scelto per svolgere lo studio è stato SimaPro, nella sua versione più aggiornata 8.3, per le sue caratteristiche di flessibilità e per il suo ampio range di funzionalità.

Come database di riferimento è stato usato Ecoinvent poiché molto completo, coerente e versatile. Esso si è rivelato una risorsa importante in quanto contiene dati internazionali riguardanti il ciclo di vita di una vasta gamma di processi e compatibili con gli standard ISO 14040 e 14044.

I risultati ottenuti dallo studio hanno dimostrato che gli impatti più rilevanti per il ciclo produttivo analizzato non sono imputabili alla produzione del prodotto finale ma all’estrazione e al trasporto delle materie prime che lo compongono. Per ridurre l’impatto ambientale di questo prodotto si dovrebbero ad esempio utilizzare materiali riciclati o

acquistarli da fornitori più vicini.

Dai risultati ottenuti si è inoltre evidenziato che per l'azienda produttrice del trattore sarebbe utile effettuare anche una LCA del tipo "gate to gate". Un'analisi di questo tipo infatti permetterebbe di analizzare con maggior dettaglio il solo processo produttivo, ovvero tutte quelle fasi che vengono svolte da quando i componenti, necessari all'assemblaggio del trattore, giungono all'azienda fino a quando il trattore finito esce dalla catena di produzione. Infatti, è proprio in questa parte del processo che l'azienda potrebbe intervenire direttamente per migliorare la propria performance ambientale.

Lo studio condotto ha inoltre permesso di evidenziare come i punti di forza e quelli di debolezza riscontrati in questa analisi siano in linea con quanto riportato in letteratura.

# SUMMARY

Life Cycle Assessment (LCA) is a methodology of great efficiency used to study and assess the environmental performance of a given product or service along its life cycle. It analyzes the interaction between the product (or the service) and the environment by taking into account all the processes (i.e. from the extraction of raw materials used for its manufacturing, up to its final disposal), with the final aim to quantify environmental impacts.

This way, LCA allows to highlight any weaknesses in the production process such as the adoption of techniques characterized by a strong environmental impact or the use of highly energy consuming equipment. Therefore, it allows experts to assess and identify the best process' alternatives for optimizing the production process at both environmental and economic levels.

However, in order to obtain accurate results by applying this methodology, a large number of (primary or secondary) data are needed, which is not always possible to obtain or find. For this reason, and sometimes to simplify the complexity of the analysis, some assumptions have to be made, trying to keep a good balance between the level of achievable accuracy and the degree of subjectivity of the analysis.

In this context, the objective of this thesis work was to highlight both strengths and limitations of the LCA procedure by applying it, from the cradle to the grave, to a real case study: a lawn mower.

The software chosen to carry out the study was SimaPro, i.e. its latest version 8.3, because of its flexibility and wide range of functionalities.

Moreover, Ecoinvent was used as reference database because it is very complete, coherent and versatile; it has proved to be a valuable resource because it contains international data related to the life cycle of a wide range of processes and compatible with ISO 14040 and 14044.

The results obtained from this study pointed out that the largest impacts caused by the analyzed productive cycle are not due to the manufacturing of the final product rather to the extraction and transport of raw materials that compose it. To reduce those environmental impacts e.g. recycled materials should be used or the travel distance of supplied base components should be decreased.

From the obtained results it was also possible to highlight that for the manufacturer of the lawn mower it would be useful to carry out also a "gate to gate" LCA. Such an assessment would allow to deepen the knowledge on the manufacturing process only, i.e. from the arrival of the base components to the exit of the finished lawn mower from the production's chain, where the company could directly act to improve its environmental performance.

Finally, this thesis work allowed to point out that the strengths and limitations of this LCA study were in line with what is reported in the literature.

# MOTIVATIONS AND OBJECTIVES

In recent years the concept of sustainable development has become increasingly important at international level. The increased attention toward the need to pursue sustainable development, i.e. capable of satisfying the needs of the present generation without compromising the possibilities of future generations to meet their own, has led to the birth and development of standards, initiatives, methodologies and tools for both private companies and public administrations.

Among the various institutional initiatives undertaken by the European Union, the most relevant ones' regard encouraging the marketing of those products and services showing the lowest pattern of consumption and pollution during their entire life cycle.

In fact, since all the products and services produce environmental impacts along their life cycle (production, use, disposal etc.), the European Union has placed among its objectives the improvement of environmental performances of products and services.

In this context, one of the main tools for assessing and quantifying the potential environmental impacts of products and services is represented by Life Cycle Assessment (LCA). LCA allows to assess the environmental performance of products, processes and organizations starting from the acquisition of raw materials through the manufacture and use, up to the treatment of end-of-life recycling and final disposal (i.e. from the cradle to the grave).

Conducting an LCA is not only useful to promote company's environmental commitment or environmental performance of a particular product; an LCA can give a complete picture of the entire life cycle of a system, allowing to identify both its critical points and positive aspects and therefore supporting its improvement.

Applying LCA can be time consuming and complex due to the great amount of data to be managed and their intrinsic relationships. However, the study of a system become easier thanks to well-defined standards (ISO 14040-44) and suitable software.

In this thesis work, in an attempt to demonstrate strengths and limitations of this methodology, LCA was applied to the case study of a lawn mower.

In agreement with the company providing this case study, the goal of this exploratory LCA was to assess the environmental performance from the cradle to the grave of the flagship product of the company, with the aim to identify environmental "hotspots" and possible opportunities for the product's improvement as well as to provide the company with a methodological reference, systematically applicable to all products and branches of the organization. Ultimately, the results of this as well as future LCA studies on company's products could be useful for communication with clients and/or suppliers and for improving the overall environmental profile of the organization.

# THESIS STRUCTURE

This thesis is structured similarly to a scientific paper into: Materials and methods (Chapter 1), Results and discussion related to a case study application (Chapter 2), and finally Conclusions (Chapter 3).

In the first chapter, the methodology adopted in the thesis work i.e. Life Cycle Assessment (LCA) is introduced by describing its development and current application. The four methodological phases for its implementation as well as the software and databases supporting it are also presented.

In the second chapter, after briefly presenting the case study, the application of LCA to it is described in detail according to the four methodological phases introduced in the previous chapter. Results are presented and discussed by highlighting both strengths and limitations of the study.

Finally, conclusions are drawn in the third chapter by illustrating how the thesis objectives were achieved as a result of the conducted study.

# 1. MATERIAL AND METHODS

## 1.1. Introduction to Life Cycle Assessment (LCA)

The Life Cycle Assessment, generally defined with the acronym LCA, is a powerful tool that can be applied not only to compare two or more competing systems, but also to optimize an existing system.

The LCA framework has been developed over time. In 1990, for the will of the Society of Toxicology and Environmental Chemistry (UNEP/SETAC 2011), LCA was applied for the first time in a series of Pellston-labs (Fava et al. 2014). Although other LCA analyses were earlier performed in different forms, it was during that workshop that the document coining the name of the method was drafted. At the beginning, the original LCA framework was composed by only three stages (the definition of the goal-phase was missing). This omission was corrected in 1993 at a SETAC seminar, held in Sesimbra, Portugal, where a new component called ‘Goal Definition and Scoping’ (GS&D) was inserted to depict the interconnectedness of phases (Curran 2017).

Indeed, the definition of goal and scope is not merely a simple introduction to LCA but it is an essential and integral part of this analysis that is useful to link all the other phases.

Nowadays the structure of the LCA methodology has been well established by the International Standard 14040 (ISO 2006b) and 14044 (ISO 2006a). LCA analysis is divided into four phases, that will be listed with greater detail in the following paragraphs:

1. Goal and Scope Definition – definition of the goal and scope of the study (including the choice of a functional unit);

2. Inventory Analysis – compilation of an inventory of relevant energy and material inputs and environmental releases (Life Cycle Inventory (LCI) analysis);

3. Impact assessment – evaluation of the potential environmental impacts associated with identified inputs and releases (Life Cycle Impact Assessment (LCIA);

4. Interpretation – interpretation of the results to help decision makers make a more informed decision.

Because of the interactivity of the LCA analysis, it is important that, in the result and interpretation phase, any of the relevant result aspects are mentioned and conclusion aspects drawn must be already stated or mentioned in the goal and scope phase (ISO 2006b).

Conducting an LCA can help answer to a number of important questions of concern to decision makers from the creation of a basic line of the environmental profile of a product for the internal use of the manufacturer to the development of a product label for external public use. Both the private sector and the public one can benefit from LCA analysis.

In the private sector, LCA is embedded in many applications that include different aspects of products throughout design and development: production; marketing; use and reuse; and disposal and end-of-life management. For example to define a baseline of overall environmental impact to identify environmental ‘hotspots’, identifying possible opportunities for improvement across the product life cycle, comparing alternative manufacturing processes or supply chains to identify potential tradeoffs, determining the environmental preferability between alternative product choices, improving products through continuous improvement set often with concrete reduction targets (Curran 2017).

Unlike the private sector, governments and the public sector have only subsequently used the LCA as a tool to support decision-making. However, even for these sectors there are many opportunities to use the data and the results obtained from the LCA to create adequate public policies.

This can occur at multiple levels leading to an environment scenario that allows life cycle thinking and helps to set the course towards a greener, more environmentally sustainable economy. LCA analysis can be useful to inform government programs and prioritizing their activities, establishing consistent policies across consumers, producers, suppliers, retailers and waste managers, establishing consistent policies and policy goals such as harmonizing regulations, voluntary agreements, taxes and subsidies or introducing policies that appropriately support take-back systems to strengthen resource conserving-based economies (Curran 2017).

### 1.2. Goal and Scope Definition

The first stage of LCA is the definition of the goal and the scope of the system. In many cases results of the LCA heavily depend on the choices made at this key stage. The International Organization for Standardization (ISO), in the norm 14040, referred to this stage as the “goal and scope definition” (ISO 2006b).

The definition of goals and scope must be guided by data which can be collected. It is noteworthy that the goal and scope may change iteratively during the course of a study and this may cause additional data collection effort or previously collected data to be discarded (Matthews et al., 2015).

In this phase are described in the first place the objectives and purpose. For the first time, are outlined here the results that must be obtained and is also identified who is the audience and who are the stakeholders.

Secondly, the function of the system to be considered has to be analyzed to define a unit that represents this function. Different scenarios are described to achieve this functional unit (FU). Finally, the system boundaries must be specified (Jolliet et al. 2016).

### 1.2.1. Objectives

The goal and system definition begins with the description of the objectives of the study where the problem is determined and the expected application for the LCA results, including the desired audience, the stakeholders and the scope of the study, are defined. Compared to the more technical steps of an LCA, this one has a descriptive approach.

Moreover, discussion of all options and possible alternatives between the various stakeholders is required, in order to increase credibility and to ensure relevant results. (Jolliet et al. 2016).

### 1.2.2. Goal

According to ISO 14044 in order to define the objective of an LCA, it is necessary to clearly identify the following aspects:

- The intended application,
- The reasons for carrying out the study,
- The intended audience (i.e. to whom the results of the study are intended to be communicated), and
- Whether the results are intended to be used in comparative assertions to be disclosed to the public.

The intent of a given LCA should be clearly specified to avoid ambiguity among the potential applications and audiences giving:

- Information on an existing product
- Development of a new product
- Elaboration of political strategies
- Regulation of an existing product

Although all audiences are interested in reducing environmental impacts, consumers, producers and governments have different perspectives on how to do that.

In addition to this, identity and addresses of the main stakeholders, including independent sponsors, authors, board of directors, analysts, and independent experts, must also be provided. If there is an interaction with an outside audience, LCA's credibility is increased by having the LCA commissioners, analysts, and peer reviewers all be independent entities. An external review is generally optional, but becomes necessary for an ISO-compatible study involving a comparative assertion (Jolliet et al. 2016).

### 1.2.3. Scope

Once the goal is determined, the scope of an LCA must take into account and clearly describe the following elements (ISO 14044):

- The product system to be studied,
- The function of the system, or of the systems in the case of comparative studies
- The functional unit (FU)
- The system boundary
- Allocation procedures
- Life cycle impact assessment (LCIA) methodology and types of impacts
- Interpretation to be used
- Data requirements
- Assumptions
- Value choices and optional elements
- Limitations
- Data quality requirements
- Type of critical review, if any
- Type and format of the report required for the study

To ensure that the amplitude, depth, and level of detail are consistent with the objective set, the scope of the study must be sufficiently well defined. As LCA uses an iterative approach; the scope of study can be recalibrated based on the information collected during the analysis.

Considering the scope of an LCA, it is possible to broadly distinguish between two types of modeling approaches: attributional and consequential LCA: the first one "is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems" (Finnveden et al. 2009). While consequential LCA "is defined by its aim to describe how environmentally relevant flows will change to possible decisions” (Curran et al. 2005).

The distinction between attributive and consequential LCA stand out how the definition of the different target affects both methodological and data choices to be filled for LCI (Life Cycle Inventory) and LCIA phases (Verones et al. 2017).

Consequential LCA is conceptually complex because it includes additional and economic concepts such as marginal production costs, elasticity of supply and demand, etc. Consequential LCA depends on descriptions of economic relationships embedded in models. It generally attempts to reflect complex economic relationships by extrapolating historical trends in prices, consumption and outputs. Therefore, this implies that the risk of assumptions or other inadequate errors significantly affect the final LCA results. To minimize this possibility, it is important to ensure that different results related to different consequences can be explained by using credible arguments (Curran 2017).

### 1.2.4. System Function

After defining the purpose of a comparative study, the different systems or the different products must be compared using a common comparison meter. Scenarios, which represent the different alternatives, must be chosen to fulfill the same function. This function starts to be essential to the system and it requires a clear definition. In fact, it is the basis for determining two fundamental LCA elements: the functional unit and the boundaries of the system. To objectively evaluate each alternative, it is necessary to determine the function before defining the functional unit (FU) or the system boundaries.

It is not always easy to find just one exact function of a system because a single product can be equipped with more features. In this case, it must be identified the main function and the secondary functions. The primary function, by definition, is common to the different alternatives. The secondary functions are specific to each scenario, and if they greatly differ between alternatives, they can reveal bias in the comparison. When a component of a larger system is studied, the function chosen is generally that of the whole system (Jolliet et al. 2016).

When an LCA is reviewed, it must be checked the system function to be valid in all scenarios, explaining the differences between scenarios. Particular attention should be paid when secondary functions of alternative scenarios differ.

### 1.2.5. Functional Unit and Reference flow definitions

Once the system function is determined, the functional unit (FU) can be defined.

According to ISO 14044 (ISO 2006a), the FU is the “quantified performance of a product system for use as a reference unit.”

The functional unit describes the main functions met by a product system indicating how much this feature should be considered in the expected LCA study. This data will be used as a basis for selecting one or more alternative product systems that could provide these functions (de Bruijn et al. 2002).

Products often fulfill more than one function. For independent LCAs of single products, the definition of the functional unit may not be as critical. However, greater consideration of the functional unit becomes necessary when the objective of the LCA is to compare two or more products. In this case the basis of comparison should be equivalent use, each system should be defined so that an equal amount of product or equivalent service is delivered to the consumer (Curran 2017).

The FU must be the same for all scenarios, with inventory flows and impacts for each scenario calculated for FU. For example, different transportation methods are often compared based on a FU of transporting one person over a distance of 1 km (i.e., 1 person/km) (Jolliet et al. 2016).

The FU must be a quantifiable and additive measure, so that the impact of two FUs is double that an FU. The FU for assessing one component of a larger system is based on the FU of the system as a whole. For a given FU, the reference flows are the amounts of goods or services purchased to fulfill the function and generate this FU (Jolliet et al. 2016).

The FU and the reference flows can be used both to estimate the costs for the entire product life cycle and to estimate the environmental impacts of existing products and to provide information to guide the design of new products. This process of life cycle costing (LCC) is not technically part of the environmental LCA, but since it uses the same lifecycle thinking and the same framework and concepts, the two can be easily combined (Jolliet et al. 2016).

When comparing products or services, if their functions are not identical but similar, it is important to clearly indicate this and evaluate all potential consequences on the results of the study. Functions may differ in the performance of the product or service. Relating the environmental impacts of different means of transport (rail, road and air), the travel time for a given distance can greatly vary and therefore this travel time cannot be directly included in the FU. Still, as is done with economic performance, this technical performance can be measured and compared with the environmental performance in the final interpretation phase. When the multifunctional aspect changes the necessary reference flows, the FU must be adjusted to account for this (Jolliet et al. 2016).

There are some systems that perform simultaneously multiple functions. In these cases, it is important to correctly identify the function chosen for the analysis.

### 1.2.6. System Definition

The reference flows and impacts caused to each FU, are calculated by reference to a well-defined system. System modeling is based on a holistic approach that provides a comprehensive understanding of the system considering it as a whole, in all of its dynamics and complexity (Le Moigne 1990). The system is not just the sum of its elements. The modeling approach of the system also considers the relationships between the elements that make up the system rather than the elements themselves.

The system is then described in terms of these relationships and their significance to the function of the system. In the LCA analysis, the world is distinguished between the environment and the system that provides a product or function and the rest of the business. It is also defined as a group of dynamically interacting elements, organized to achieve one or more functions. The system is identified by the elements that contains which are called processes, the links between these elements and boundaries that outline it from the surroundings (Jolliet et al. 2016).

The extracted resources, which include energy and land used, are considered as inputs from the environment to the system; while emissions from the system in the environment are considered as emissions into air, water and soil. The output of the system in the economic world is the service offered by the product.

The assessed and modeled system is built by linking different process modules. Once the processes and elements needed to run the function have been identified, they are expressed as a series of unit processes, which are the smallest elements of the analysis, each of them quantifies the inputs and outputs. Through intermediate flows, the unit processes are connected to each other within the system. This union is made possible by the connection between the amount of each unit process required for the subsequent unit process. The outputted product flows to the economy are any products that leave the system. Elementary flows link unit processes to the environment through the use of input elementary streams which correspond to the use of natural resources such as extracted raw material, energy and land use. Elementary flows exiting a unit process are emissions to water, air, or soil (Jolliet et al. 2016).

According to the objectives required by the study, an appropriate modeling of unitary processes is needed. In fact, each unit process can be subdivided into other unit processes down according to the level of detail required.

Since this is a physical system, it is necessary to make mass and energy balances to verify that all unit processes and the global system respect the mass and energy conservation.

The theoretically ideal system is one defined such that the economic world has no inputs to the system and only one output from the system, namely the product corresponding to the studied function. All processes that serve to satisfy the system function must be part of the system itself. Often this in practice does not happen both to lack of data and for the time to run the LCA. In addition, the compared system may have different outputs respect to the product being studied, so once determined the coproducts of value it is necessary to assign them a portion of the emissions produced (Jolliet et al. 2016).

The flow diagram provides an outline of all the major unit processes to be modeled, including their interrelationships. It is helpful in understanding and completing a system to describe the system using a process flow diagram (de Bruijn et al. 2002).

Starting from the reference flows, the flow diagram (the one required for the purchase of an FU) is constructed, identifying the intermediate level flows (number of processes of the previous unit) associated with each reference flow. The operation is then repeated, starting from the tier 1 intermediary flow, yielding a second set of tier 2 elementary flows. In practice, for a new study, the flow diagram will display all linkages from reference flows up to existing database unit processes, whose upstream and downstream links are described in further detail in the database itself and therefore do not necessarily need to be shown in the flowchart (Jolliet et al. 2016).

Each scenario that is taken into account in the LCA must have its own flowchart properly visualized and subdivided into unit modules. Each scenario must have the same primary function, that is to cover the same functional reality and produce the same FU.

### 1.2.7. System Boundaries

The definition and description of the boundaries of the system is one of the most important aspects of the goal and scope definition. In fact, the boundaries of the system affect both data collection and background data choices, as well as of foreground modeling aspects. Interventions that cross the boundaries of the system are defined as elementary flows and the processes within the system boundaries describe the system under study (Curran 2017).

A complete LCA would foresee the analysis and modeling of all the global production processes that occur at every point of the production, use or disposal chain.

For the LCAs analysis, based on sets of processes, it is important to determine the criteria for the inclusion or exclusion of certain processes and apply them according to ISO 14000 standards (Jolliet et al. 2016).

Starting from the reference flows, the system should include all flows required to fulfill the function and cover the main life cycle stages (ISO 14040):

- Extraction and refining of raw materials and energy
- Provision of infrastructure, machinery, inputs, and transport
- Main manufacturing stage
- Use stage, including maintenance
- Waste treatment, taking into account the recovery of used products (including reuse, recycling, and energy recovery).

Since waste disposal generates emissions, their treatment must be included within the limits of the system. Waste streams are to be considered as intermediate flows, rather than elementary elements, and therefore should not be considered in the inventory as such. Emissions and other elementary flows associated with the waste treatment stages must be reported in the inventory (Jolliet et al. 2016).

### 1.3. Inventory Analysis

Once in the first phase of an LCA the different scenarios, the functions that they fill and the systems to be studied are defined, the second phase of an LCA can be implemented. This phase quantifies the inventory of the various streams of material extraction and the emissions of substances that cross the boundary of the system. Two methods to calculate the inventory currently prevail: the process-based approach and the input–output (I/O) approach (Jolliet et al. 2016).

The process-based approach uses physical reference flows and intermediary flows to identify and link the unit processes of a system. The input–output approach, instead, bases its analysis on the economic flows generated by the product or service considered (Jolliet et al. 2016).

The inventory analysis simply combines the reference flows of unit processes in the system, that had previously been calculated, with emissions and extraction for each unit process. A complete inventory generally accounts for hundreds of substances out of the

100,000 possible anthropogenic emissions. Despite the ease of inventory calculation principles, data collection can need a lot of effort and long time. Fortunately, there are databases that leave only, through data integration for a wide range of processes, the processes specific to the considered application and industries to be modeled in detail (Jolliet et al. 2016).

## 1.4. Impact Assessment

After collecting data on raw material extraction and after identifying the emissions of the substances associated with the life cycle of a product, the third stage of LCA consists in the assessing of the impact of the life cycle.

A key difference between life cycle impact assessment (LCIA) and other frameworks, like risk assessment or performance benchmarking, is its link to a particular functional unit (and of course the entire life cycle as a boundary), which focuses the attention on impacts as a function of that specific normalized quantity (Matthews et al. 2015).

The different stages of impact assessment are: the classification of emissions into different impact categories, the characterization of midpoint impacts and the characterization of the end point. Although impact assessment methods are simple to apply, some difficulties may arise in their development, which may be relatively complex (Jolliet et al. 2016).

### 1.4.1. Purpose of Impact Assessment

In the Impact assessment phase, the results of the Inventory analysis (presented in paragraph 1.3) are translated into contributions to relevant impact categories, such as depletion of abiotic resources, climate change, acidification, etc. To this end, relevant impact categories must be identified (de Bruijn et al. 2002).

Generally, the inventory phase involves a first aggregation of data, summing the emissions produced by each substance and by each extracted resource during the life cycle. This leads to the formulation of an inventory table of total emissions and extraction for each substance and resource. Even if one scenario has lower emissions of most substances, it generally has higher emissions for several others. To determine the best scenario, it is necessary to evaluate the magnitude of the impacts generated by each substance. Therefore, it is also necessary to have aggregation methods to link the based emissions on their potential cause to have one or more environmental impacts. Due to the uncertainty of exposure models that are used to predict impacts, caused by a wide variety of substances, the development of these environmental impact assessment methods is not always easy and may involve the use of complex models. Given the complexity of the task, some argue that it is better to compare the results of different scenarios on the basis of the inventory alone. However, the analysis considering only the inventory generally leads to an implicit weighting in which, for each pollutant, the same weight is assigned roughly; or in some cases some inventory flows are arbitrarily considered more important. An impact assessment based on a consistent and explicit criterion is better than an implicit evaluation, although uncertainty is important when considering the results (Jolliet et al. 2016). Several LCIA methods exists and a brief overview of most relevant ones will be presented in paragraph 1.4.4.

It should be emphasized that although the development of impact assessment methods can be very complex, its application is usually trivial, as it simply consists in multiplying emissions by predefined characterization factors (Jolliet et al. 2016).

### 1.4.2. Principles of Impact Assessment

Since environmental LCAs are linked to environmental impacts, it would be right for substances to be compared based on their ability to harm the environment and the human health. When a polluting substance is emitted to a certain environmental medium, its concentration increases in that medium, and the substance also often transfers to other environmental media (air, water, or soil), bioaccumulates in the food chain, transforms into other substances, and is eventually ingested or inhaled by humans or other species. It ultimately impacts either human health (HH) or the quality of the environment. The pathway that the pollutant follows is called impact pathway, and encompasses all the environmental processes ranging from the emission of the substance to its final impact. LCIA methods analyzes the impact paths of different substances to link more accurately each inventory data to its potential environmental damage based on these pathways. To combine inventory data with environmental damage, a methodological framework was developed in the Life Cycle Initiative (Verones et al. 2017). First, all inventory results that have similar effects (such as all greenhouse-emission-related substances emissions) must be grouped into an impact category at an intermediary level, called midpoint category (Jolliet et al. 2004). For each midpoint category, a midpoint marker is defined. All inventory flows are multiplied by a characterization factor that serves to characterize its contribution to that midpoint category. The midpoint term suggest that this point is situated somewhere on the impact path between inventory results and damage. Global warming, for example, is a midpoint category representing the impact of greenhouse gases (Jolliet et al. 2016).

Each midpoint category is then allocated to one or more damage categories, which address the damage to different areas of protection, such as HH and ecosystems. The damage category is represented by a damage indicator, which is sometimes referred to as an end point indicator. Since every impact assessment step normally implies assumptions about the contribution of the damage to the group, accentuates the uncertainty of the result from the inventory to the midpoint and from the midpoint to the result of the damage. On the other hand, each of these grouping phases produces simpler results to interpret (Jolliet et al. 2016).

### 1.4.3. Steps of Impact Assessment

According to the methodological framework described above, the impact assessment is divided into three phases: classification of emissions, midpoint characterization and damage characterization. In addition to these three steps there are other three optional steps: normalization, grouping and weighting (Finnveden et al. 2002).

In the classification step, is defined a set of midpoint environmental impact categories for the types of environmental problems identified. Emissions are then classified into any relevant midpoint categories on which they have an effect even if a given substance can contribute to several impact categories (Jolliet et al. 2016).

During midpoint characterization, the second phase of impact assessment, emissions and extractions are weighted to represent their contribution to each midpoint category. These weighting factors are called midpoint characterization factors, and they express the relative importance of substance emissions (or extractions) in the context of a specific midpoint environmental impact category (Jolliet et al. 2016).

In the characterization phase of the damage, the contribution of each midpoint category is assessed for one or more categories of damage associated with greater protection areas. Just as each polluting substance contributes to one or more midpoint categories, each midpoint impact may contribute to one or more damage categories.

Nevertheless, it is often useful to keep the contributions of each of the midpoint categories separated for interpretation.

The calculation of the damage score involves more uncertainties than for the midpoint scores, but is still based on scientifically determined or estimated values and a shared damage category; thus, it should not be considered as a value-based weighting as defined by ISO 14044 (ISO 2006a).

The reference units of many midpoint categories, and some damage categories, are often not initially intuitive, and the meanings of the resulting impacts are thus difficult to interpret. The normalization step expresses a given impact per functional unit relative to the total impact in that category to better understand the magnitude of the damage. It thus compares the respective contribution of the considered product or service to the current total effect on a global, continental, or regional level for a given category (midpoint or damage). The results of the impact characterization are reported relative to these total reference values or normalization values.

It is necessary to normalize the damage rather than the midpoint score because midpoint normalization only indicates the relative magnitude of the contribution within that midpoint category, lacking the midpoint-to-damage information about the importance of that midpoint category in the total impacts (Jolliet et al. 2016).

Grouping is a qualitative or semiquantitative process that helps prioritize results by sorting or ranking, and can be done in several ways. Impact categories can be grouped according to area of protection, the types of emissions/resources, or by spatial scale (global, regional, or local). Impact categories can also be ranked based on a predefined hierarchy; for example, high, medium, and low priority. This second procedure is based on value choices that reflect the importance given by society or the user to a particular category.

Rather than have multiple scores for each scenario, for every midpoint or damage category, some users just want a single score for each scenario, which is calculated by weighting the scores in each damage category based on its relative social value. Applying these weighting factors to each damage category leads to a final aggregation into a single weighted environmental impact score.

It is recommended to only apply this weighting to the damage characterization, since the midpoint-to-damage factor already provides an effective natural science–based characterization of midpoint categories (in contrast to weighting, which is value-based) that contribute to a given area of protection.

Weighting factors are based on social, political, and ethical values and cannot be estimated only using only natural science–based methods. The methods that define these factors are thus generally based on monetization (encompasses all methods that estimate weighting factors on a monetary basis), surveys (of experts or samples of the population can also provide weighting factors based on questionnaires that reveal the perceived relative importance of damage), or distance-to-target approaches (links the weighting factors to a target value, based on policy environmental goals) (Jolliet et al. 2016).

### 1.4.4. Overview of the Main Impact Assessment Methods

An overview of the main impact assessment methods and their historical development is now presented.

One of the first LCA impact assessment methods to be elaborated was the critical volumes method, which considered as the first stage the grouping emissions from the emission compartment (emissions, air, water and soil) (Bus 1984). This methodology, however, does not take into account the persistence or the fate of pollutants, and therefore it is not valid today. In 1992, CML 92 was the first method that paid attention to the effects of emissions, and for this reason it has been used as a basis for many further developments. However, fate was not considered in the assessment of the toxic substances, as it followed a similar approach to the method of critical volumes (Heijungs 1992). In 1999, to fill this gap Huijbregts recalculated the impacts of toxicity taking into account the fate of pollutants and he integrated these calculations into the midpoint characterization method describe in the Dutch handbook on life cycle assessment (Huijbregts 1999).

For over 20 years, the Environmental Priority Strategy (EPS) method suggested assessing impacts in terms of damage (Ryding et al. 1993; Steen 1996). This method was based on an excellent analytical framework, but sometimes the basis for the calculations, necessary for find the coefficient, was not very transparent. This method was then upgraded, in 1999 by Steen which created the EPS 2000d method (Steen 1999).

Eco-indicator approach, was developed in 1995, by Goedkoop, primarily for the purposes of ‘eco-design’ (Goedkoop 1995). Designers were deemed unable to work with 10–20 indicator results, and the Eco-indicator therefore employs only 1 to 3 weighted indices. In the first version of the Eco-indicator weighting was based partly on a damage approach, partly on a distance-to-target approach (i.e. based on predefined damage targets). Originally conceived as an experiment, the Eco-indicator method has since been improved. In the latest version, called Eco-indicator 99; a completely different approach to Impact assessment has been adopted in which a limited number of damage categories are weighted (Goedkoop and Spriensma 1999). Specifically, three types of damage are distinguished, for which weighting is taken to be more readily feasible: damage to resources; damage to ecosystem quality; damage to human health (de Bruijn et al. 2002).

ReCiPe then built on and replaced Eco-indicator 99 and the Dutch handbook on LCA to combine midpoint and damage approaches (Goedkoop et al. 2009).

The EDIP97 method, on the other hand, uses an approach that stops at midpoint level and it is specifically designed to help industries to develop ecological products (Wenzel et al. 1997). Its updating, EDIP2003, considers space differentiation in modeling characterization factors (Hauschild and Potting 2004).

The ecological scarcity method (Braunschweig et al. 1998; Frischknecht and Büsser Knöpfel 2013) compares the impacts of the various emissions and links them to the different political goals. This method goes beyond environmental impacts, taking into account the areas where environmental pressure is greater and therefore indicates the risks of increasing environmental costs for the companies. Although it was first developed in Switzerland, there are a lot of alternatives in different countries such as Netherlands, Colombia and several regions of Japan (Jolliet et al. 2016).

The U.S. EPA has developed the TRACI method (Bare et al. 2003; Bare et al. 2006), which assesses impacts at the midpoint level and is closely related to the risk assessment methods of the U.S. EPA. It has been updated to include USEtox (Bare et al. 2003; Bare et al. 2006) for the toxicity-related categories. In Japan, LIME (Life cycle Impact Assessment Method based on Endpoint modeling) quantifies Japanese environmental impact, including damage calculations that are coherent and original (Itsubo and Inaba 2003).

In accordance with the Surface Critical Time Method (CST95), IMPACT 2002+ was made for evaluate the impact at midpoint and damage levels (Jolliet et al. 2003a, b). As a new it was introduced in the evaluation of the damage to HH and the quality of the ecosystem, adapting the latest risk analysis concepts to the specifics of the LCA. This method has been replaced by the IMPACT World + method (Jolliet et al. 2003a,b), which provides factors for each continent at midpoint level and damage level (Jolliet et al. 2016).

To conclude, the European Impact Assessment method (Hauschild et al. 2013) was chosen to include various life cycle initiatives recommendations. The recommendations contained in this guidance document are based on an analysis of a wide range of existing characterization models used in LCIA. For each impact category, the first step of the analysis is the pre-selection of an existing model. If a method is used in multiple LCIA methodologies, only the most recent and upgraded version of that method is considered. The next phase includes the development of general recommendations for each category and the drafting of evaluation criteria to be used in evaluating and comparing selected methods. In 2011, Hauschild reported the selection criteria for each impact category (Hauschild et al. 2011). The final document presents recommendations for each impact category, implementing the USEtox Consensus Model (UNEP-SETAC toxicity model) presented, in 2008, by Hauschild and Rosenbaum (Hauschild et al. 2008; Rosenbaum et al. 2008). Although this method is recommended for use by the Joint Research Center (European Commission's Scientific Agency), there is little consistency in the midpoint indicators that are not necessarily compatible between the categories (Jolliet et al. 2016). In this thesis work, the ReCiPe method for LCIA was used as implemented in the SimaPro software (https://network.simapro.com/2b/). For this reason, the ReCiPe method and the SimaPro software have been described in more details in paragraphs 1.4.5 and 1.6.1, respectively.

### 1.4.5. ReCiPe 2008

ReCiPe 2008 (Goedkoop et al. 2009) was born with the intention of combining the midpoint approach of the CML method with the approach of the Eco-indicator 99 method. Thanks to the collaboration of the National Institute for Public Health (RIVM) and the University of Nijmegen, the access to the knowledge and to the models related to a wide range of environmental issues, from acidification to climate change, has been gained. This synthesis has defined the LCIA ReCiPe method, with impact category indicators and characterization factors at the midpoint and damage levels. The model structure is similar to methods presented previously in linking the life cycle inventory (left) to a midpoint indicator (middle) and damage indicator (right). An added feature of the ReCiPe method is that results are presented for three different social perspectives, based on subjective value choices, such as time horizon and uncertainty management (Goedkoop et al. 2009).

Eighteen categories of midpoint impact are considered in the ReCiPe, leading to 18 characterization factors. A commonly used criterion to define these impact categories and indicators is that all the midpoint impact categories should have a stand-alone value in a midpoint-oriented LCIA approach, but they must also be usable as an intermediate step in a focused approach to the damages.

ReCiPe uses the following three damage categories: damage to HH expressed in DALYs, damage to ecosystem diversity (ED) expressed in loss of species per year, and damage to resource availability (RA) expressed in U.S. dollars (Goedkoop et al. 2009).

### 1.5. Interpretation

Most of interpretation phase is performed only after the goal definition, inventory and impact assessment, although it must be applied at every stage of each iterative process.

The interpretation phase needs to analyze the outcomes of the LCA related to the goal and scope definition (Curran 2017).

The stage of interpretation consists in the identification of the life cycle phases where an appropriate intervention can significantly reduce the environmental impacts of the system or of the product and analyze uncertainties. This LCA phase allows to evaluate the results, draw conclusions, explain the limitations of the study and make recommendations based on all the results of the previous inventory phases and on the basis of impact assessment. This phase would aim to provide clear and useful information for decision-making. To achieve these goals, the stage of interpretation identifies the critical points in the life cycle (for example, where much of the impact occurs), as well as evaluating the quality and robustness of the results by referring to a series of controls (e.g. quality control, sensitivity analysis, and uncertainty analysis). The results of the preceding phases should be combined with reference to quality data, methodological choices (such as assignment rules, system boundaries, and templates used), value choices (which may differ for study and study purposes) analysis and data regarding such studies if they exist. Interpretation should be carried out systematically for each stage of the LCA: after the goal and scope definition, the inventory of polluting emissions, the midpoint and damage definition and after the overall impact assessment. Interpretation is particularly useful for discuss and analyze all the inventory results before moving on to impact assessment (Jolliet et al. 2016).

For each phase of the life cycle, all contributions, including extraction and preparation of raw materials and energy, transport, production, use and disposal, should be compared and analyzed. In addition, it is necessary to analyze the contributions of each pollutant and each extracted substance by reporting the emissions and extracts that generate the most impact for each impact category (Jolliet et al. 2016).

The results of the interpretation phase could then internally weigh in on whether such a decision was appropriate given the study goal. If a (qualified) conclusion can be drawn, the study could be left as-is, if not, a broader system boundary could be chosen, with or without preliminary LCI results (Matthews et al. 2015).

### 1.5.1. Identification of Action Priorities

The purpose of the interpretation is to analyze various methods to reduce the environmental impacts and to identify the priorities for which action is needed. The inventory and impact results are used to identify the key of environmental impacts and thus identify all possible improvements to reduce resource consumption, energy demand, or emissions (Heijungs et al. 1992).

First, it is necessary to analyze the life cycle phases and the groups of processes that generate the greatest impact. However, the grouping of processes is not unequivocally defined and therefore can be arbitrary and depend on modeling the system. For example, it is possible to subdivide the production phase into five substeps unlike the use phase, which is often considered as a single step. In this case, each single substep of production appears small, although the phase as a whole is significant. It is necessary to pay attention to the inclusion of large groups of individual processes that seem to have small impacts but lead to substantial impacts when added. The process of interpretation can also focus on lifecycle phases that have the greatest potential with the aim of reducing impacts without resorting to extensive investment. In some cases, win-win, you can reduce both impacts and costs. In some cases, even limited and low-cost intervention can be extremely effective in reducing impacts (Jolliet et al. 2016).

The role of interpretation is crucial and it is demonstrated by the common practice of companies to study and invest in changes related to their business activities, although many environmental impacts occur upstream or downstream of these operations.

Interpretation also allows the optimization of lifecycle investments, based on cost-benefit analysis (Jolliet et al. 2016).

ISO standard 14044 states that: “Data quality requirements shall be specified to enable the goal and scope of the LCA to be met.” Data quality requirements include time-related coverage, geographical coverage, technology coverage, and more (Curran 2017).

The essential point of quality control is to verify the consistency of the results and to pay attention to anything unexpected (Jolliet et al. 2016).

To use LCA as a useful tool for decision making, it is necessary to have information that can guarantee the robustness of the results. This element of the interpretation phase analyzes the influence that data variations on the process, model choices, and other variables, have on the results. In sensitivity analysis, these changes are deliberately introduced to determine the robustness of the results in relation to these variations (de Bruijn et al. 2002).

The LCA analysis can be done to give a better decision-making, such as accepting or selecting a particular product and choosing a policy. This role does not belong to the traditional LCA, which focuses on environmental assessment, but it is important to see how decision makers can be evaluated in a consistent manner with the LCA approach (Jolliet et al. 2016).

## 1.6. LCA Software

LCA studies use a large amount of data, making it impossible to perform calculations manually, and therefore requires using specialized software for interpretation.

SimaPro (https://network.simapro.com/2b/) is well designed to simply present and interpret the inventory and impact assessment results, and to easily review detailed contributions of each unit process. It allows for simultaneous analysis using both the process-based and input–output approaches, while estimating uncertainty propagation with the Monte Carlo method (Goedkoop et al. 2003). GaBi uses more aggregated processes based on industrial data, and is thus particularly relevant for industrial applications in the automotive and electronics sectors and for modeling nonlinear processes (GaBi 2003). The Quantis Suite (https://quantis-suite.com/free_product.html) software has been developed recently to achieve the balance of a company as a whole and over all of its life cycle.

None of these databases are free, and a license must be obtained to use them. On the other hand, there are a variety of globally available and publicly accessible life cycle databases. In the US, LCI data from the National Renewable Energy Laboratory (NREL)'s LCI database (https://www.nrel.gov/) and the USDA's LCA Digital Commons (https://ndb.nal.usda.gov/ndb/) are popular and free.

Another free LCA software program is openLCA (http://www.openlca.org/). This program was created within the framework of the openLCA project to provide a modular software program for life cycle analysis and sustainability assessments. Initially, it begin with a basic framework for LCA calculations of results and uncertainty, along with a tool to convert among different data formats.

Other free software are: Open-IO (http://www.openio.io/), a project that has already released a U.S. input–output database specifically for openLCA (Ciroth 2007); Brightway2 (https://brightwaylca.org/), that is a powerful recently developed tool allowing analysts to quickly perform cutting-edge calculations and visualizations, and CMLCA, Chain Management by Life Cycle Assessment (http://www.cmlca.eu/), that is a program intended to support the technical aspects of LCA (Heijungs and Frischknecht 2005). Although its user interface is not very flexible, it can be used for rich data analysis, including a complete matrix algebra tool with matrix inversion, as well as integrated methods for sensitivity analysis and uncertainty assessment. CMLCA supports fully hybrid inventories that consist of both process-based and IO-based data, though the comprehensive IO database is not free. Finally, there are various non-LCA-specific tools that use a life cycle approach, such as the carbon tool of the Association Bilan Carbone (https://www.associationbilancarbone.fr/), originally developed by the French Ministry of the Environment (ADEME) (BC Bilan Carbone 2010).

### 1.6.1. SimaPro

SimaPro is a tool used to achieve LCA studies (Herrmann and Moltesen 2015) following ISO norms. It is also used to assess the environmental impact of products and services throughout their life cycle (Goedkoop et al., 2016).

The new version, SimaPro 8.3, is equipped with several Life Cycle Inventory (LCI) databases including the database Ecoinvent v3.3. This is one of the most extensive LCI international databases with 10.000 processes relative to a wide range of sectors.

In the left side of the main screen there is a bar called LCA Explorer that allows the access to all the functions of SimaPro. The upper part permits to use specific data for the project, e.g. the data required for the description of the target and the scope of application through the use of bibliographic sources that refer to data and standard impact assessment methodologies. With the use of specific data, it is possible to define the inventory phase and the impact assessment. The Explorer bar has an inherent part for the explanation of the obtained data. This is a checklist (that includes completeness and consistency checks), according to the standard ISO 14044, to verify if the conclusions are supported by the data and procedures used. The completeness check allows to check if the information inserted during the various stages of life cycle analysis are sufficient to obtain the conclusions in accordance with the definition of the objective and with the scope. Instead, the consistency check permit to verify if the formulated hypotheses, the developed methods and the used data are coherently applied in the all life cycle analysis, always in accordance with definition of the objective and with the scope, before reaching to the conclusion (ISO 14044, 2006a).

At the bottom of the bar, called SimaPro “general data” there are information that there are not in the projects but that they are used to support SimaPro analysis. The LCA Explorer bar is structured as a checklist and allow to modify the data in the order defined by the list in order to conduct the analysis in the best way. The toolbar buttons, located at the top of the screen, are used to execute the most commonly used commands as opening and closing a project, show formulas and values, analyze or compare data or perform a Monte Carlo analysis (Goedkoop et al., 2016).

This analysis can be used to study uncertainty, but the greatest challenge is the lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates (Curran 2017).

### 1.7. Inventory Databases

When setting a target, the boundaries of the system are also defined and all processes within these boundaries are listed and quantified. The associated elemental flows need to be computed for inventory of incoming processes (raw materials and energy vectors) and outgoing processes (airborne substances, water, etc.) obtained from industrial partners or using literature as a reference. It is not easy to have reliable, clearly-described and regularly up-to-date inventory data, and this can seriously impede the application of lifecycle assessment, but the use of public databases now available for the public can facilitate this work (Jolliet et al. 2016).

The inventory databases available to the public around the world were compiled, in 2002, by Norris and Notten (Norris et al. 2002) and in 2011, by Sonneman and Vigon (Sonneman et al. 2011), referring to previous work carried out by the Society for Life Cycle Assessment. This data set is regularly updated under the United Nations Environment Program (UNEP) Life Cycle Initiative, and after the 2011, a set of global principles of orientation for lifecycle assessment databases has been published. The European Commission also provides a regularly updated collection of LCA resources, including access to 20 database sites, 35 tools and 80 service providers.

Initially, most databases were developed in Europe in the mid-1980s. These databases were born to conduct university studies or to conduct consultations for characterize specific industrial sectors or product groups. The resulting databases were highly diversified, fragmented and non-harmonized.

Improvement of data bases was mainly carried out in Switzerland by an initial study of the OFEFP (Office Fédéral de l'Environnement des Forêts et du Paysage) that focused on packaging materials (Bus 1984; Habersatter and Widmer 1991). The study, which concerned the environmental consequences that different types of packaging might have had (aluminum, glass, plastic, paper, paperboard and pond), required a lot of higher-quality data on energy systems. This led to a collaboration among the Swiss Federal Institutes of Technology, with a goal to create a centralized, coherent, and more complete database, called Ecoinvent (Jolliet et al. 2016).

Nowadays a specific database has been developed for each continent (Asia, Australia, North America, Europe). The European Center for Life Cycle Research (ELCD) was created by the Joint Research Center (JRC) of Ispra, Italy, using the European scope inventory data sets. The ELCD database is made up of LCI data provided by European business associations, but also from other sources for example: raw materials, energy carriers, transport and waste management. Significant effort has been made to improve data quality, consistency and applicability, although data is provided only aggregated from cradle to gate, without detailed information on unitary processes. This limits the use of this database for uncertainty analysis or for more advanced studies on system boundaries. The use of this database is free of charge with unlimited use for all LCA professionals. The European Life Cycle Assessment Platform also provides the guidance document, the International Lifecycle Data Lifecycle Reference Manual (ILCD), which describes available and recommended practices for data LCA in general, LCI data sets and LCIA.

For Europe, in addition to Ecoinvent and the JRC ELCD databases, the following country-specific databases are available: (a) LCA Food Database—Denmark (from the Danish Institute of Agricultural Sciences; data also available in the LCA tool SimaPro); (b) Swedish National LCA database SPINE@CPM (which contains more than 500 well-documented LCI data sets in the SPINE format); (c) IVAM Environmental Research database on Dutch building materials (based in Amsterdam, the Netherlands); and (d) other sector-specific databases on industry association websites (e.g., Association of Plastic Manufacturers in Europe and European Aluminium Association) (Jolliet et al. 2016).

For North America, the inventory database of Franklin LCI 98 is freely available in software such as SimaPro. However, these data must be used with caution due to certain inconsistencies with other LCI data sets (Jolliet et al. 2016).

The National Renewable Energy Laboratory (NREL) is creating a new North American database (US LCI database). However, this database needs to be verified and compared to other databases as some errors have already been detected, as well as the calling of intermediary flows that do not yet correspond to any existing process. The Digital

Commons LCA of the National Agricultural Library of the United States Department of Agriculture provides a set of free lifecycle life cycle evaluation data and tools. The project makes North American LCA data more accessible to the community of researchers, policy makers, industrial process engineers, and LCA professionals. The North American project providing reliable regional data is currently underway at the Canadian Institute, the International Center for Product Lifecycle, Process and Services Lifecycle (CIRAIG), with the aim of adapting the Ecoinvent under the conditions of North America and produce databases for Quebec (already available), Canada and, finally, North America as a whole.

Databases are also developed for classes of products, such as the World Food LCA Database that provides data for more accurate food and beverages LCAs (Jolliet et al. 2016).

In summary, the compatibility and coherence of a database must be verified prior to usage or combination with other databases.

Since the Ecoinvent database is used by around 4,500 users in more than 40 countries and contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, etc., it has been selected also for carrying out LCA in this thesis work. For this reason, a more detailed description of such database is provided in the next paragraph.

### 1.7.1. Ecoinvent

Ecoinvent is the result of a national effort for many years in Switzerland, which led to a qualitatively leading and (possibly worldwide) outstanding LCI database at present in Europe. The data consider both Switzerland and Europe, which makes them applicable both nationally as well as internationally provided it is put to correct use. The software integrated into the purchasable product also permits the conduct of impact assessments according to different standard methods. Detailed additional information which cannot be found within the freely accessible reports also belongs to the product. The most recent version appeared in 2013 (Walter Koppfler and Grahl 2014).

Inventory data includes a large number of products and services, starting in the year 2000, representing production and supply. In addition to quantitative information on inflows and outflows, additional descriptive (meta-information) information on technologies, temporal and geographic validity is provided.

The database is organized according to the following main categories:

- Energy sources
- Construction materials and processes
- Chemicals
- Detergents
- Paper
- Waste treatment services
- Agricultural products and processes
- Transportation

The Ecoinvent database consists of more than 4000 processes linked by material and energy flows covering more than 400 substances and resources.

Ecoinvent database was initially developed for Western Europe, with national or regional values for certain processes. If available data are provided on a process unit level and they are aggregated only when the drive process data is unavailable or reserved.

Inputs and outflows for production processes are generally provided separately from those in the production infrastructure, allowing the user to choose whether to include some infrastructure.

In the Ecoinvent database, careful attention has been given to the quality of data and their analysis (Jolliet et al. 2016).

# 2. RESULTS AND DISCUSSION

## 2.1. Background to the study

The case study was provided by a leading manufacturer of garden products in Europe and beyond. In this thesis work the name of the company, for reasons of privacy, is not disclosed. Since its establishment, this company has directed its organizational efforts toward achieving and maintaining a high level of quality of its products, together with the need to contribute to environmental protection and the prevention of all forms of pollution.

The company wants to adopt a life cycle perspective to identify environmental aspects and associated environmental impacts, and use this knowledge to create a strategic path moving toward an improvement of the environmental performance of the organization. As a result, the manufacturing has commissioned an exploratory Life Cycle Assessment (LCA) study on its flagship product, a lawn mower, to establish a methodological reference that can be systematically applied to all products and branches of the organization. Besides, the factory wants to strengthen its leadership position over its competitors and be at the forefront of innovation, efficiency and environmental performance of products, and adopt a proactive approach to environmental legislation. Finally, the increasing environmental awareness of company’s stakeholders and the demand for more environmentally innovative products is generating new opportunities that can be assessed and supported by the adoption of LCA.

This LCA study seeks to provide a well-researched representation of the environmental performance of the lawn mower, case study in this thesis work, in terms of environmental and human impacts. However, as with all LCA studies, findings are tempered by a series of limitations, which are believed to have affected the outcomes and increased uncertainties of results. The identified limitations are discussed in paragraph 2.6.

The studied lawn mower (Figure2.1) is a garden tool and precisely a ride-on lawn mower with seated operator. This lawn mower was designed and built to cut grass. The lawn mower is equipped with an engine, which drives a cutting unit protected by a casing, as well as a transmission unit that moves it.

Figure2.1 An example of lawn mower tractor

## 2.2. Goal and Scope of the Study

### 2.2.1. Goal

> The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study, the intended audience (i.e. to whom the results of the study are intended to be communicated) and whether the results are intended to be used in comparative assertions intended to be disclosed to the public.
>
> *ISO 14044:2006 Section 4.2.2*

The main goals of this explorative LCA study was to evaluate the environmental performance (from cradle to grave) of the company's flagship product (i.e. a lawn mower tractor) and to identify environmental "hotspots" and possible opportunities for improvement across its life cycle. This allowed also to satisfy the need of the commissioner to establish a methodological reference systematically applicable to all products and branches of the organization.

The main intended audience of the report was personnel in the factory including top management, Quality and EHS teams, and R&D. In the long run, LCA projects originating from this baseline study can also be used for communication with clients and suppliers to improve environmental communication of the organization.

### 2.2.2. Scope

> The scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied.
>
> *ISO 14044:2006 Section 4.2.3.2*

The life cycle of the lawn mower is central to this study’s scope and therefore it forms the focal point around which the LCA system boundaries are defined.

Aspects related to raw materials, manufacturing, use, maintenance and disposal of the lawn mower and its components are included and central to the scope of this study. The materials and construction/decommissioning processes of plant’s industrial facilities (e.g. machineries for material processing, manufacturing and disposal) are not included in this study. Finally, this study does not consider the infrastructure on which the supply chain relies (e.g. fuel refineries, transport and supply infrastructure, electrical network, etc.). A summary outlining these system boundaries is shown in Table 2.1**Errore. L'origine riferimento non è stata trovata.**.

*Table 2.1 System scope summary.*

| | |
|---|---|
| **Input and output of raw materials in the main processing sequence** | All raw materials needed to produce any part of the lawn mower |
| **Production and use of fuels, gas, electricity** | All production and use of fuels, gas and electricity within the main processing sequence which contributes to the production of any part of lawnmower. |
| **Manufacturing, maintenance** | Applied to any part of the mower |
| **Distribution/Transportation** | All distribution and transportation of materials, energy, wastes, and assembled lawn mower to and from manufacturing sites. |
| **Direct emissions** | All the relevant emissions and waste were included in the scope. |

Figure 2.2 shows a simplified flow diagram illustrating the life cycle of the lawn tractor and the system boundaries defined for the LCA study.

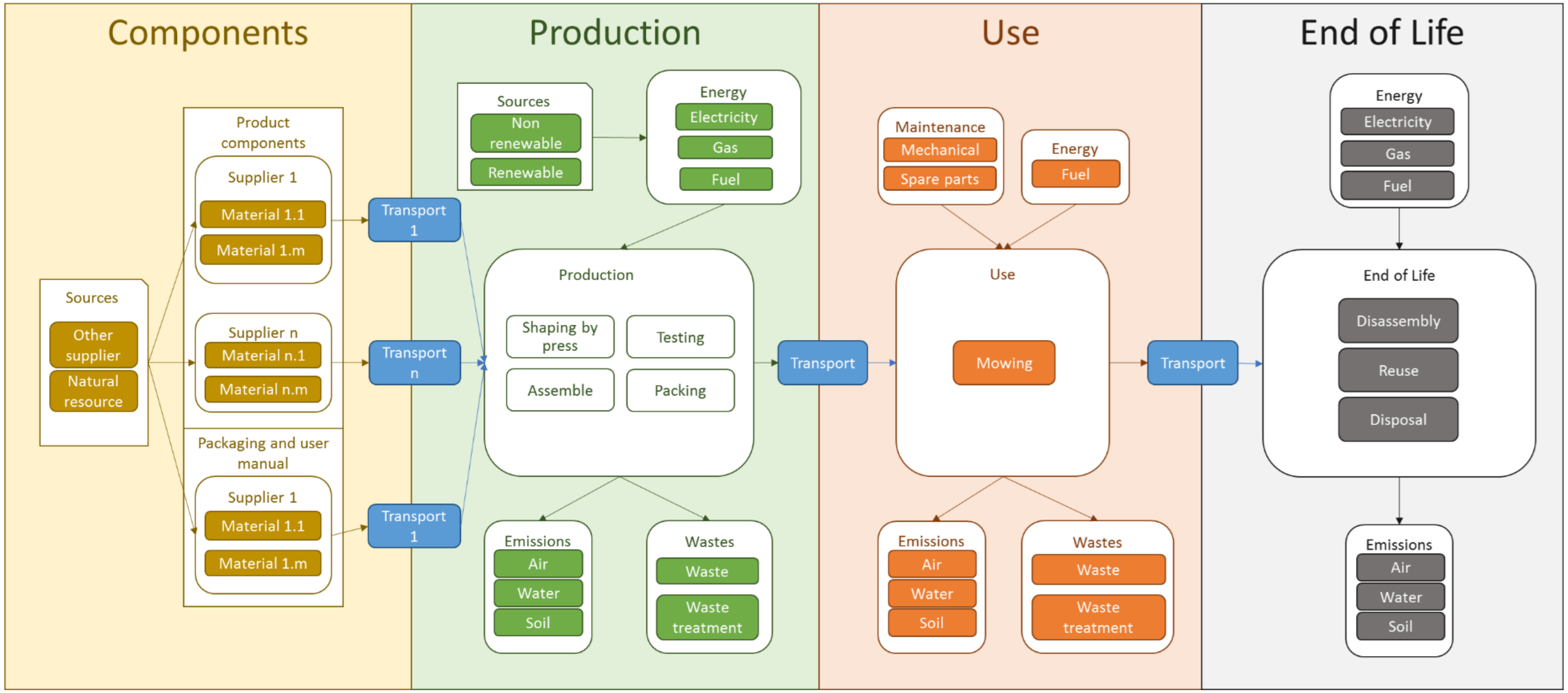

*Figure 2.2 Flow chart of the life cycle of lawn mower*

### 2.2.3. Functional Unit

> One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). Therefore, the functional unit shall be clearly defined and measurable, and consistent with the goal and scope of the study.
>
> *ISO 14044:2006 Section 4.2.3.2*

In this study, the functional unit is the metric through which the environmental performance of the mower is described. The functional unit is based on the life cycle of a lawnmower over its estimated lifetime (500 hours). Mowing 4000 $m^2$ lawn for 10 years was defined as functional unit.

### 2.2.4. Data collection and calculation procedure

In this study, for most raw materials production phase general data were used. For processing phase, data were as far as possible obtained from factory's personal communication and internal documents. Where primary source data were not available, secondary data were used. This study has been undertaken using an "attributional approach" to modeling. As described in the ISO 14040 standard, an attributional LCA uses average data, namely data representing the average environmental burden for producing a unit of the good or service in the system assessment.

### 2.2.5. Impact categories

> The selection of impact categories, category indicators and characterization models shall be both justified and consistent with the goal and scope of the LCA. The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.
>
> *ISO 14044:2006 Section 4.4.2.2.1*

To address the impacts upon the environment, the ReCiPe method has been selected. The primary objective of the ReCiPe method is to transform the long list of Life Cycle Inventory results into a limited number of indicator scores, which are determined at two levels, as shown in Figure 2.3:

- Eighteen midpoint indicators

- Three endpoint indicators

The motivation to calculate the endpoint indicators is that the large number of midpoint indicators are very difficult to interpret, partially as there are too many, partially because they have a very abstract meaning. The indicators at the endpoint level are intended to facilitate easier interpretation, as there are only three, and they have a more understandable meaning. In this study, it was decided to have the result at the endpoint level:

- Damage to Human health (DALY)
- Damage to ecosystems (Species/yr)
- Damage to resource availability (Surplus cost)

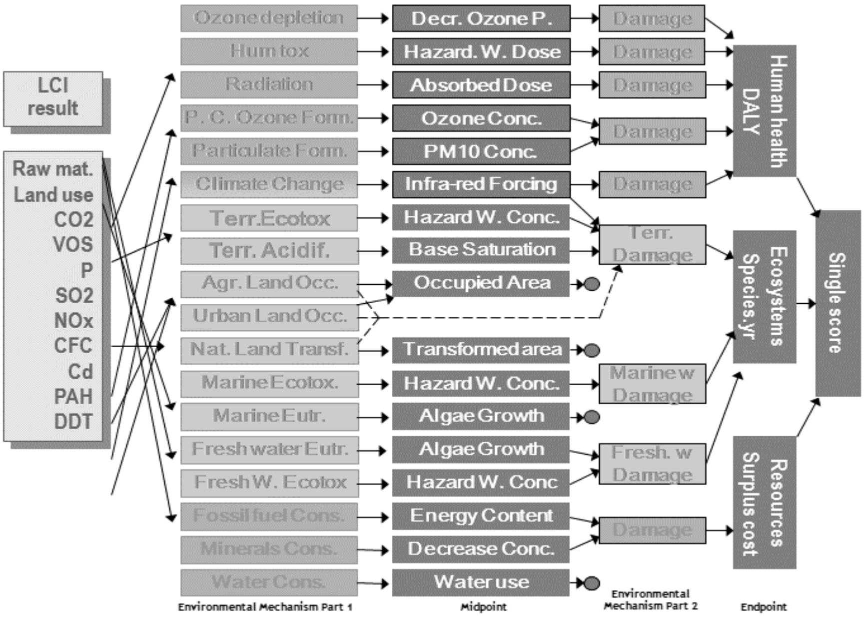

*Figure 2.3 Relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008 (Goedkoop et al. 2012).*

## 2.3. Life Cycle Inventory Analysis

### 2.3.1. The lawn mower system

In the phase of Inventory Analysis for this case study has been used the "process-based approach".

The lawn mower is made up of approximately 1200 parts. The factory doesn’t produce all the parts needed to build the lawn mower, most of them are bought from external suppliers. These pieces are then assembled at factory’s facilities. Nevertheless, some components are subjected to a sequence of working processes. In this study four main production stages, which will be described later in this section, have been defined:

- Stamping discussed at paragraph 2.3.4.1
- Welding discussed at paragraph 2.3.4.2
- Painting discussed at paragraph 2.3.4.3
- Assembling discussed at paragraph 2.3.4.4

### 2.3.2. Raw materials

The constituent parts (semi-finished products) of the mower have been identified by consulting the Bill of Materials (BOM) provided by the company. The semi-finished products listed in the BOM have been used for the estimation of the raw materials included in the lawn mower. It was possible to associate raw materials to almost all the semi-finished products listed in the BOM by consulting the available literature review and technical manuals. For those semi-finished products that could not be associated with raw materials, factory’s experts provided an estimate of those.

Specifically, 27 raw materials were identified. These materials can be grouped into 3 main categories: metals (e.g. steel, copper, iron, aluminum), polymers (e.g. polyamide, polyester, polyethylene) and other materials (e.g. paper, cardboard, wood).

A specific type of material from the Ecoinvent 3.3 database was then associated to each raw material, as listed below in Table 2.2.

*Table 2.2 Relationship between type of material and raw material*

| Raw material | Type of material in Ecoinvent 3.3 |
|---|---|
| **Steel** | Steel, chromium steel 18/8, hot rolled {GLO}\| market for \| Alloc Rec, U |
| **Copper** | Copper {GLO}\| market for \| Alloc Rec, U |
| **Iron** | Iron pellet {GLO}\| market for \| Alloc Rec, U |
| **Zinc** | Zinc {GLO}\| market for \| Alloc Rec, U |
| **Aluminum** | Aluminium alloy, AlLi {GLO}\| market for \| Alloc Rec, U |
| **Cast iron** | Cast iron {GLO}\| market for \| Alloc Rec, U |
| **Lead** | Lead {GLO}\| market for \| Alloc Rec, U |
| **Polyamide** | Glass fibre reinforced plastic, polyamide, injection moulded {GLO}\| market for \| Alloc Rec, U |
| **Polyester** | Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}\| market for \| Alloc Rec, U |
| **Polyethylene** | Polyethylene, linear low density, granulate {GLO}\| market for \| Alloc Rec, U |
| **Polypropylene** | Polypropylene, granulate {GLO}\| market for \| Alloc Rec, U |
| **Polystyrene** | Polystyrene, general purpose {GLO}\| market for \| Alloc Rec, U |
| **Polyurethane** | Polyurethane, flexible foam {GLO}\| market for \| Alloc Rec, U |
| **Polyvinyl Chloride** | Polyvinylchloride, suspension polymerised {GLO}\| market for \| Alloc Rec, U |
| **Rubber** | Synthetic rubber {GLO}\| market for \| Alloc Rec, U |
| **Silicon** | Silicon, electronics grade {GLO}\| market for \| Alloc Rec, U |
| **Fiber** | Glass fibre reinforced plastic, polyamide, injection moulded {GLO}\| market for \| Alloc Rec, U |
| **Fiberglass** | Glass fibre reinforced plastic, polyamide, injection moulded {GLO}\| market for \| Alloc Rec, U |
| **Wax** | Wax, lost-wax casting {GLO}\| market for \| Alloc Rec, U |
| **Cardboard** | Corrugated board box {GLO}\| market for corrugated board box \| Alloc Rec, U |
| **Paper** | Paper, wood containing, lightweight coated {RER}\| market for \| Alloc Rec, U |
| **Paint** | Electrostatic paint {GLO}\| market for \| Alloc Rec, U |
| **Sulfuric Acid** | Sulfuric acid {GLO}\| market for \| Alloc Rec, U |
| **Fuel** | Light fuel oil {RER}\| market group for \| Alloc Rec, U |
| **Lubricant** | Lubricating oil {GLO}\| market for \| Alloc Rec, U |
| **Wood** | EUR-flat pallet {GLO}\| market for \| Alloc Rec, U |

### 2.3.3. Raw materials' allocation strategy

One of the major drawbacks of the present study is the absence of primary data related to the raw materials contained in the semi-finished products and their respective weights.

Base components are defined as components in the BOM without any sub-component. For each base component, an expert of the factory associated one or more raw material with a percentage representing how much of that material is present in the base component. The only well-known weight was the total weight of the lawn mower, 235 Kg. This total weight has been distributed all along the BOM to base components and from those to raw materials. To distribute the weights cost based allocation has been used. The company supplied standard costs for all components, when costs were at base component level it has been divided to raw materials on the basis of their predefined percentages, in the other cases the cost has been first subdivided equally between all subcomponents up to base components before being split by raw material percentage. Once the total cost was subdivided among all base components and weighted for each base component, raw material has been established by applying the ratio between total cost and component cost to the total weight of the lawn mower.

### 2.3.4. Production stages

This section lists and explains in detail the production stages used to describe the manufacturing process of the lawn mower.

A manufacturing process is a procedure that results in physical and/or chemical changes to a starting work material with the intention of increasing the value of that material. Manufacturing operations are usually divided into two basic types:

- **Processing operation:** transforms a work material from one state of completion to a more advanced state that is closer to the final desired product;
- **Assembly operation:** joins two or more components to create a new entity, called an assembly, subassembly, or some other term that refers to the joining process.

In this study, the production of the lawn mower is described by the following four production stages:

- Processing operations:
  - Stamping (STA)

    - Painting (PAI)
- Assembly operations:
    - Welding (WEL)
    - Assembling (ASS)

Each production stage could be further subdivided in more specific processes. However, at this level of assessment it was not considered as necessary. Production stages were simulated using the most similar process already available in the Ecoinvent database – except for the “Assembling” stage, that was created and implemented specifically for this case study.

#### 2.3.4.1. Stamping

Stamping (STA) is applied to shape sheets and bars of metal (e.g. steel) acquired from suppliers. It is the operation process where the starting workpiece (i.e. the sheet/bar of metal) is shaped by the application of forces that exceed the yield strength of the material. Deformation resulting from the use of a tool applying a compressive stress deforms the metal and gives it a shape determined by the geometry of the die. The shaping process adopted to simulate the shaping of the semi-finished products for the lawn mower is known as “deep drawing”. In a deep drawing process, forming and cutting operations are performed on sheets of steel.

To simulate stamping in SimaPro, the EcoInvent 3.3 process “Deep drawing, steel, 3500 kN press, single stroke {RER}| deep drawing, steel, 3500 kN press, single stroke | Alloc Rec, U” was selected. Default mass values for input (except for raw materials) and emissions to environmental media were used, as no primary data were available from the factory.

#### 2.3.4.2. Welding

Welding (WEL) is the manufacturing process used to join two or more parts into an assembled entity material by causing fusion. Welding produces a solid connection between two pieces, called a weld joint. A weld joint is the junction of the edges or surfaces of parts that have been joined by welding. In this LCA study, the fusion-welding process was used as representative process of this production stage. Fusion-welding uses heat to melt the base metals.

To simulate the fusion-welding process in SimaPro the “Welding, arc, steel {RER}| processing | Alloc Rec, U” process was selected from the Ecoinvent 3.3 database. Data indicating the total length of weld joints (cm) are needed. As no information regarding the length of weld joints were available from the company, data were obtained indirectly. It was possible to measure the length of the weld joints of two components listed in the BOM:

- ASS. SUPPORTO PEDALE FRENO TC GRZ;
- ASS. TELAIO INFERIORE SACCO GREZZO TC 20

The factory provided the welding operation time (min.) of each component of the lawn mower undergoing the welding process. The weld lengths (cm) of the two components, first quoted, were then compared with the welding times. In this way, the conversion factors ($CF_{WEL}$, cm $min.^{-1}$), reported in Table 2.3, were calculated. The two $CF_{WEL}$ were then averaged to obtain a single value applicable to each component of the lawn mower undergoing the welding process. The total length of weld joints in one lawn mower was calculated as the sum of weld lengths of each component undergoing the welding process.

*Table 2.3 Conversion factor (CF) calculated to obtain the painted surface for each component of the lawn mower.*

| **Components** | **Length (cm)** | **Welding time (min.)** | **CF (cm $min.^{-1}$)** |
|---|---|---|---|
| **ASS. SUPPORTO PEDALE FRENO TC GRZ** | 4 | 0.5 | 8 |
| **ASS. TELAIO INFERIORE SACCO GREZZO TC 20** | 5 | 0.8 | 6.25 |
| | | **Averaged CF** | 7.125 |

### 2.3.4.3. Painting

Painting (PAI) is one major category of coating operations. It does not only generate the look designed by the manufacturer but also provides protection against corrosion. In this study, powder coating, a type of electrostatic painting, was considered.

To simulate the painting process in SimaPro, the “Painting” process was selected from the Ecoinvent 3.3 database. To simulate the process, data indicating the total painted surface ($m^2$) were needed. As no information regarding the amount of surface undergoing the painting process were available from the factory, data had to be obtained indirectly. The company provided the dimensions of length (m) and width (m) of the lawn mower and the painting time (min.) needed to paint the surface of each component of the lawn mower. No information regarding the size of each component of the lawn mower was available. It was possible to calculate the size of one component listed in the BOM:

- ASS. PIATTO TC 102 10/11 NERO 9005

Its length and width were hypothesized as being respectively ¼ of the total length of the lawn mower, and the maximum width of the lawn mower.

The calculated surface ($m^2$) was then compared with its painting time (min.) and the conversion factor (CF, $m^2$ $min.^{-1}$) was calculated (Table 2.4) and applied to each component of the lawn mower. Assuming that two layers of paint are applied for each component undergoing the painting process, it was possible to obtain the total painted surface of the lawn mower, which equals to 6.32797 $m^2$.

*Table 2.4 Conversion factor (CF) calculated to obtain the painted surface for each component of the mower.*

| | **Surface ($m^2$)** | **n. layers** | **Painted surf. ($m^2$)** | **Painting time (min.)** | **CF ($m^2$ $min.^{-1}$)** |
|---|---|---|---|---|---|
| **ASS. PIATTO TC 102 10/11 NERO 9005** | 0.54054375 | 2 | 1.0810875 | 4.5 | **0.24024** |

The EcoInvent 3.3 “Painting” process was modified by changing the default values of the parameters “Water inputs from nature” and “$CO_2$ emissions to air” with primary data provided by the company, as indicated in Table 2.5.

*Table 2.5 Modified parameters in the “Painting” process.*

| **Parameter** | **Value** |
|---|---|
| **Water input from nature (resource)** | 0.000660292 $m^3$ $m^{-2}_{Painted\_Surface}$ |
| **$CO_2$ emissions to air** | 0.504199075 kg $m^{-2}_{Painted\_Surface}$ |

### 2.3.4.4. *Assembling*

The assembling stage (ASS) describes the mechanical assembling processes necessary to assembly the lawn mower. In this study, the process of mechanical fastening was selected as representative of all mechanical assembly operations. Mechanical fastening involves the use of discrete hardware components, called fasteners, that are added to the parts during the assembly operation. Fasteners are discrete hardware components that have external or internal threads for assembly of parts. The most common fastener types are screws, bolts, and nuts.

Assembling consists in the final production stage of the lawn mower. Here, all the semi-finished products are assembled together to originate the final product. The process implemented in SimaPro was created specifically for this LCA study and does not rely on any existing process present in the Ecoinvent 3.3 database. The material-input is equivalent to the sum of material-output from the other processes (STA, PAI, WEL). No emissions to the environment are associated to this production stage.

### 2.3.5. Energy demand

This section describes the modelling of the electricity and gas consumed during the production stages of the machine. The factory monitors the monthly consumption of electricity and gas at each production site. In this study, the production sites were considered as a single production site. Data for departments and production stages were not available and had to be obtained indirectly, as explained in detail in this section of the report.

#### 2.3.5.1. *Electricity*

Electricity production in a country relies on different energy sources. In this study, the "Rest of Europe, medium voltage - RER" electricity mix was selected from the Ecoinvent 3.3 database. Machine manuals and power tests were used to obtain the electricity consumptions values (kWh $yr.^{-1}$) and were then compared with the machines' operational times to obtain an estimate of energy consumption associated to the annual production at the site. This value was then compared with the weight of the annual production to calculate the conversion factor needed to estimate the energy consumption associated to a single unit.

#### 2.3.5.2. *Natural gas*

Natural gas consumption (scm $yr.^{-1}$), essentially made up of methane ($CH_4$: 50 $g_{CO2}$ $MJ_{eq\text{-}gas}^{-1}$), was also considered in the balance of energy consumption. The "high pressure" network profile was selected, as representative of industrial processes.

#### 2.3.5.3. *Emissions*

This section describes the modelling of emissions to air, water and soil during the production stages of the machine that we studied. All available emissions were provided by the factory.

The company adopts all the necessary precautionary measures to prevent spilling on its production sites. Moreover, manufacturing operations are not likely to generate direct emissions to soil. Accordingly, soil emissions were not modeled in the study. In the manufacturing stage of the machine, water is only used in the painting process (PAI).

The plant adopts a closed-loop water system that avoids direct emissions to natural waters. Consequently, water emissions were not modeled in this study.

Air emissions were calculated for the Painting process (PAI), the only process that makes direct use of natural gas.

### 2.3.6. Transportation

This section analyzes the transport processes by including both the supply of components to the company producing the lawn mower and the distribution of the final product to the clients.

#### 2.3.6.1. *Supplying*

The lawn mower components are supplied from different countries and with different means of transport. Supplying simulation is based on data provided by the company. To simulate the supplying system, two assumptions had to be made. First, only first tier suppliers were considered, while transport of raw materials to production sites default data from the Ecoinvent 3.3 database have been used. Second, the environmental impact of construction of vehicles, roads, or other infrastructure was neglected. Suppliers are located worldwide and are not exclusive for each component, implying that more suppliers can provide the same component.

Moreover, different means of transport are used to ship components to the manufacturing sites, depending on the location of the supplier. The factory provided data for each component relative to the number of shipments and the distance covered in each trip (km). As the same component can be shipped from different location, distances were averaged to obtain an average distance for each component. Afterwards, distances were attributed to each raw material based on the percent composition previously calculated. Thanks to data provided by the company it was possible to implement detailed transport data for each specific origin. For some components, information regarding distance and mode of transport was not available. The shipping of these components was not taken into account as the study was performed considering raw materials, and their distance is mediated by the distances of the other components.

#### 2.3.6.2. *Distribution*

The lawn mower is sold worldwide both at factory’s points of sale and authorized dealers. In this study, this distinction is neglected as the only required data was the distance (km) between the manufacturing site and the sale point. Lawn mowers are distributed using different types of transport: wheels, rail or ship.

A representative means of transport selected from the Ecoinvent 3.3 database has been associated to each type of transport as follows:

- Transport on wheel: Lorry greater than 32 class euro 5.
- Rail transport: freight train using diesel and electricity.
- Ship transport (within Europe): inland waterways barge for continental travel
- Ship transport (rest of the world): transoceanic ship intended for conveying oceanic transport.

The company sends lawn mowers in several European and non-European countries. For each country, the total number of kilometers travelled by each used mean of transport has been calculated. As the unit of measure for transport in Ecoinvent 3.3 is weight by kilometer, distances have been multiplied by the weight of a lawn mower. The obtained value has then been normalized to reflect the transport of a single lawn mower - instead of one mower for each journey - by dividing it by the number of journeys in a year.

### 2.3.7. Use and maintenance

According to data supplied by the factory, the life span of the lawn mower is expected to be ten years. The company indicate a mowing area up to 6500 $m^2$ $hour^{-1}$ and an average mowing area of 4000 $m^2$. In the ten years of life of the lawn mower the company expects, after a certain time interval, a series of maintenance operations of the various mechanical components.

Replacing the battery is provided after 5 years. Accordingly, two battery replacements are expected within the life time of the lawn mower. The same applies both for the replacement of blades belts as well as transmission belts. Blades should be replaced every two years for a total of ten blades within 10 years of usage. Cartridge and fuel filters needs replacement each year for a total amount of ten filters, of all types, in ten years. Two Spark plugs must be replaced every year for a total of twenty spark plugs in ten years.

The consumption of fuel amounts to 3.24 liters per hour assuming a 50% of load. Every year a full of oil replacement is required by 1.9 liters of oil plus lubrification between 27-30 g $yr.^{-1}$. These two values have been averaged at 28.5 g $yr.^{-1}$.

### 2.3.8. End of Life and Waste management

At the end of its life cycle the lawn mower is dismantled and the various parts are subjected to further processing on the basis of their composition. No reuse of any component is expected.

A waste type has been associated to each raw material from the Ecoinvent database. Subsequently, on the basis of information obtained from literature (ISPRA 2016), percentages indicating how much of each specific waste is sent to the identified possible treatments were used. Three types of treatments have been considered: recycling, incineration, and landfill.

In addition to waste materials directly related to the end of life of the lawn mower, waste materials generated during production have also been accounted. The company has provided general data relating to all waste products in each production line. These quantities of waste are related to the total production of the factory. To calculate the weight of the generated waste to the production of a single lawn mower, the total weight has been compared to the weight of the plant’s total production. The obtained conversion factor was then applied to the weight of the lawn mower.

Waste has also been associated to the four production stages. Some weights were already directly related to specific processes, while for others allocation based on working time has been applied. Again, a waste type has been associated to each waste by joining each supplied CER (European waste code) to the corresponding waste process in SimaPro. Subsequently, as for the materials that constitute the lawn mower, each waste type has been associated to the different types of treatment.

## 2.4. Impact Assessment

In this paragraph, the Life Cycle Impact Assessment (LCIA) resulting from the production of 1 lawn mower is presented. Unlike the Life Cycle Inventory, which only reports sums for individual emissions, the LCIA includes methodologies for weighting and combining different emissions into a single metric. The applied LCIA method is ReCiPe as described in 2.2.5 - Impact categories.

Recipe Hierarchist with European normalization (i.e. assumptions are based on the most common policy principles with regards to time-frame and other issues, while normalization values are based on the average European citizen) has been applied both at Midpoint and Endpoint level. Midpoint results are more robust as less calculation steps and precise characterization factors are involved in their assessment, nevertheless their interpretation is complex; on the other hand, Endpoint results are less robust as damage conversion involves big approximations but results are understandable also by a layman. In both cases Normalization has been applied in order to compare results of different indicators which are otherwise relative to the specific impact. The Endpoint assessment also applies weighting and single score aggregation which allows to compare the different damages as well as the different life cycle stages on the same scale.

### 2.4.1. Endpoint results

Endpoint results provide an overview of damages generated by impacts caused by the different Life Cycle Stages (LCS) considered in the production of the lawn mower. Figure 2.4 displays the network diagram of the whole LCA study, where line thickness represents relative contribution to impacts from the different processes. In the graph, Production waste, Distribution and End of life stages are not included because their values were too small (i.e. below 1%) to be represented by the SimaPro software.

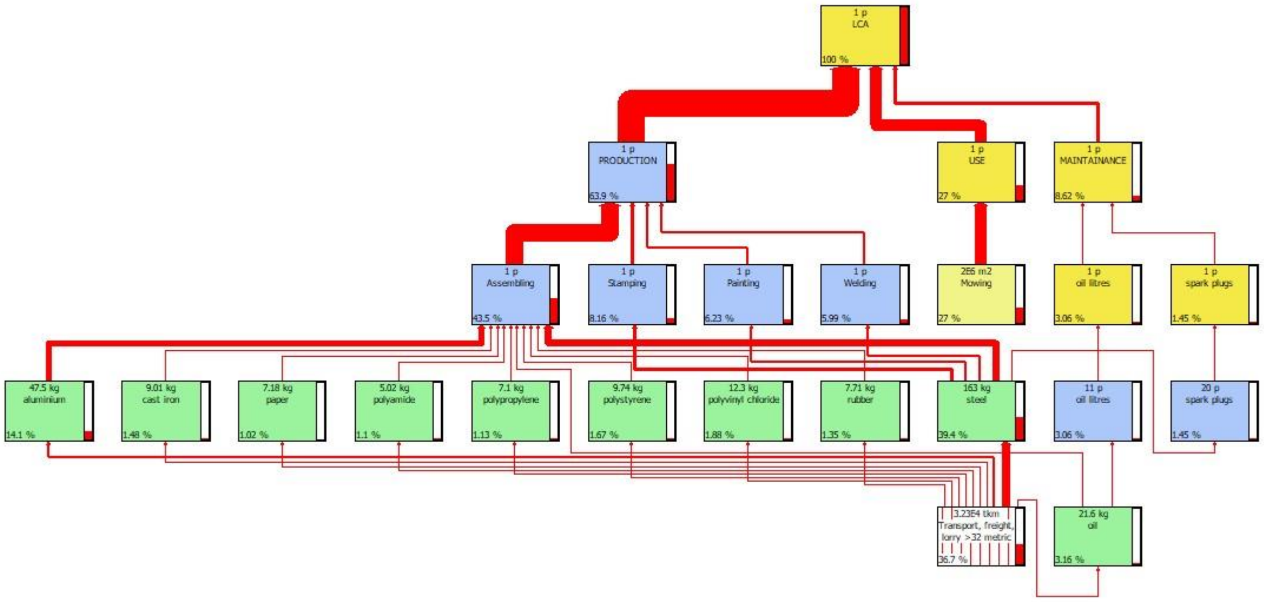

*Figure 2.4 Endpoint single score network diagram. Thickness of arrows is directly related to percentage of impact for the different processes included in the system named LCA (box on top)*

Production is the most impacting stage with around 64% of total damage followed by Use and Maintenance. In the following paragraphs, for each product's process the different LCSs will be assessed separately in order to identify the causes of the depicted damage level. Figure 2.5 depicts damage percentage levels by LCSs while Figure 2.6 shows that the most endangered categories are Human Health and Resources which both account for around 40% impact each.

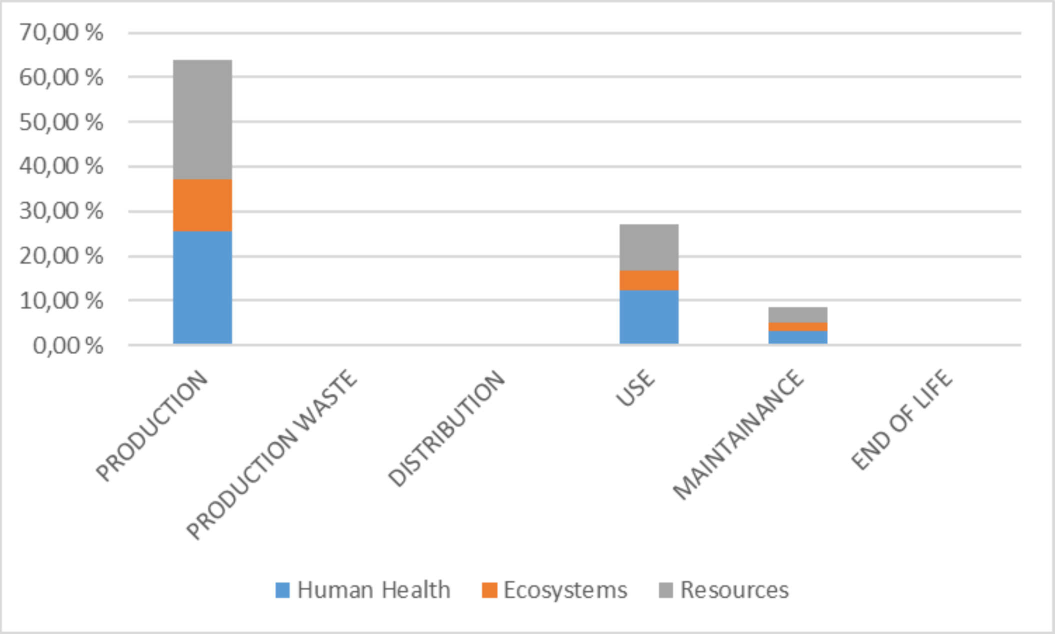

*Figure 2.5 Endpoint results, damages by phases.*

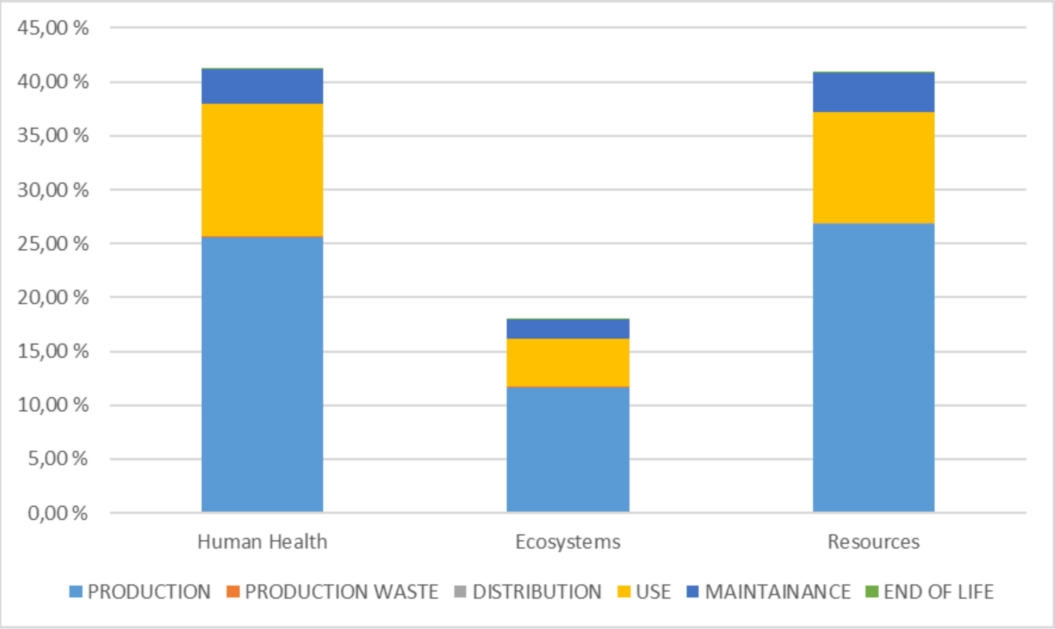

*Figure 2.6 Endpoint results, phases by damage.*

### 2.4.2. Midpoint results

Midpoint results are more precise than Endpoint results as less aggregations took place. As anticipated by Endpoint results, Production and Use stages are the most impacting for most of the categories, exceptions are Freshwater eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Agricultural land occupation, Urban land occupation, Metal depletion where Maintenance surpasses Use. Freshwater eutrophication and Marine eutrophication categories are the only categories where End of Life stage appears to have a noticeable impact as clearly visible in Figure 2.7. Figure 2.7 represents Midpoint characterization results normalized to 100%. Characterization results are obtained by aggregating impacts from processes on the inventory related to each category multiplied by the corresponding characterization factor as defined by the Recipe method. Characterization results are not comparable as each is in a different unit of measure, for this reason Figure 2.7 columns have all been normalized to 100% and should not be compared each other, only relative contributions inside each column are meaningful.

Figure 2.8 portrays normalized characterization results. Normalization shows to what extent an impact category indicator result has a relatively high or a relatively low value compared to a reference. The Recipe recommended reference has been utilized which is average annual impact of a European citizen. Normalized results show a predominance in impacts to Freshwater ecotoxicity, Marine ecotoxicity and Natural land transformation.

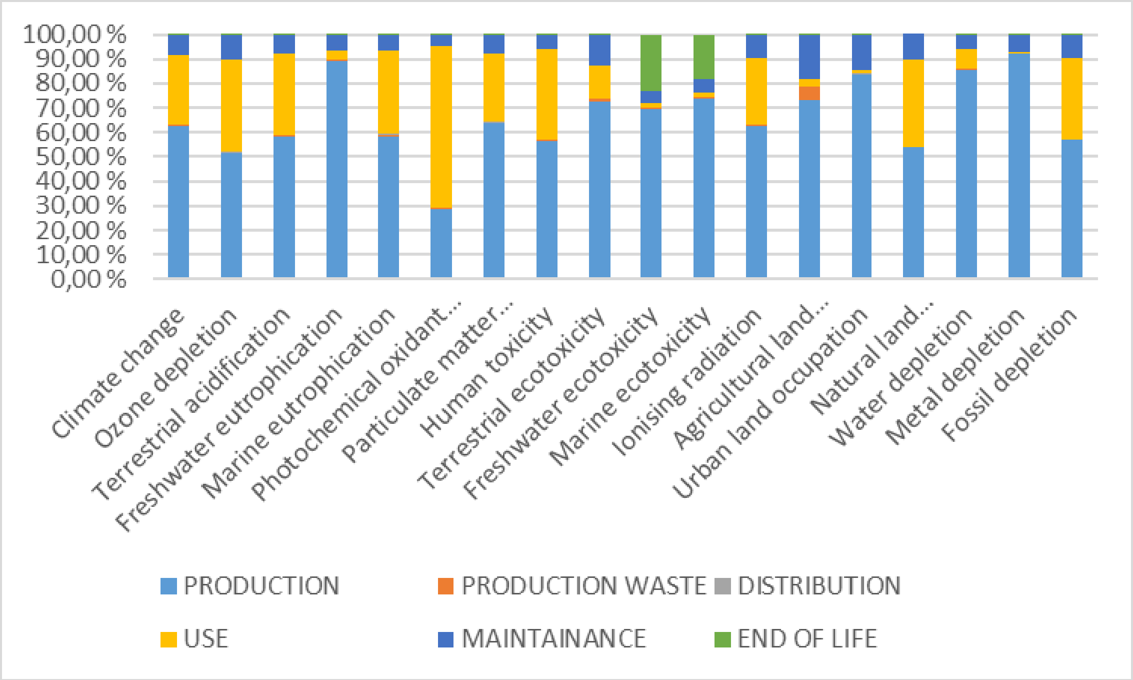

*Figure 2.7 Midpoint characterization results.*

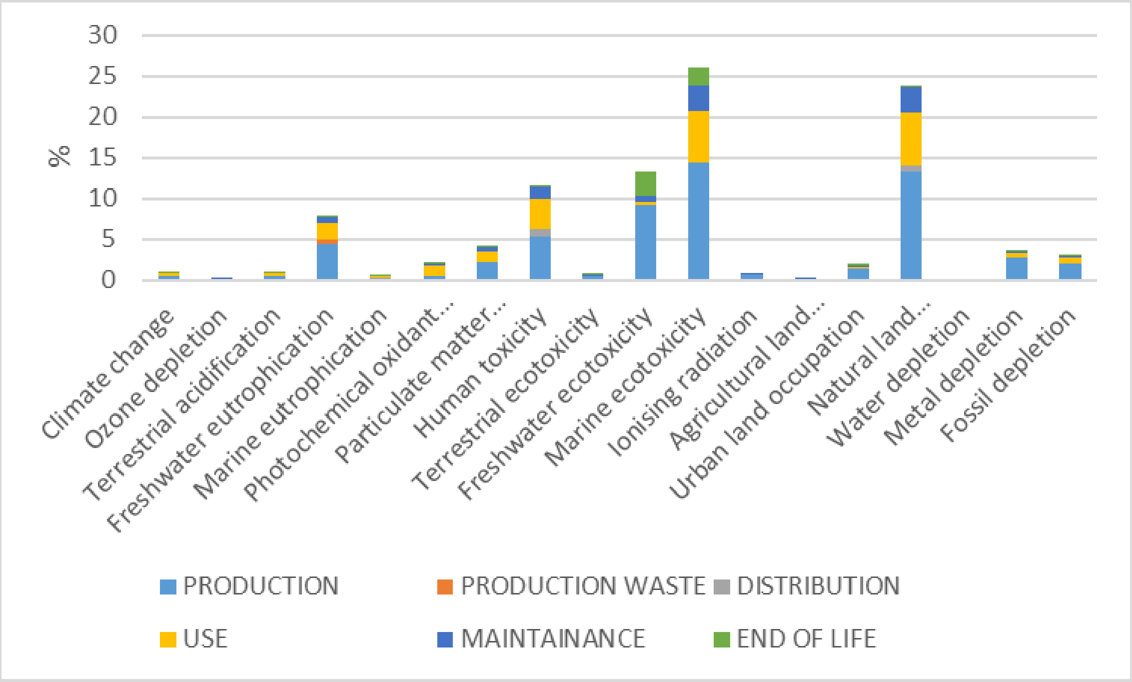

*Figure 2.8 Midpoint Normalization results*

Below results from each assessed Impact Category are presented.

All the midpoints, except one, are mainly driven by raw materials production and use. Aluminum and steel are the most impacting materials among all. This is due to their large use and their substantial impacts for extraction and first manufacture.

The exception is represented by the Photochemical oxidant formation midpoint where the main driver of impact is use because of the $CO_2$ emissions related to the petrol-powered engine of the lawn mower.

For the climate change, the midpoint characterization factor selected is the widely used global warming potential (GWP), which quantifies the integrated infrared radiative forcing increase of a greenhouse gas (GHG), expressed in kg $CO_2$-eq (Intergovernmental Panel on Climate Change 2014; Joos et al. 2013). The "Midpoint Climate Change Network Chart" is reported in Figure 2.9, as an example of detailed midpoint results. Figure 2.10 repeats the same data as in the previous figure in an easier and more immediate apparel to understand.

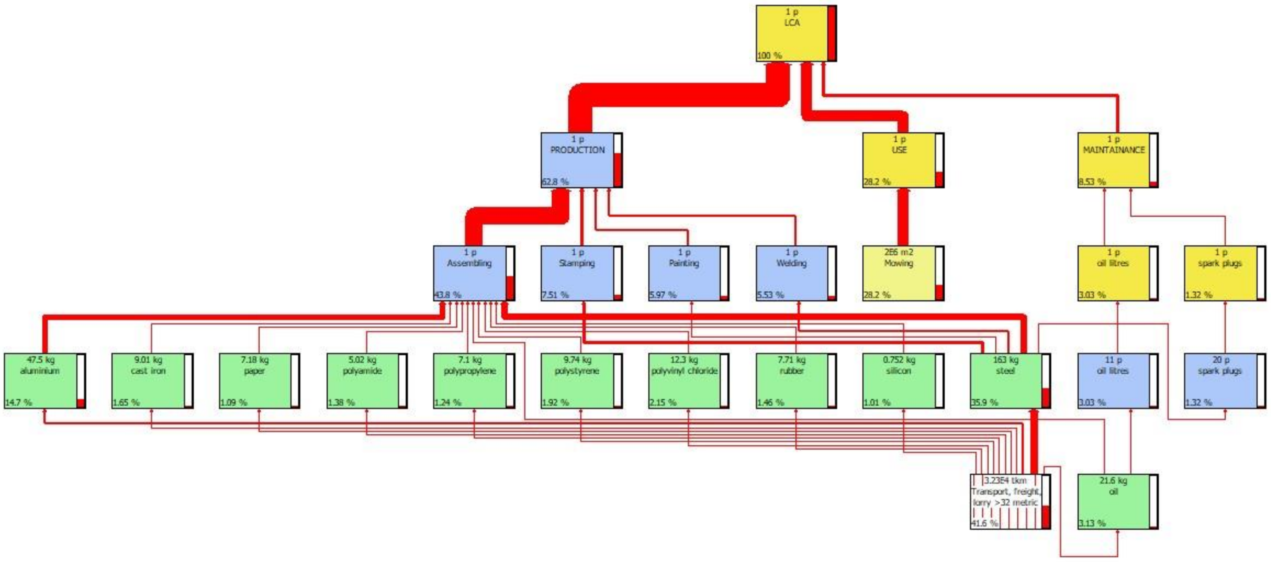

*Figure 2.9 Midpoint Climate Change Network Chart.*

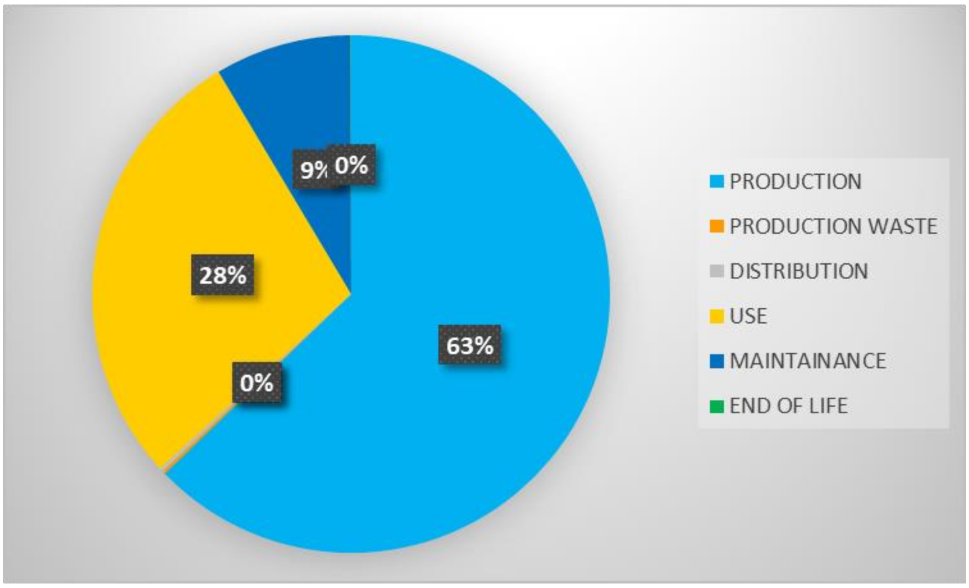

*Figure 2.10 Climate change impact category results.*

The ozone depleting potential (ODP), expressed in kg CFC-11 equivalents, was used as characterization factor on the midpoint level. ODPs refer to a time-integrated decrease in stratospheric ozone concentration over an infinite time horizon (US Department of Commerce n.d.).

For the midpoint characterization factors of acidifying emissions, the fate of a pollutant in the atmosphere and the soil as calculated by (Roy et al. 2014) were taken. Acidification potentials (AP) are expressed in kg $SO_2$-equivalents. Changes in acid deposition, following changes in air emission of $NO_x$, $NH_3$ and $SO_2$, were calculated with the GEOS-Chem model (Roy, Huijbregts, et al. 2012). Subsequently, the change in acidity in the soil due to a change in acid deposition was derived with the geochemical steady-state model PROFILE (Roy, Deschênes, and Margni 2012).

The fate of phosphorus forms the basis of the midpoint characterization factors for freshwater eutrophication. Freshwater eutrophication potentials (FEP) are expressed in kg P to freshwater-equivalents. Global fate factors for phosphorus emissions to freshwater were taken from (Helmes et al. 2012).

For the midpoint characterization factors of photochemical ozone formation related to human exposure, the human population intake of ozone was considered. Human health ozone formation potential (HOFP) is expressed in kg $NO_x$-eq. The change in ambient concentration of ozone after the emission of a precursor (nitrogen oxides ($NO_x$) or non-methane volatile organic compounds (NMVOC)) was predicted with the emission—concentration sensitivities matrices for emitted precursors from the global source-receptor model TM5-FASST (van Zelm et al. 2016).

For the midpoint characterization factors of fine particulate matter formation, the human population intake of $PM_{2.5}$ was considered. Particulate matter formation potentials (PMFP) are expressed in kg primary $PM_{2.5}$-equivalents. The change in ambient concentration of $PM_{2.5}$ after the emission of a precursor, i.e. $NH_3$, $NO_x$, $SO_2$ and primary $PM_{2.5}$, was predicted with the emission-concentration sensitivities matrices for emitted precursors from the global source-receptor model TM5-FASST (van Zelm et al. 2016).

The fate and effects of chemical emissions expressed in kg 1,4-dichlorobenzene-equivalents (1,4DCB-eq) was used as characterization factor at the midpoint level for human toxicity, freshwater ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity. It is used the global multimedia fate, exposure and effects model USES-LCA 2.0, the Uniform System for the Evaluation of Substances adapted for LCA (van Zelm, Huijbregts, and van de Meent 2009), as a basis for our calculations, updated to deal with dissociating chemicals (van Zelm et al. 2013) and using the chemical data from the USEtox database (Rosenbaum et al. 2008). The ecotoxicological effect factor represents the change in PDF of species due to a change in the environmental concentration of a chemical. The human-toxicological effect factors were derived for carcinogenic and non-carcinogenic effects separately, reflecting the change in lifetime disease incidence due to a change in intake of the substance.

The ionizing radiation potential (IRP), is reported in Cobalt-60 eq to air. The collective dose resulting from the emission of a radionuclide is the point where the characterization factor at midpoint level was derived.

The characterization factors of midpoints of agricultural land occupation, urban land occupation and natural land transformation (in $m^2 \cdot yr$ annual crop equivalents) refer to the relative species loss caused by a specific land use type (annual crops, permanent crops, mosaic agriculture, forestry, urban land, pasture). Relative species loss was determined by comparing field data on local species richness in specific types of natural and human-made land covers (de Baan, Alkemade, and Koellner 2013) and (Elshout et al. 2014). For land conversion, passive recovery towards a (semi-) natural, old growth habitat was assumed, based on average recovery times from (Curran et al. 2014).

The characterization factor at midpoint level for the water depletion midpoint is $m^3$ of water consumed per $m^3$ of water extracted. For agriculture, the consumptive part of the withdrawal was estimated with water requirement ratios based on (Döll et al. 2002). For industry and domestic water use, assumptions were made based on (Hoekstra et al. 2012).

The midpoint characterization factor for mineral resource scarcity is Surplus Ore Potential (SOP), expressed as kg Cu-eq. The primary extraction of a mineral resource will lead to an overall decrease in ore grade, meaning the concentration of that resource in ores worldwide, which in turn will increase the amount of ore produced per kilogram of mineral resource extracted. The SOP expresses the average extra amount of ore produced in the future caused by the extraction of a mineral resource considering all future production of that mineral resource (Vieira et al. 2017).

The midpoint indicator for fossil resource use, determined as the Fossil Fuel Potential (FFP in kg oil-eq), is defined as the ratio between the higher heating value of a fossil resource and the energy content of crude oil (Hischier et al. 2010).

### 2.4.3. Processes contributions

By assessing single score Endpoint results it is possible to dig into causes of impacts at a general level and examine which stages contributed more in the overall generated impact and which processes caused much impairments. Results are summarised in Figure 2.11 where relative contributions to the overall LCA assessment from the different LCSs is presented. Figure 2.11 shows that production, use and maintenance are the more impacting LCSs with production weighting more than half of the total.

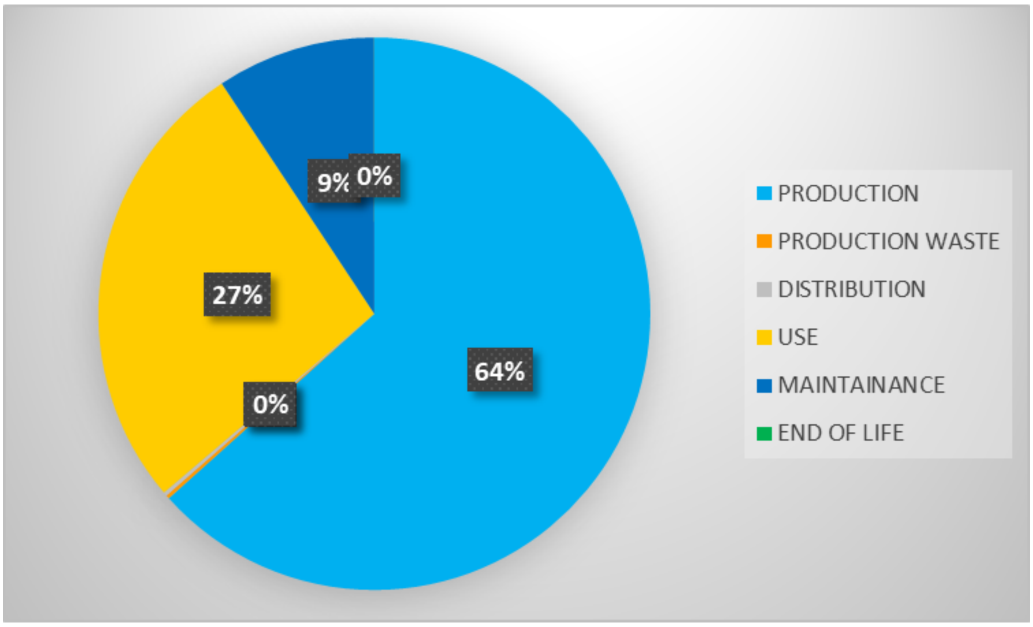

*Figure 2.11 Contributions to overall LCA calculated impacts from the different LCSs.*

In the following sections, results from each of the assessed LCSs are presented in order to understand the causes of their impact level.

#### 2.4.3.1. Production

The production Life Cycle Stage (Figure 2.12) contains impacts related to the whole initial stages of the lawn mower production. This includes raw materials extraction, transport to manufacturing site, manufacturing info components and supply to the factory.

Inside the production LCS the two processes with highest impact are assembling and stamping as suggest by the thickness of their two lines. In both cases processes are detrimental due to the high quantity of material processed and therefore due to raw material manufacturing.

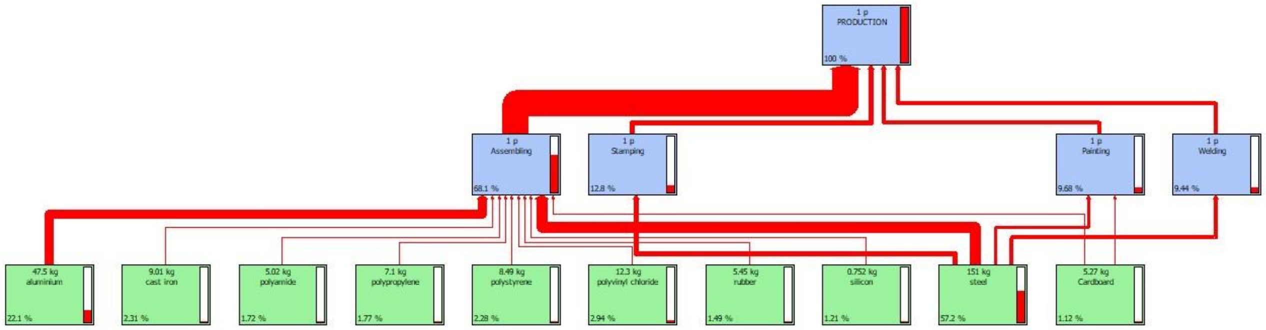

*Figure 2.12 Production LCS network chart.*

#### 2.4.3.2. Use

The use Life Cycle Stage (Figure 2.13) contains impacts related to the use of the lawn mower all along its life cycle (10 years). Impact produced by the use phase are all pertaining emissions related to combustion of petrol inside the engine.

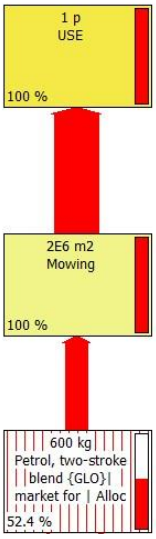

*Figure 2.13 Use LCS processes contribution.*

#### 2.4.3.3. Maintenance

The maintenance Life Cycle Stage (Figure 2.14**Errore. L'origine riferimento non è stata trovata.**) contains impacts related to the components and consumables which are necessary throughout the whole life of the lawn mower.

Inside the maintenance LCS the two processes with highest impact are oil liters and spark plugs. In both cases processes are detrimental due to the high quantity of material processed and therefore due to raw material extraction and manufacturing.

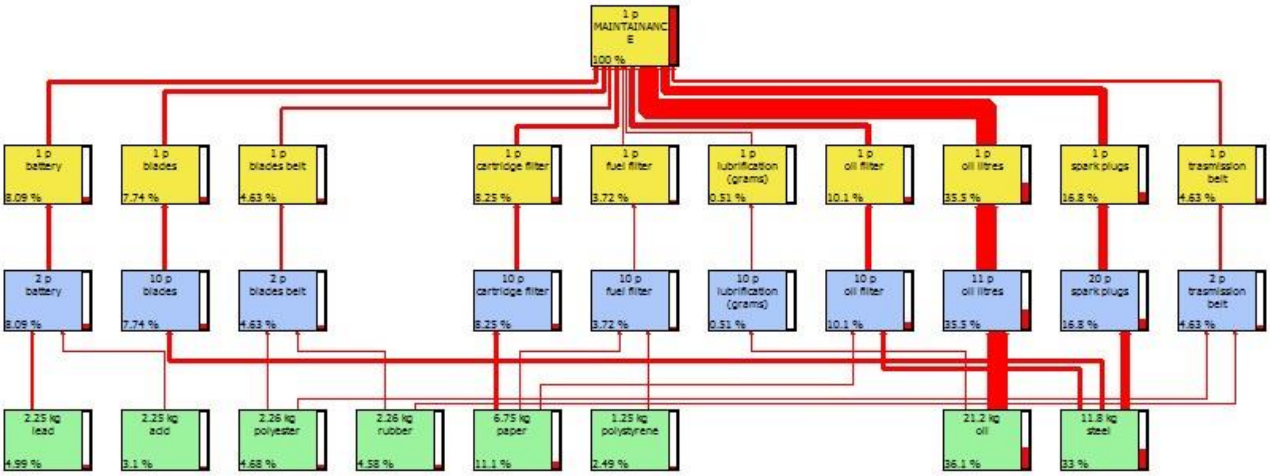

*Figure 2.14 Maintenance LCS processes contribution.*

#### 2.4.3.4. Distribution

The distribution Life Cycle Stage (Figure 2.15) contains impacts related to the distribution of the lawn mower to the different resellers around Europe. Three means of transport are used by the company: Road, Rail and Sea.

Inside the distribution LCS the destinations with highest impact are Poland, Czech Republic and Germany. In all three cases processes are detrimental due to the presence of Road transport only and the high number of trips per year.

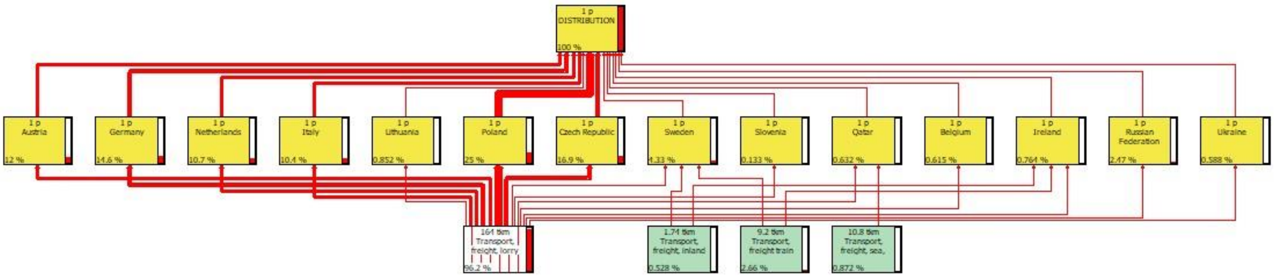

*Figure 2.15 Distribution LCS processes contribution.*

#### 2.4.3.5. Production waste

The production waste Life Cycle Stage (Figure 2.16) contains impacts related to the waste generated from the factory which can be apportioned to the production of the lawn mower.

Inside the production waste LCS different materials are expected to follow different treatments, the treatment with most material flow is recycling followed by incineration and landfill.

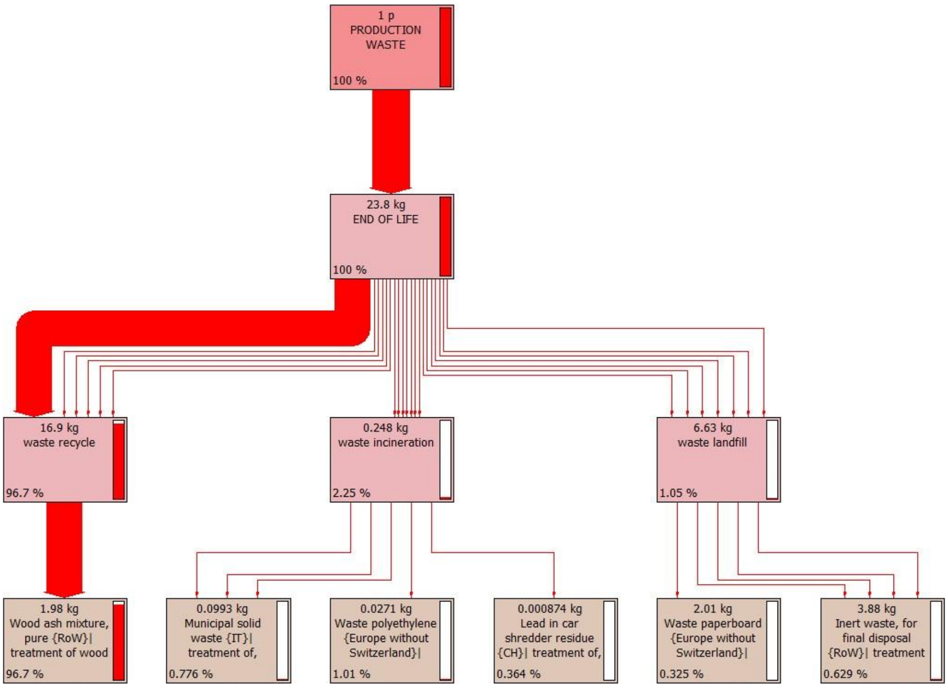

*Figure 2.16 Production waste LCS processes contribution.*

#### 2.4.3.6. *End of Life*

The End-of-life Life Cycle Stage (Figure 2.17) contains impacts related to the waste generated from the disposal of the lawn mower.

Inside the End-of-life LCS different materials are expected to follow different treatments, the treatment with most material flow is incineration followed by recycling and landfill.

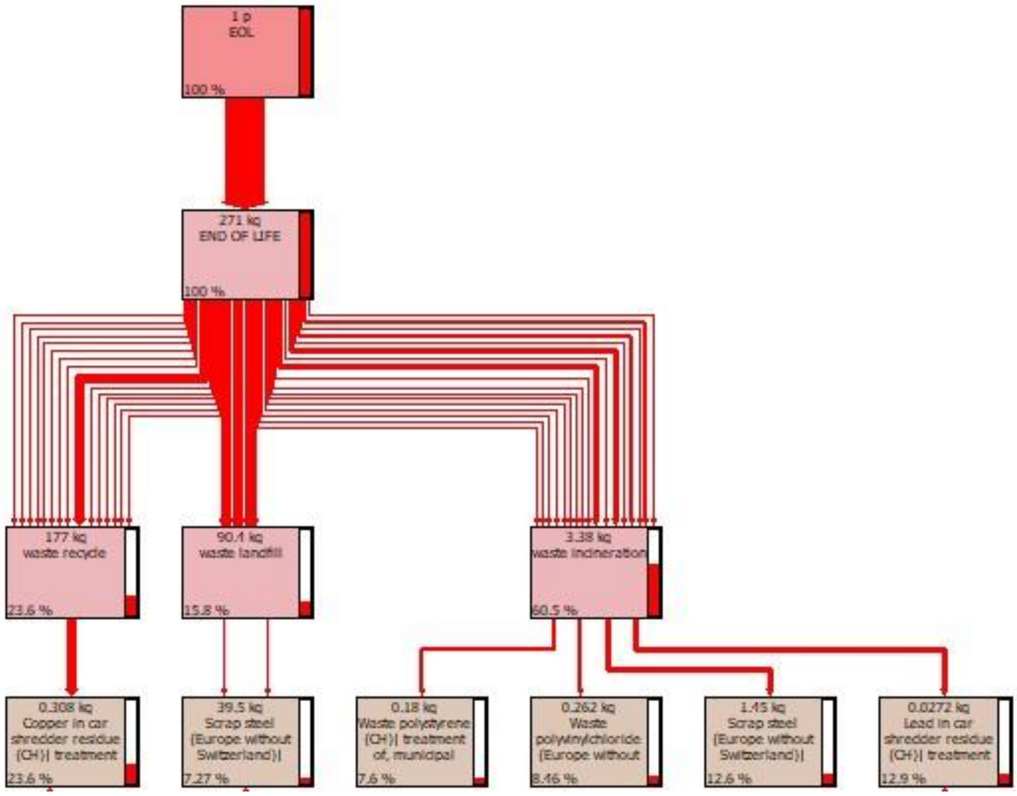

*Figure 2.17 Production waste LCS processes contribution.*

### 2.5. Interpretation of results

LCIA results have been produced with the Recipe method (Goedkoop et al. 2012) both at Midpoint and Endpoint level. General considerations can only be summarized from Endpoint level results which allow for a single score result considering the aggregation of the different impact categories assessed at Midpoint level.

As expected in studies concerning production sites mainly related to assembling processes, Endpoint results expressed the predominance of Raw material production related impacts. Extraction, transport, manufacturing, supply of raw materials alongside the mower production have a 64% of contribution on the total impacts, where direct impacts of production from the factory account for something around 2%.

Use and maintenance account for the 36% of total impact where use alone is about 27%. This is due to the high impact of the petrol based engine of the lawn mower and the needed amount of oil for its working life of 10 years.

Distribution and waste treatment LCSs have a total impact below 1%. Reductions in distribution impacts could be lowered by moving transport carriers from roadways to railways or waterways while waste treatment can be positively impacted by reducing the amount of non-recyclable materials. Nevertheless, those changes would not impact significantly Endpoint results.

Figure 2.18 displays the relative amount of impacts related to the different life cycle stages assessed as discussed in the previous sentences.

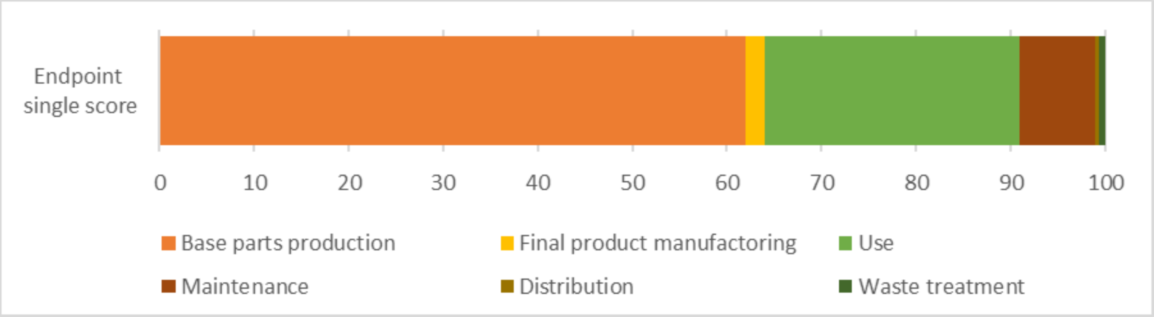

*Figure 2.18 Endpoint single score results percentage of impact from the different life cycle stages.*

Sensitivity and Uncertainty analysis were not performed in this study as considered unnecessary due to the screening level of assessment applied and the lack of primary data on materials and consumptions. The kind of results which could be obtained from Sensitivity and Uncertainty could be useful in scenario comparisons or to understand which information quality should be improved more.

### 2.6. Limitations of the LCA study

Being a screening LCA, this study is characterized by some limitations and major assumptions.

One of the main limitation is due to the lack of information about raw materials weights and base components composition. Base components' composition has been obtained by expert judgment from the company while raw materials' weights has been obtained by allocation from the lawn mower total weight based on components' supply costs. Where costs were supplied at no base component level, the original cost has been equally split among all base components.

Moreover, involved processes' consumptions were in general not directly measured, the only exception being the water used for Painting. As far as energy (i.e. electricity and gas), data were supplied at company level and was allocated by multiplying measured consumptions from a previous study by the hours of use for each process, rescaling to the total amount for the period of interest and calculating the impact from a single lawn mower by using the weight ratio of one lawn mower versus the total factory production.

In addition, $CO_2$ emissions related to Painting were obtained by applying stoichiometric ratio to natural gas consumption as measured by the supplier.

Finally, production waste was only known at factory level; specific types of waste were associated to specific processes while others were general wastes. Allocation of waste weight to specific processes has been performed by using working time of the production lines while allocation to a single lawn mower were obtained by weight ratio of one lawn mower versus the total factory production as previously done for energy.

# 3. CONCLUSIONS

The general objective of this thesis work was to highlight and discuss strengths and limitations of the LCA procedure. To pursue this objective, LCA was applied to a specific case study i.e. a lawn mower. Other specific objectives were: to assess the environmental performance of this product, to identify environmental “hotspots” and possible opportunities for the product’s improvement as well as to provide the company with a methodological reference, systematically applicable to all products and branches of the organization.

LCA was performed from the cradle to the grave in order to account for all impacts related to the production of the lawn mower. Obtained results pointed out that the environmental impacts of the lawn mower are not directly related to factory’s production but rather mostly pertained to raw materials extraction, base components manufacturing and supply. This could be expected from the assessment of a production site mainly related to assembling and confirms that the company follows already good production practices. However, while on one hand the company could try to evaluate whether the pre-production phase could be improved (e.g. by reducing the travel distance of supplied base components), on the other hand it would be worth to perform a detailed gate-to-gate assessment in order to identify which of the impacts directly influenced by the company are the most detrimental and should be reduced. This proposal has been presented to the company and is currently under discussion, while the possibility to apply LCA to other products, by using this thesis work as methodological reference, has been postponed to next year.

Regarding the general objective of this thesis work, it is known that when an LCA is conducted, many practical and conceptual limitations could be found. First, on the basis of the level of detail and the availability of data required, an LCA may take a long time, especially during the data collection phase. In agreement with what is reported in the literature, even in this thesis work most of the time was spent to find and catalog all the information necessary for carrying out the analysis.

Second, often, especially if the rules of good practice do not apply, it is possible that the results are influenced by many subjective factors like: people conducting the LCA, the choice of assumptions or the method of assessing the impact. The fact that this subjectivity exists might question the reliability and quality of the information obtained, and therefore the results obtained could lose value. Therefore, it is necessary to adopt a critical approach and scrutinize both hypotheses and their consequences on the results of the study (Jolliet et al. 2016). Even in this thesis work, in view of the complexity of some data, such as the composition of certain components, it was necessary to make assumptions. This has led to the results that imply a certain degree of subjectivity, due to the operator who has conducted the study. However, to limit this subjectivity a common logic was used, throughout the course of the study, to carry out any assumption.

As third element, particular attention must be paid to interpretation and communication of results. In this thesis work, in fact, the results were presented in a clear way, providing percentages and graphs of easy and clear reading.

Fourth, for some substances in certain categories of impact, such as toxicity, the results only indicate orders of magnitude; these uncertainties should be considered during the interpretation, for example, by examining and presenting results on a logarithmic scale (Jolliet et al. 2016). However, in this thesis work, this limitation does not apply because the case study was not including those kinds of substances.

An additional limitation regards the fact that both the spatial and the temporal dimensions are not generally differentiated, and the results are often aggregated both in time and space. The environment in which the system is located is considered uniform, with the adaptation for the system studied. Moreover, impacts are considered to be additive, which means that high scores of a category can be offset by lower scores in other categories depending on the weight assigned to each category. Also in this thesis work these approaches were adopted.

Finally, there are limitations in the ability to predict real-life consequences, because implementing an action designed to reduce one kind of impact can cause other “collateral” impacts that can be positive or negative. The LCA does not account for many potential consequences, such as the risks to human health and the natural environment due to changes in behaviors induced by the alternative; the risks to health caused by changes in available income; and the risks to health and environment due to structural changes or innovations (Jolliet et al. 2016), and obviously this limitation applies also to this thesis work.

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