Methodology for Corporate Sustainability Quantification

A Case Study on a Car Rental Company

Enrico Orani

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. César Alberto Valderrama Angel
Prof. Duarte de Mesquita e Sousa

Examination Committee

Chairperson: Prof. Susana Isabel Carvalho Relvas
Supervisor: Prof. César Alberto Valderrama Angel
Member of the Committee: Prof. António Mário Pereira Ferraz

December 2021

Abstract

Corporate sustainability is a relatively new concept that has been claiming always more interest due to the significant possibilities it may bring into the industrial sector. But how is corporate sustainability calculated? This research aimed at developing an easy and reliable framework to measure the sustainability performance of a car rental company. The framework is composed of two sections, one is dedicated to the sustainability measurements, with a consequent analysis of the results through the Life Cycle Sustainability Analysis method (LCSA). The second one concentrates on the interconnections of the results obtained from the LCSA using alternatively three different Multi-criteria Decision Analysis methods (MCDA), the Multi-attribute Value Theory (MAVT), Analytic Hierarchy Process (AHP) and a methodology developed in this work called Sustainability Function method. The results showed that the LCSA can be applied to service companies with some modifications, and that the framework can present results in a form easy to understand also for non-experts. Furthermore, this methodology represents an interesting possibility for experts and decision-makers to better define the share that each aspect of sustainability has on the final score, an issue found in most research regarding this topic. In fact, the measurement of sustainability in the corporate sector is one of the current hot topics, and it is found to be in the interest of stakeholders, shareholders and society. The corporate sustainability field is constantly growing, and this work provides insights on how to measure it and defines a potentially reliable framework for its quantification.
Keywords: Corporate Sustainability Quantification, Life-cycle Sustainability Analysis, Multi-criteria Decision Analysis, Triple bottom line.

Resumo

A sustentabilidade empresarial é um conceito relativamente novo e que tem despertado cada vez mais interesse pelas significativas possibilidades que pode trazer ao setor industrial. Esta dissertação teve como objetivo desenvolver uma estrutura simples e válida para medir o desempenho de sustentabilidade das empresas. Para melhor analisar o desempenho sustentável num caso real, uma empresa de aluguer de automóveis com sede na Sardenha foi analisada. A análise é composta por dois vetores, um dedicado às medições de sustentabilidade, com a consequente análise dos resultados através do método de Análise de Sustentabilidade do Ciclo de Vida (LCSA), e o outro, concentra-se nas interconexões dos resultados obtidos no LCSA usando alternativamente três métodos diferentes de Análise de Decisão Multicritério, a Teoria do Valor Multiatributo, Processo de Hierarquia Analítica e uma metodologia desenvolvida na dissertação denominada método da Função de Sustentabilidade. Os resultados mostraram que o LCSA pode ser aplicado a empresas de serviços com algumas modificações, e que esta metodologia é capaz de apresentar resultados de uma forma que possa ser de fácil compreensão também para não especialistas. Além disso, essa metodologia representa uma possibilidade interessante para especialistas e tomadores de decisão definirem a influência que cada parâmetro da sustentabilidade tem na pontuação final. A medição da sustentabilidade no setor empresarial é um assunto premente, sendo do interesse de empresários, acionistas e da sociedade em geral. O campo da sustentabilidade corporativa está em constante crescimento, e este trabalho fornece pistas sobre como medi-lo e define uma estrutura potencialmente viável para sua quantificação.
Palavras-chave: Quantificação da sustentabilidade corporativa, Análise de Sustentabilidade do Ciclo de Vida, Análise de Decisão Multicritério, resultado financeiro triplo.

Table of Contents

List of Figures

List of Tables

Acronyms

ABS Activity Based Sustainability

AHP Analytical Hierarchy Process

APOS Allocation at the Point OF Substitution

CALCAS Coordination Action for innovation in Life Cycle Analysis for Sustainability

CEMS Certified Environmental Management Systems

CSED Contribution to the Sector Economic Development

CSM Corporate Sustainability Management

DALY Disability-adjusted Life Years

E Environment

EDVC Equally Distributed Vehicle Categories

EDVC-G Equally Distributed Vehicle Categories-Grid

EDVC-P Equally Distributed Vehicle Categories-Photovoltaic

E-LCA Environmental Life-cycle Assessment/Assessment

EV Electric Vehicle

FLBSE-DSS Fuzzy-Logic Based Sustainability Evaluation Decision Support System

FPMF Fine Particular Matter Formation

FS Fair Salary

GD Green Deal

GHG Green House Gasses

GW Global warming

HCT Human Carcinogenic Toxicity

HH Human Health

IARG International Agency for Research on Cancer

LCC Life Cycle Costing

LCSA Life Cycle Sustainability Analysis

MAUT Multi Attribute Utility Theory

MAVT Multi-Attribute Value Theory

MCDA Multi-criteria Decision Analysis

ME Marine Eco-toxicity

NMVCs Non-Methane Volatile Organic Compounds

PSR Promoting Social Responsibility

PV Photovoltaic System

RDVC Current Distribution of Vehicle Categories

RDVC-P Realistic Distribution of Vehicle Categories-Photovoltaic

ROA Return of Assets

ROI Return of Investments

SA Sensitivity Analysis

SD Sustainable Development

SETAC Society of Environmental Toxicology and Chemistry

S-LCA Social-life Cycle Analysis

SMAA Stochastic Multi-criteria Acceptability Analysis

TOPSIS Technique Order Preference by Similarity to Ideal Solution

UNEP United Nations Environment Program

WC Water Consumption

WEEE Waste Electrical and Electronic Equipment

WHO World Health Organization

YLD Years of Life Disabled

YLL Years Life Loss

Chapter 1

Introduction

1.1 The concept of sustainability in the current period

Climate crisis, ocean depletion, natural resources scarcity may be considered the tip of the iceberg of the problems our world has been facing over the past 50 years, in a constantly increasing way. Over time, these issues have become more and more tangible and many protests all around the world have been taking place. Even though individuals are starting to act and governs are trying to take action, no holistic solution has been found yet to head back to an eco-friendlier behavior, both for individuals in their daily life and for businesses in the industrial sector. Nevertheless, many are the government that are trying to take action, an example is Europe with the Green Deal, which seeks to define and implement a new growth strategy to make Europe a self-sufficient economy by zeroing net emission by 2050 for the environment, decoupling the economic growth from the resource usage in the financial side, and by decreasing the wealth gap between rich and poor for the social aspect. From the energy point of view, the main target is by 2030 to diminish the emission of GHG by 55% with respect to 1990 as shown by the European Climate and Energy Framework [1]. But how to achieve these ambitious goals on the industrial side?
The answer to this question is embedded in the application of Sustainable Development (SD), an approach able to take into account social, environmental, and economical aspects. The first definition of this concept was given in the Brundtland Report in 1987 as a method to "ensure balance between human needs of present generation with the protection of the natural environment, so that those needs can be met by future generations" [2]. Over time this concept is increasingly becoming more crucial both for the current management sector and for decision-making in the long term. It can be defined as a new way of thinking, which describes

new approaches and strategies to advance in an eco-friendlier way toward society, economy, and environment. The core of SD is met in the interconnection between these three traits, and it can be applied to any aspect of human development and management.
This thesis will focus on Corporate Sustainability (CS), field of study that proposes in general terms the application of sustainability in the business core of companies in the production sector, or that offer a service [3]. CS is becoming progressively more crucial for companies regarding financial, economic, and social aspects. This way of thinking can be summarized in the concept of Triple Bottom Line (TBL), term coined in the 1994 by John Elkington [4]. Furthermore, as previously stated the interest of the public and government in sustainability, do make its application central for all stakeholders involved in the company. Nonetheless, as nice as it sounds the application of CS is incredibly complex. It requires deep study of the market, the company structure, and its managements. As a matter of fact, CS normally pays off in the long term, and asks for high initial investments. This explains the difficulty of its implementation, in a historical moment stuck in a crisis that involves most sectors. Furthermore, being CS a new concept, no standardized ways for its quantification have been yet defined. This thesis will tackle this issue focusing on the quantification of sustainability in the corporate sector, by defining a methodology to measure the sustainability of services offered by a car rental company. After the sustainability quantification a sensibility analysis will be performed to help decision making in the long term, helping to direct future investments. This analysis will first define the contribution of the company impact under the environmental, social and financial point of view, and start the creation of a new benchmark for this sector in terms of sustainability performances. Finally, this thesis will propose a methodology to better interconnect these three aspects and try to give a simple, overall and complete value to the sustainability performance of the analyzed company.

1.2 Literature Review

1.2.1 Introduction of corporate sustainability

Corporate sustainability is becoming increasingly more important in the business management for companies. This can be shown over three main different reasons. Firstly, the introduction of sustainability into the business model can give substantial benefits over the long term. This is stated by Kim et al. and Przychodzen et al. [5, 6], which analyses the benefits obtained from the introduction of Corporate Sustainability Management (CMS) for shareholders. The study also shows how the introduction of CMS increases the value of the company, not only as a brand, but it also has a positive influence on investors. The introduction of sustainability may require high initial investments that can be repaid over the years if accompanied by a good management system, improving in many cases the Return of Investments (ROI) and the Return of Assets (ROA). Secondly given the current climate crisis governments started developing policies targeted to enhance sustainability implementation in firms. This may be accomplished by granting subsidies to help the transition toward eco-friendlier management development and assets. A contemporary example is Europe with the Green Deal (GD) [7], which seeks to define and implement a new growth strategy to make Europe a self-sufficient economy by zeroing net emission by 2050 for the environment, decoupling the economic growth from the resource usage for the financial side and by decreasing the wealth gap between rich and poor for the social aspect. Under the energy point of view the main target is to diminish the emission of Green House Gasses (GHG) by 55% with respect to 1990. To reach this goal, incentives are expected to grow in the next years, since 30% of funds have been allocated to sustainable initiatives to prevent climate change. Companies on their side, will need to show their improvements in terms of sustainability in order to obtain resources. Thirdly, sustainability is a concept that is becoming always more important for the public and the social sphere. The study performed by Wolf et al. and Camilleri et al. [8, 9] underlines how external stakeholders can pressure the decision making of a company, modeling, and changing their business management and contributing to a more sustainable supply chain. In this era of constant information, the public has an increased interests on the sustainability of products and services bought, and plays an important role in the CS side for companies. All these aspects require a higher level of transparency from companies in their operations and management. This is fortunately easily possible thanks to the continuous digitalization, where now the gathering of data is common both for manufacturing and service companies [10, 11]. This trend has been busted even more with the COVID pandemic as stated by Almeida et al. [12].

1.2.2 Introduction of sustainability into the company business model

But how does a company introduce sustainability into its business model? First sustainability performances of the company need to be quantified, in order to understand where the main flaws are. The quantification of sustainability gives the possibility to understand whether a company is approaching its production processes or providing its services respecting the social, environmental sides, but considering also financial aspects. The relevance of such studies relies on two main attributes: firstly, by showing the gaps in the management system and by understating in a scientific way the changes required to improve sustainability. Enhancements in terms of sustainability not only promotes a more environmentally friendly behavior

of the company, but also bring financial benefits in the long run through well-defined management strategies, strengthened by the gathering of data brought by the digitalization; secondly by defining a benchmark between companies of similar sectors, stakeholders will increase their interest in sustainability performances of companies. On their side, companies will be pushed to perform sustainability analysis in order to be more competitive in the market. This highlights how the interests for company and stakeholders in sustainability is positively related, since one increases the other and vice versa.
Given the previously shown importance of sustainability into the corporate sector, many are the methodologies tried in the recent history for its quantification. Rodríguez et al. [13] uses an Activity Based Sustainability model (ABS), which takes as reference the method (ABC). It first defines the resource consumption of each of the activities or services of the company, then an impact activity is assigned to the object of impact. Thanks to this model managers are able to identify where do the impact come from and where to diminish or completely eliminate a given object with a too high impact in the supply chain or service provided. The model presents limitation since no ABS models have been performed previously in this field, given the high requirements of data. Further, this model still demands for field validation, being still new to the scientific community. Vinodh et al. [14] instead uses a Fuzzy-Logic Based Sustainability Evaluation Decision Support System (FLBSE-DSS). This model uses fuzzy logic and complements it with a decision support system. The first is a system able to express data based on the context they are in, while the DSS is a computer software used for decision-making application. The model was then applied to an organization to find weaker points in the management and improve them. The main interest in this article stands in the development of a DSS created strictly for a sustainability evaluation in a fuzzy environment. Another possible method is the Life Cycle Sustainability Analysis (LCSA), an extended Environmental-Life Cycle Assessment (E-LCA) which takes into account not only the environmental aspects, but also the social and financial ones with the Social Life Cycle Analysis (S-LCA) and the Life Cycle Costing (LCC) respectively.

1.2.3 Life cycle sustainability analysis

Between the cited methodologies, after an in-deep research, this thesis favored the LCSA method, which takes into account the three-layered structure (environmental, economic and social), by defining respectively three distinct procedures: E-LCA, LCC and SLCA. The LCSA is a relatively new methodology that can be used to evaluate the sustainability performances both for products and services. Being it a new approach, no standardized framework has been developed yet. In the next part a literature review will be performed in order to understand the typology of case studies LCSA has been applied to, and which are the main gaps in the methodology. As of now, the literature review highlighted two main approaches as more credited between the frameworks to perform the LCSA as stated by Corona et al. [15]. The first one is the life cycle sustainability assessment developed through the Life Cycle Initiative [16] and its report Guidelines for Social Life Cycle Assessment of Products. Particularly, this method performs E-LCA, LCC and S-LCA separately, then derives the conclusions by merging the results of each one of the aspects at the end of the study. This approach found its main criticism in the difficulties in merging the three layers, environmental, social, and financial which sometimes can be too independent between themselves. The second most used approach is the framework developed by the "Coordination Action for innovation in Life Cycle Analysis for Sustainability" (CALCAS project) [17]. This framework consists in widening the LCA introducing the social and economic part. This method allows to easily perform a sensitivity analysis and to better shift the interest of the research by the definition of question and sub-questions, hence being more flexible. Nonetheless, it presents more difficulties than [16] in its applicability being it more data demanding. In the next section LCSA applications will be presented.

The paper presented by Onat et al. [18] analysed the latest fields where LCSA have been applied in recent years and considered the latest developments and future perspectives. The study underlines the difficulties related to the interconnection between the three different aspects of the LCSA. Furthermore, it emphasizes the limitations of the LCC and S-LCA which have not reached the maturity and reliability of the LCA. It highlights also the difficulties in the data gathering and in the standardization of a given framework. From the study emerged that most works covered the field of Environmental Science (40%), followed by Engineering (18%), Energy (15%) and Social Science (9%). Similar issues to the previous paper were encountered by Costa et al. [19], where harmonization seems to be the biggest difficulty of LCSA. The study highlights that Multi-criteria Decision Analysis (MCDA) is the most widespread for the interconnection of the results, but still needs further improvements.

The work of Corona et al. [15] presented a case study to evaluate the sustainability of a new hybrid solar power technology, named HYSOL is performed. It also analyses the effect that this technology would have on the electricity market in Spain and uses the LCSA framework CALCAS. The model present flexibility in the decision of the final scope. The main limitation is found in the time dependency, which is implemented only in the LCC. Lu et al. [20] assesses the possibility in re-usage or recycling for the mobile phone industry, assessing two different possible routes in order to improve the Waste Electrical and Electronic Equipment (WEEE) recycling system in China. This approach uses the UNEP/SETAC method and found difficulties in the final part, where one route of recycling was better for the environmental and financial part, but not for the social one. This implies the intervention of decision makers to see whether the environmental and economic risk were more important than the social one. Similarly, Zheng et al. [21] uses the UNEP/SETAC method to define which is the best pavement alternative in sustainability terms. To better analyze the final results of the three-life cycle phases the study uses a MCDA model. Finally, a sensitivity analysis is performed on the weights of the model. Martínez et al. [22] performs an LCSA using the UNEP/SETAC method to define most suitable fertilizer to be used in the fields of Catalonia. This study found its main difficulties in the unavailable data for the LCC and S-LCA, that made difficult the merging of the three model for the final results. Furthermore, Roinioti et al. [23] performed an LCSA assessment for the electricity system in Grece. Also, in this study a Multi-criteria Decision analysis is performed giving equal weight to the three sustainability aspects (social, economic and environmental), together with the stakeholder's preferences. Then a sensitivity analysis changing the weights of the aspects is performed, changing the outcome of the study. This shows how a proper Life cycle impact assessment is fundamental for the decision-making analysis. Onat et al. [24] takes into account the different possibilities for passenger vehicles using an Input-output (I-O) approach to help policy developers. Main limits here were related to social and temporal variation, which were not included in the study, along with the difficulties in data gathering. In this study the interconnection of the three aspects is not performed. In fact, most studies concentrate on the definition and development of the three pillars of sustainability, but do not take into consideration the most difficult part, which is represented by their interconnection.

1.2.4 Integration of environmental, economic and social aspects

By looking at these case studies the main considerations extrapolated are the following:

- Most case studies used the UNEP/SETAC method;
- Most case studies were applied to the quantification of sustainability for a product of a given company, but hardly for a service company;
- The main limitations are encountered in the interconnection of the three aspects of the sustainability study (environmental, economic and social).

Taking a closer look to the last point, challenges related to the integration of the three pillars of sustainability assessments define a crucial step for a complete sustainability analysis. These issues are covered in part by the study Fauzi et al. [25] where nine different challenges were encountered, and divided as follows: E-LCA and LCC, LCC and S-LCA, E-LCA and S-LCA. This thesis will be assessing some of the issues mentioned by Fauzi et al. [25], trying to present possible ways to overcome them. After an in-dept literature review on methods to combine the results of the LCSA, the use of multi-criteria-decision-making (MCDM) seems to be the more validated. In the analysis performed by Angelo et al. [26] the more widely used approach in recent LCSA studies is the Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The previous approach creates a hierarchical structure of the elements of each aspect, which are then pairwise compared following the preference of the decision-maker. The former defines an ideal solution; the closer to the ideal solution is considered ad positive and vice versa for the farther one, Govindan et al. [27]. Opher et al. [28] used an AHP method to weight the sustainability criteria, using 20 experts of the sector to judge the method. Similarly, Xu et al. [29] performs an LCSA on chemical processes integrating an AHP method to analyze the results. Grubert et al. [30] emphasizes the importance of a standardized framework to merge the aspects of the LCSA and proposes WELFARES, a non-monetary weighting framework in which the AHP method is used. An interesting approach was used in the paper of Onat et al. [31] where a Compromise Programming approach is used to take into account the diversity of indicators. In fact, some indicators require the optimization through the minimum and other through the maximum. This article defines an interesting approach for the interconnection of the three approaches, by normalizing the indicators and selecting different weights for each of them. Finally, a sensitivity analysis is performed on the weights in order to study the output variation. The study of Hannouf et al. [32] takes an already existing LCSA and performs a decision-making analysis framework, showing the possibilities of its application, without drawing possible solutions, but analyzing the potentialities. The method used is called ELECTRE TRI, where the different categories are sorted in a way where they are not compared against each other to define a winner but evaluates its performances with respect to a set of categories previously defined. Furthermore, Gwerder et al. [33] performed a sustainability assessment of two off-grid homes in Portugal paired with an MCDA method to rank the alternative options. The method used is called Multi-Attribute Value Theory (MAVT), and this study in addition presents the use of Stochastic Multi-Criteria Acceptability Analysis (SMAA) and Variable Interdependent Parameter (VIP) analysis to evaluate the robustness of the method. Tarne et al. [34] instead used as weighting method a group of 54 decision makers of a German company, to evaluate a vehicle component. The results outlined the difficulty of the weighting phase, since decision-makers of the same company presented a large spread in weighting without clear clustering.

As can be seen from the above mentioned and analyzed studies, the pairing of the two methods, first LCSA to quantify the sustainability, and then the MCDA for the criteria evaluation is a highly credited framework in the scientific community, with many limitations and space for improvements. This thesis will follow a framework similar to the ones analyzed above. The main idea is to develop an LCSA on a company, then apply two different MCDA approaches, and finally confront or integrate them. The software "Decerns" [35, 36] will be used to perform a MCDA, using the Multi Attribute Value Theory (MAVT) [35]. Subsequently, a MATLAB code will be developed using the same weights but a different procedure in order to define a sustainability equation, but always following the concept of MCDA. Then pro and cons of the two methodologies will be analyzed.

1.3 Objective

The objective of this thesis is to lay the foundation of a standardized path for the sustainability quantification of service companies. The method used for the sustainability quantification is the LCSA, together with two MCDA methodologies. Since LCSA methodologies concentrate on product and this case study describes a service, an adaptation of the UNEP/SETAC [16] and the methodology explained in [37] by Jolliet et al. will be used. The idea is to develop a framework that is easy to understand, apply and that with additional studies, will be able to quantify the sustainability performances of companies of similar sectors. This methodology will help introduce sustainability in the business core of enterprises, helping to spot possible flaws in the production system, in the supply chain or in the service provision. Regarding the company's side, the aim of this study will be to understand where to enhance positive assets or where to improve or eliminate flaws, both for present and future decision-making. Furthermore, the thesis will tackle the main problem related to the LCSA assessment, by proposing and analyzing a methodology to interconnect the three aspects of the LCSA (social, environmental, and financial). The frameworks used for this final part will be two: the software "Decens" which enable the used to perform the evaluation of the results choosing between 9 different MCDA's methods; A MATLAB code that allows the user to create a sustainability function, to better visualize how possible decision could influence sustainability analysis. The testing of a method to assess the three-layered structure, has many important benefits. Most importantly it will help to understand this complex system in an easier way. The future outcome will be the creation of a new benchmark for companies of similar sectors to have a clearer view for stakeholders, public and private investors.

1.4 Methodology

The thesis will follow the framework previously stated taking as reference the procedure presented by of the UNEP/SETAC [16]. Since the main focus will be the

LCSA of a service company, the methodology will be slightly adapted in order to match the requirements of the study. The LCSA will be performed with the software openLCA using the combination of two different databases [38], together with data furnished by the company. For the E-LCA and LCC the database Ecoinvent 3.7.1. [39] will be used. For the S-LCA, the PSILCA database [40] will be used. Initially the goal and scope section is presented. This section includes the functional unit and the boundary system description. The former represents the unit used to define the impact of each one of the categories in the life cycle inventory. The latter defines the activities that are included or not in the three different aspects, based on the relevance of each one of them. For this case studies, activities are meant as service offered. Each service needs to be relevant for at least one of the three aspects. Subsequently the life cycle inventory analysis is performed, in which the amount and quality of the data is defined. In this section input of the system are defined and outputs are calculated. The gathering of data is a crucial phase of the LCSA since it defines the quality of the study and the limitations. Then the impact assessment is performed, in this section the impact categories are defined and calculated for the three aspects, environmental, financial and social. Then the interconnection of the results, to evaluate the overall sustainability performance of the company is assessed with two MCDA. In this section, a sensibility analysis of the weights will be performed. Then, a framework for the weight definition that interconnects the three MCDA methods will be presented. Finally, the discussion with the encountered limitations and conclusions and further studies.

Chapter 2

Life cycle sustainability analysis

2.1 Company description

The selected company for the sustainability quantification analysis is a car rental company located in Sassari, a city in the north of Sardinia, Italy. The company was founded in 2001 in the province of Sassari and now counts a total of three employees. The company presents a fleet of 52 vehicles, which comprehend standard auto vehicle for passengers, refrigerated-cell trucks, vans, mini-vans, electric vehicles and one minibus. The company possesses a shed used both to allocate the vehicles, operate maintenance, recharge the electric vehicles and host the offices for the personal and other companies. Space of the shed is also rented to third parties for the allocation of goods or vehicles. The building also presents a photovoltaic system of 120 kW on the rooftop, which account for most of the electricity consumed by all the services. The electricity produced in advance is not curtailed but sold to the network of the city. Inside the private property of the building, the cleaning and disinfection of the cars is operated, with water furnished by the city provider. Products for the cleaning and disinfection are provided by the company itself, while the maintenance of the cars in case of engine problems are generally taken by a third party. The company already started introducing sustainability measures inside its core business, leaving the electricity production to the photovoltaic system and by sustaining a transition to electric vehicles, which has now reached the number of 10 cars. The building is also endowed of three charging stations, which can be used both for the owned electric vehicles and for private owner of electric cars.

2.2 Goal & scope definition

The goal of this LCSA (assessment) is to define the sustainability performance of the car rental company Iesse. Data and information will be provided by the company, obtained from the databases, extrapolated from research and in some cases acquired from assumptions. The study is a preliminary quantification of the sustainability, subjected to further studies in case of positive feedback. It is meant as a starting point for the standardization of a framework for sustainability quantification in the corporate sector, provided as a service to companies which want to boost their transition toward an eco-friendlier management. Main benefits will be obtained by the company which from one side will be able to locate positive activities and enhance them whether possible, from the other to locate negative activities in order to eliminate or improve them. LCSA analysis will also help managing decision-making for new initiatives and future investments. The study is not only directed to shareholders, but also to investors and stakeholders. The quantification of sustainability will be a new parameter able to show where does the company stands in financial, social and environmental terms. Specifically, the last aspect has been acquiring always more importance in the corporate sector, being indicator of work quality, transparency and flexibility, qualities increasingly required over the past years. The study is also directed to public investors, since the social intrest was found to be given towards process which target the reduction of toxic and environmentally damaging emissions, improvements of working environments and green initiatives [7]. All these reasons also create a new outcome. In fact, this thesis defines a starting point for the definition of a benchmark for companies belonging to a similar sector. This feature will have positive effects for two reasons: firstly, the definition of a sustainability label will easily show external stakeholders sustainability qualities, which are now difficult to quantify and identify, helping them to better decide whether to promote or invest depending on their interests; on the other side companies will be more prone to promote and perform sustainability studies in order to improve their values and their image in the eyes of stakeholders. The time horizon of the study will be the provision of the service over 4 years.

2.3 System function & Functional unit

The system function for the E-LCA and LCC has been selected in order to be able to better achieve the final objective of the study. As previously mentioned, the purpose of the study is the quantification of the sustainability performances of the company Iesse, which provides a service of car rental, thanks to a fleet of 52 vehicles. Vehicles are of different types, so they are grouped in four different categories: electric vehicles, small size petrol vehicles, medium size diesel vehicles

and refrigerated vehicles. Further, a PV plant is present in the general office. To consider all these different aspects, the selected system function is the provision of the service offered by the company, meaning the car rental service. Following these criteria, the chosen functional unit is the traveled distance of the entire fleet of vehicles, to offer the rental service for 4 years, which is the average amount of time vehicles are kept in the company. It was assumed to be 3.2 million [km]. In this way also the production of electricity will be dependent on the number of kilometers traveled by the cars. The functional unit has also been selected in order to allow the performance of a sensitivity analysis after the LCSA is computed.
Regarding the S-LCA a different unit was selected. In fact, in the scientific community, no standardized method has been yet defined for the quantification and measurement of this aspect. Furthermore, S-LCA can be expressed as a more qualitative than quantitative assessment. For this reason, the functional unit presents a less crucial role. The selected functional unit is US dollars, which is the default unit proposed by the PSILCA database. It was selected as the amount of [USD] needed to provide the manufacturing of the fleet of vehicles used for the service over the four years. It was assumed to be around 1 million [USD].

2.4 System boundaries

2.4.1 E-LCA & LCC

For the E-LCA and LCC most of the assets needed to ensure the provision of the service for four years. The boundaries of the vehicles include the manufacturing of the cars, their usage and their lifetime maintenance. The generic maintenance for vehicles during the whole lifetime is considered in the program openLCA as an input flow, but the daily maintenance is normally performed by a third party, therefore not considered in the system boundary. The boundaries for the electricity usage include the production of the Photovoltaic System (PS) used to provide the service and the whole PS for the electricity production, together with the electricity provided from the city provider. The flows considered to perform the E-LCA and LCC are better described in section (3.1).

2.4.2 S-LCA

The S-LCA boundaries have been defined taking into account only global impact, not considering the local one. This decision was taken considering the little impact the company service has on the local community, since the company has only three employees, and the fleet of vehicles is too small to have a significant impact on a city level, so the effect on the local community have been considered negligible. The global impact instead can be quite significant since it would include the manufacturing of the vehicles, highlighting the differences between internal combustion engine and electric vehicles, in the car purchase. Simultaneously this decision simplifies the S-LCA. The flows considered to perform the S-LCA are better described in section (3.1).

Chapter 3

Life cycle inventory analysis

The inventory definition of the study is one of the most critical stages since it comprehends the research and gathering of data. As already mentioned, the gathering of data is one of the most difficult parts of LCSA studies since it asks for in-deep research for each flow of the assessment. If fact, since life cycle analysis is a method that can consider each flow of the production of goods, it may be difficult to find data to assess all the chosen impact categories. The complications mainly rise for developing countries and small companies which do not keep track of all the information. Fortunately, thanks to digitalization, more and more businesses are keeping track of all inputs and outputs that enable the service provision as stated by Mentsiev et al. [10]. In this study data for the E-LCA and LCC have been taken from two main sources, the Ecoinvent 3.7.1 database [41] and the company. For the S-LCA data have been taken from the PSILCA database [40, 42]. As suggested by the UNEP/SETAC framework, data for the three aspects have been gathered at a unit process level from the Ecoinvent and PSILCA databases and at an organizational level from the company [16]. Ecoinvent is a non-profit association that gathers and distributes environmental data for companies and associations interested in the development of LCA. The team is composed by LCA experts who keep the databases updated and upgrade the system with new categories, better defined and more specific data. While the data regarding the number of vehicles, consumption of fuel and energy, cost data and social aspects have been gathered with the collaboration the employees of the company Iesse.

3.1 Flows description & Assumptions

In this section the structure of the three aspects of the Life Cycle Sustainability Analysis used in the program open LCA are presented and explained. This section is important to show which are the variables considered in the calculation of the impact categories, and how all the variables are interconnected. The model is structured in two main sections: the first one uses the Ecoinvent database to calculate the categories for the E-LCA and LCC, while the other section uses the PSILCA database to calculate the categories relative to the S-LCA. This explains how for the two calculations, two different flow structures have been created, and this also explains the limitations and assumption considered for the calculation. The next section will be divided into two paragraphs, explaining the two flows.

3.2 E-LCA & LCC

The flow structure for the E-LCA and LCC was developed to cover the whole rental service offered by the company. It takes into account the car rental service and the production of electricity. Thanks to the presence of a large space the company also offers space rental for cars and offices, but for lack of data availability it was neglected. The majority of the data for the manufacturing and usage of cars is given by the database Ecoinvent as previously stated. The database gave the possibility to use three different versions, namely the cut-off, the Allocation at the Point OF Substitution (APOS) and Consequential. The main differences between the three databases systems stands in the allocation of the wastes after the product or service is used. The cut-off approach remains the easiest one, where recycled materials are available burden-free, and primary use material place the burden to the primary user, which does not receive any credit to recycle the material. This means that recycling materials carry only the burden of the recycling process. The APOS database instead shares the burden of the products between producers and subsequent users that benefits from the by-product. The consequential model is used for prediction of changes in the future or perspective studies. In order to do that, basic assumptions are used to evaluate the possible consequence of changes in the system [41]. Between the three approaches, the cut-off was selected for this study, being it the closest to the final objective of the thesis and the more mature. Furthermore, the company uses the assets for an average of 4 years and is not interested in the use for their entire life cycle. For this reason, the assumptions that no burden are left to the company after the end of the 4 years was taken.
Below, the description of the four main flows that compose the service offered by the company are explained:

- Diesel car large size: This category includes all diesel vehicles used by the company for the rental service. It is composed by 35 vehicles of different sizes and different weights. The average weight was considered of around 2 tons, which corresponds in the Ecoinvent database to the section denominated as "*transport, passenger car, large size, diesel, EURO 6 | transport, passenger car, large size, diesel, EURO 6 | Cutoff, U*". Since the data-set of Ecoinvent only had the category of vehicles EURO 5, the data have been modified by changing the values of (NO_x), (CO), and (PM) emissions to respect the category EURO 6. This category comprehends the manufacturing of cars, their usage and maintenance. It also considers the emissions related to the road usage and maintenance. There are flows related to the usage of the wears, wheels, and brakes. Since the average lifespan of a vehicle was estimated to be from around 15 to 20 years, and vehicles from the company are generally used for 4 up to 5 years, all the number related to the construction, maintenance and disposal of the vehicle were divided by 4. In this way, only a fourth of the lifespan of the vehicle is attributed to the company emissions. The only data kept constant is the fuel, since the usage of the car is measured in km.

- Petrol car small size: This category includes all petrol vehicles used by the company for the rental service. It is composed by only 3 vehicles of different sizes and different weights. The average weight was considered of around 1.2 tons, which corresponds in the Ecoinvent database to the section denominated as "*transport, passenger car, small size, petrol, EURO 6 | transport, passenger car, small size, petrol, EURO 6 | Cutoff, U*". Since the dataset of Ecoinvent only had the category of vehicles EURO 5, the data have been modified by changing the values of NO_x, CO, and PM in order to respect the category EURO 6. This category comprehends the manufacturing of cars, their usage and maintenance. It also considers the maintenance and emission related to the road usage. There are flows related to the usage of the wears, wheels, and brakes. Since the average lifespan of a vehicle was estimated to be from around 15 to 20 years, and vehicles from the company are generally used for 4 up to 5 years, all the number related to the construction, maintenance and disposal of the vehicle were divided by 4. In this way, only a fourth of the lifespan of the vehicle is attributed to the company emissions. The only data kept constant is the fuel, since the usage of the car is measured in [km].

- Electric cars: This category includes all electric vehicles used by the company for the rental service. It is composed by 10 vehicles of same sizes and weights. In the Ecoinvent database the section is denominated as "*transport, passenger car, electric | transport, passenger car, electric | Cutoff, U*". This category comprehends the manufacturing of cars, their usage and maintenance. It also takes into account the maintenance and emission related to the road usage. There are flows related to the usage of the wears, wheels, and brakes. For this category the production, usage and disposal of the battery is also considered, which in average takes up to the 30% of the total cost of the car [43]. The vehicles are charged in the office of Iesse, thanks to chargers connected to a Photovoltaic plant of around 120 kW. Since the average lifespan of a vehicle is considered around 15 to 20 years, and vehicles from the company are used for

4 up to 5 years, all the number related to the construction, maintenance and disposal of vehicles were divided by 4. Only the data related to the battery were divided by a factor of 2, considering a life expectancy of electric car's battery of 6-7 years years [44]. Like in the other categories, the data relative to the electricity to power the car was kept constant.

- Lorry with refrigeration machine: This category includes all diesel vehicles endowed of refrigeration machine used by the company for the rental service. It is composed by 52 vehicles of different sizes and different weights. The average weight was considered between the 3.5 and 7 tons, which corresponds in the Ecoinvent database to the section denominated as "*transport, freight, lorry with refrigeration machines, 3.5-7.5 ton, EURO6, R134a refrigerant, cooling | transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO6, R134a refrigerant, cooling | Cutoff, U*". This category comprehends the manufacturing of the trucks, their usage and maintenance. It also takes into account the maintenance and emission related to the road usage. There are flows related to the usage of the wears, wheels, and brakes. For this category also the production of the refrigeration machines, and the usage and emissions of the refrigeration liquids ($R134$). This is considered as the most emitting category. Since the average lifespan of a vehicle was estimated to be from around 15 to 20 years, and vehicles from the company are generally used for 4 up to 5 years, all the number related to the construction, maintenance and disposal of the vehicle were divided by 4. In this way, only a fourth of the lifespan of the vehicle is attributed to the company emissions. The only data kept constant is the fuel, since the usage of the car is measured in km.

These four categories are interconnected and used to calculate the total emissions caused by the rental service. As previously stated, the functional unit considered was the amount of emission produced to provide the rental service for four years, which was translated in 3.2 million km of traveled distance by the entire fleet. This distance was found considering the average travelled distance of all the vehicles for one year, and then multiplying it by four. The data was gathered through the service offered by "Targatelematics" [45], an application paid by the company that allows to track each vehicle and register, from the distance traveled to the maintenance, even checking when it switches on and off. Once obtained the distance traveled the assumption that each vehicle travels the same distance in the four-year period was considered. Thanks to a simple proportion the distance traveled by each vehicle was found and used for every different scenario.
The production of electricity for the powering of electric cars was divided into two flows considered separately. The first one was the standard one which uses the electricity from the grid, while the second one used the production from a flat roof photovoltaic plant. This second flow section was considered by integrating a flow

related to the photovoltaic production called in the Ecoinvent database "*electricity production, photovoltaic, 3kWp flat-roof installation, single-Si | electricity, low voltage | Cutoff, U*". This flow considers the manufacturing, production, usage and maintenance of the photovoltaic plant. It does not take into consideration the disposal and recycling of the panels. The electricity produced by the grid takes instead the Italian electricity production mix, which is mainly driven by natural gases with 55% share, oil and petroleum for 5% and 40% of green energy [46].

3.3 S-LCA

The flow structure for the S-LCA was built in order to only cover the manufacturing process that allows the provision of the service. This decision was taken for three reasons: First, the company counts only three employees. Second, since the fleet of vehicle is mall counting a total of 52 vehicles, the impact on the local community can be considered negligible. Third, the limitation related to the lack of data relative to the local community was too broad to obtain acceptable results. As previously mentioned, the database used for this part is called PSILCA, which uses the Multi Regional Input-Output (MRIO) database called Eora. The version available for this thesis is the starter version v3.3. PSILCA uses as activity variable the so called "worker hours" (WH), which are meant as "the time workers spend to produce a certain amount of product in the given process or sector" [42]. The WH are directly related to the cost of 1 USD of process output. All the values are not taken from an external source, but directly calculated using the following [42].

$$Worker\ Hours = \frac{Unit\ labour\ of\ costs}{Mean\ hourly\ labour\ cost\ (per\ employee)} \tag{3.1}$$

As for the E-LCA, here the structure is subdivided into two main categories, one relative to electric cars, and the other related to diesel and petrol cars. The two main flows are explained below:

- Diesel car: This flow includes all the non-electric cars of the fleet of vehicles used to provide the car rental service. In this category the assumption that all cars are of the same size and of the same weight was taken, because of the lack of data in the database PSILCA. The category is denominated under the name "*Passenger cars and parts*" in Germany, since most of the car's production is performed in Germany. On PSILCA the manufacturing of the vehicles considers almost every aspect of the chain, from the production of each part (internal combustion engine, electronics, wheels, glass) together with the wastes (water, energy, disposals), to the transportation of all materials;
- Electric cars: This flow includes all the electric cars of the fleet of vehicles used to provide the car rental service. This category is composed by two flows,

the first one related to the production of all the car parts that does not include the combustion engine, called in the PSILCA database as "*Manufacturing of motor vehicles, trailers and semi-trailers*". This production takes place in France since all the electric vehicles are Renault, which is a French brand. The second one is related to the production of storage battery, which will be integrated with the car parts production, this section is called on PSILCA as "*Storage battery manufacturing*". These two flows were combined in the flow denominated as "*Electric car manufacturing*" and are taken at different percentages. The production of the vehicle parts takes about 70% of the total production cost, while the battery production is about 30% of the cost in 2020, price that is predicted to fall in the next decade [43].

Chapter 4

Life cycle impact assessment

4.1 Impact categories

The impact categories are classes of indicators used to categorize the different impact of the various emission for the environment, costs for the economy of the company and social aspects for the global and local community. Each aspect of the LCSA will have a set of indicators which are selected in order to better represent the final scope of the analysis. The selection of indicators is fundamental to better direct the dimensions assessed by the study. For the E-LCA the impact categories have been taken from the ReCiPe 2016 Endpoint impact assessment method, for a total of six impact categories. The impact assessment method was developed by Goedkoop et al. [47], it provides harmonized characterization factors at midpoint and endpoint levels. For the S-LCA instead the impact categories have been selected from a list of the PSILCA assessment method, called Social Impacts Weighting Method, shortened. While the E-LCA impact category is defined by more quantitative results, the S-LCA in normally defined by qualitative index. For this reason, the S-LCA tends to be more dependent on the human perception, and to be different from case to case, depending on study of interest. The chosen measurement units will be defined and explained in the next paragraphs. Information for the E-LCA and LCC impact assessment have been taken from the ReCiPe guidelines of 2008 and 2016 [47, 48].

4.1.1 E-LCA

The impact categories for the environmental LCA have been selected after the completion of the LCA analysis. This decision allowed to select the more relevant categories. The units chosen to measure the emission's impacts in the E-LCA are the Disability-adjusted Life Years ($DALY$) and the species.yr, and concern respectively the human health and the ecosystem. These two units of measurements

represents the endpoint units proposed by the Recipe impact assessment method. This decision was taken to follow the main outcome that is wanted to be obtained from this thesis, meaning the development of a simple framework to obtain the sustainability quantification of a company. The endpoint characterization from one side loses certainty in the final data with respect to the midpoint one. Nonetheless, midpoint characterization becomes less useful in decision making analysis [49] and to interconnect the three different pillars of sustainability.
The $DALY$ can be seen as a concept which assess the damage to human health, it was developed by Hofstetter et al. [50], following the study for the World Health Organization by Murray et al. [51]. This method uses statistics of human health disease for life lost and disabled, considering a wide range of diseases. It can be calculated using the following formula:

$$DALY = YLL + YDL \tag{4.1}$$

Where YLL is Years Life Loss while YDL refers to Years of Life Disabled and can be calculated multiplying w by D, where w is the severity factor chosen for the given disease, it goes from 0 to 1, and D is the time duration of the disease. This metric follows various assumption, for example data are based on averages of the whole world, on the period chosen and do not consider differences in age. This may create difficulties since health care is different for different region of the world. Furthermore, often the inhalation of a given impurity has effect on the human health after many years. This differences in years may give effects also on the improvements in the health sector, which make progresses year after year. Nevertheless, despite these inaccuracies, $DALY$ remains a strong method for the analysis of such impacts.
Regarding the ecosystem, the assumption made by Recipe, is that the ecosystem quality is directly proportional to the diversity of species. Following this assumption the indicator is called species.yr, and it represents the disappearance of a species over a given amount of time. The indicator was developed following the ECO-indicator 99 method which expresses it as the Potentially Disappeared Fraction of species (PDF) integrated over area and time. The indicator is based on the assumption that all species are equal and have the same weight. It takes into consideration the complete and irreversible extinction of species and the reversible or irreversible disappearance of a species or stress on a species in a certain region during a certain time.

Fine particulate matter formation

The fine particulate matter formation index measures at what extent the emission of particular matter damages the human health. In fact, air pollution causes the formation of primary and secondary aerosols which cause health problem that range from respiratory problems to hospitalization and in some cases death. The fine particulate is intended as matter with a diameter of less than $2.5\mu m$. It can be divided in primary aerosol, which is directly dangerous when inhaled because it can reach the upper part of human lungs, and secondary aerosol which when emitted in the atmosphere react forming sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x) and other elements. As can be seen from figure Fig.(4.1,[48]) the method is divided into five consecutive steps. Initially the emission of the gasses and primary aerosol, followed by the transformation of some of the gasses into secondary aerosol. The latter is represented by the chemistry that takes place in the atmosphere. Subsequently, the human intake of the particular matter and the tracking of mortality cases is extrapolated. Finally, the calculation of the damage to human health, measured through the Disability Adjusted Life Years $DALY$.

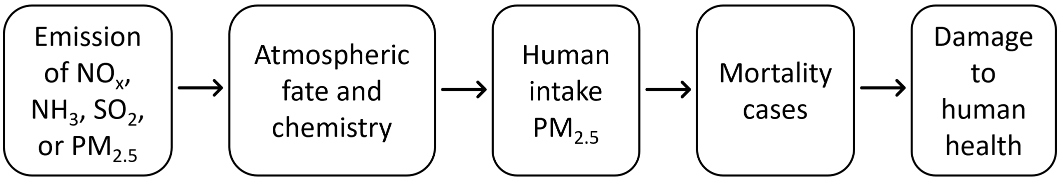

Figure 4.1: *Block scheme of fine particulate matter formation impact [48]*

Water consumption

Water usage here is considered as the water used by humans, wasted in the sea, evaporated, transferred or incorporated into products. In any case the water is not anymore available in the initial watershed and cannot be used again by the initial user, that can be humans or the ecosystem. The lack of water brings problems mainly to less developed countries, where less water in the agricultural systems means lack of food supply. Wealthier countries possess the means to import food from other countries. The model measures the water usage starting from the reduction of freshwater from lakes, rivers, and aquifers, and dividing it into three sections. Lack of water for irrigation, which reduces the production of food, hence bringing malnutrition and vulnerability for the population and damage to public health. Furthermore, the reduction of green water (water in the soil), determines a decrease in the biodiversity, causing the disappearance of terrestrial animals. Ultimately, the decrease in rivers freshwater causes the disappearance of fish species. The impact category is measured in $DALY$. In Fig.(4.2,[48]) the model is shown.

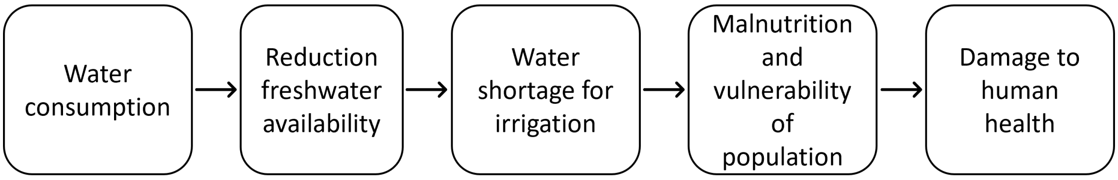

Figure 4.2: *Block scheme of water consumption impact [48]*

Toxicity indicators (Carcinogenic toxicity and marine eco-toxicity)

The toxicity factor accounts for the concentration in the human food chain, presence in the environment and toxicity of chemicals of carcinogenic substances. It is divided into two sections, human toxicity that accounts for the damage on the human health and environmental toxicity, that accounts for the environmental impact. This thesis considered only the carcinogenic toxicity and the marine eco-toxicity, which from the openLCA calculations have been found more relevant. Exposure factors were calculated through an 'evaluative' multimedia exposure model, while effect factors can be derived from toxicity data on human beings and laboratory animals. The Recipe team used the multimedia fate, exposure and effects model USES-LCA, the Uniform System for the Evaluation of Substances adapted for LCA [52], updated to version 3.0. The flow chart of the toxicity model is explained in Fig.(4.3,[48]).

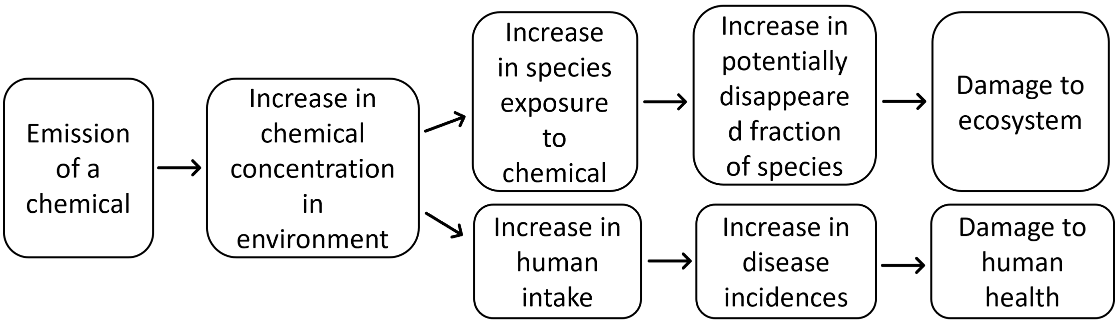

Figure 4.3: *Block scheme of carcinogenic toxicity and marine eco-toxicity impacts [48]*

Carcinogenic toxicity considers the assessment developed by the International Agency for Research on Cancer (IARC), part of the World Health Organization (WHO), which divided into classes 844 carcinogenic substances. These data are used to define two scenarios, one that takes into account only more dangerous substances, called individualistic. A second one called egalitarian that considers all 844 substances with different strength levels. The impact to the marine toxicity depends highly on the release of metals in the ocean which leads to toxic effect. Same as for the carcinogenic toxicity, two scenarios have been developed, the egalitarian that considers sea and ocean compartments. Individualistic that considers only the sea with essential toxic metals (Cobalt, Copper, Manganese, Molybdenum and Zinc).

Global warming

The global warming index is considered as shown in Fig.(4.4,[48]), first taking into account the Green House Gasses emission and calculation their concentration in the air. Then by considering the impact these gases have on the global temperature. This impact is then divided into three main sub-impact: the damage to human health and the disappearance of fish and terrestrial species. This category has been found to be relevant both for the damage to the ecosystem and to human life. For this reason, the impact of this category is measured both in species.yr and in $DALY$.

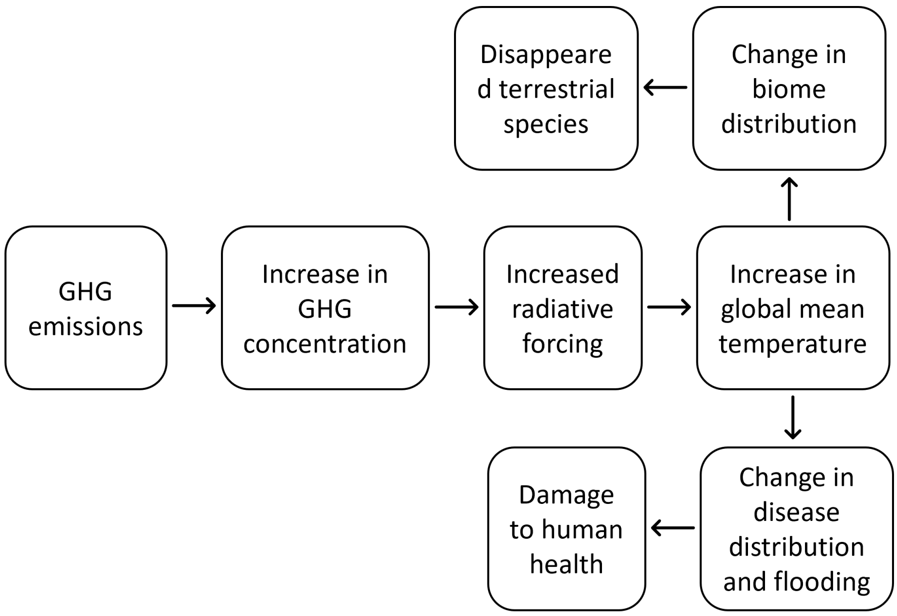

Figure 4.4: *Block scheme of global warming impacts [48]*

Ozone formation

Ozone is not a primary aerosol, it is originated from the combination of NO_x and Non-Methane Volatile Organic Compounds (NMVOCs), a process that is normally facilitated in summer. Ozone is particularly dangerous for the respiratory apparatus and lungs and where concentrations are high, the frequency of respiratory problems in human is increased. Ozone also presents a bad impact on vegetation. The modeling of this index is explained din figure Fig.(4.5,[48]). As can be seen after the emission and the combination of the two gases, the human intake and plant uptake is studied. From this the damage to human health and vegetation is studied. As can be seen it is then divided into two sections, one for the terrestrial ecosystem and one for the population.

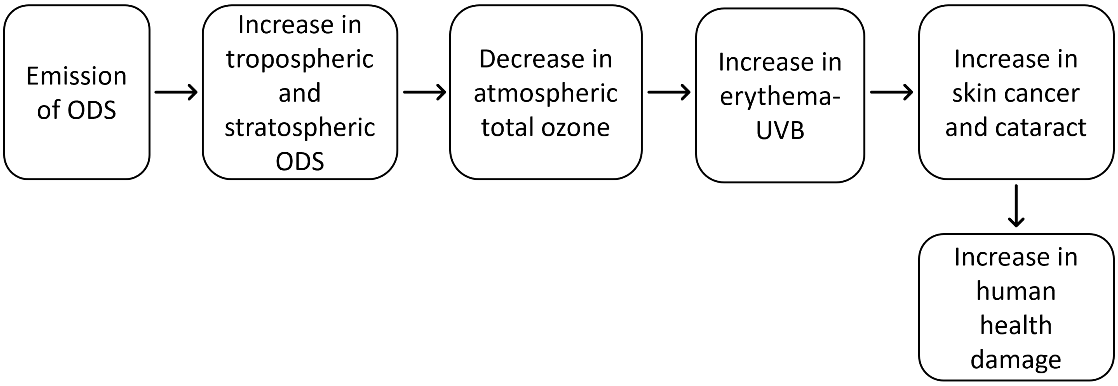

Figure 4.5: *Block scheme of ozone formation impact [48]*

Terrestrial acidification

This indicator is based on the leakage of substances such as NO_x, NH_3, or SO_2 which can increase the acidity of the soil. In fact, most of plant species have optimal acidity equilibrium which need to be kept constant. The framework for the calculation of this indicator can be seen in Fig.(4.6,[48]). From the emission of the above-mentioned gases to the atmospheric fate and decomposition. Then, the gases are deposited in the soil, the H+ concentration is increased, and the plants species disappearance is calculated. All these data are then used for the quantification of the ecosystem damage. This indicator describes the calculation of characterization factors for acidification of vascular plant species in biomes worldwide. Fate factors, accounting for the environmental persistence of an acidifying substance are calculated with an atmospheric deposition model combined with a geochemical soil acidification model [53].

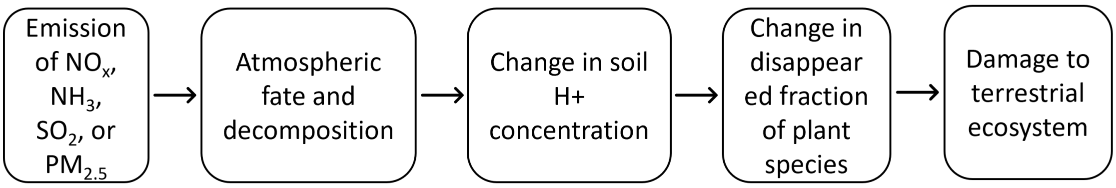

Figure 4.6: *Block scheme of terrestrial acidification impact [48]*

4.1.2 LCC

Net-cost

The Life Cycle Costing was performed following the Green Delta approach [54]. This method allows to perform the LCC strictly correlated to the environmental LCA in an effective manner using the openLCA program. The process proposed follows the calculation of the “Added value”, this indicator was developed following the concept that costs can be intended as the monetary value of a product or a service. The production of a product or the provision of a service have a cost for the company. When these products/services are sold in the market, their cost is normally higher than the cost of production, this increase is denominate as added value, and it can be considered as the value created during the process of production. This concept of added value is strictly similar to the concept of Life-cycle Costing, that is intended as the cost of the product over its entire life cycle. The index in the openLCA platform can be considered in two forms, the first one is positive, intended as added value for the company, while the second one exchanges the sign with the same value becoming the cost of the product. In the thesis the chosen indicator is the "Net-cost", then with a negative value.

4.1.3 S-LCA

Information regarding the S-LCA impact assessment method were taken from the PSILCA documentation version 1.1 [40] and 3 [42]. The social LCA uses an indicator assessment method, where each impact category is evaluated by assigning a level of risk personalized for each indicator. Each indicator can be considered as positive, meaning it is creating social opportunity for the considered sector, or negative if it is causing social degradation. In the version of PSILCA provided for this thesis, the only possible metric of evaluation is the risk assessment, which cannot be change in the program. There can be 6 different levels of risk: no risk, very low risk, low risk, medium risk, high risk, and very high risk. All the results for the social quantification are scaled up or down to medium risk, which has a factor of 1, following the characterization factors the table in Tab.(4.1,[42]). The impact assessment used is called “Social Impacts Weighting Method, shortened”, and each characterization factor will be presented in the indexes description below. This method allows a better comparison between indicators and makes the calculation easier for the software. The assignment of risk levels to the indicator values is based on international conventions and standards, labor laws, expert opinions but also experience and evaluation of the PSILCA team. Nevertheless, depending on the interested outcome of the study, the risk assessment may be subjected to individual conventions and evaluations and subjected to different conventions. This last part will be analyzed in the interconnection of the three aspects. Furthermore, indexes have been chosen using two main criteria: The most relevant for the company and sector considered and the ones developed with data of the regions considered in the system boundary and inventory analysis. The indicator will be described in the section below. More detailed information relative to the database and impact assessment can be found in the PSILCA documentation version 1.1 [40] and 3 [42].

y per 10'000 emlpoyee	Risk level
very low risk	0.01
low risk	0.1
medium risk	1
high risk	10
very high risk	100
no data/opportunity	0
Low opportunity	0.1
Medium opportunity	1
High opportunity	10
no data	0.1

Table 4.1: *Characterization factors impact assessment method in PSILCA [42]*

Certified environmental management systems

This index takes into account the presence of Environmental Management Systems (EMS) per sector, in relation to the number of employees. The concept is based on the assumption that social interests companies have for the environment protection are based on the presence of EMS. An example of EMS is ISO 14001 certification, and the index is calculated taking the number of EMS for 10'000 employees. Data is taken from the ISO Survey of Certifications 2013 for the ISO and from the ILOSTAT. for the number of employees. The risk levels are assessed following Tab.(4.2,[40]) When transformed to medium risk, the measure is considered in this case as positive, since here a social improvement is considered.

Risk level	Factor
$100 \leq y$	very low risk
$10 \leq y < 100$	low risk
$1 \leq y < 10$	medium risk
$0.3 \leq y < 1$	high risk
y < 0.3	very high risk
-	no data

Table 4.2: *CEMS impact assessment: risk of environmental damage [40]*

Contribution of the sector to economic development

This index expresses how much does a company service contributes to the economic development of a country. The contribution is expressed as the monetary increase the service causes to the GPD of the country. The economic development is intended as a whole of subcategories such as the creation of jobs, specific education and training, investments in businesses, infrastructure and so on. The value added is expressed as a percentage share of the GPD at current prices. Data is mainly derived from the United Nations Statistics Division that provides the shares of different sectors classified by ISIC of the total GDP. The measurement of the economic development brought by the company is assessed with the opportunity levels shown in the table of Tab.(4.3,[42]). As the previous indicator, also this one is considered as positive.

y, %	Opportunity level
$0 \leq y < 1$	No opportunity
$1 \leq y \leq 10$	Low opportunity
10 < y ≤ 10	Medium opportunity
25 < y	High opportunity

Table 4.3: *CSED opportunity assessment: extend of a sector's contribution to the national economic, hence social development [42]*

Promoting social responsibility

Social responsibility is intended as the obligation of the company to take into account in their management the interests and needs of its stakeholders. Interests and needs are intended as human rights, labor, environment and anti-corruption. Social responsibility can be integrated both in the business and in the supply chain. The social value created by this integration can be of great impact, but it varies from sector to sector, and it is highly difficult to quantify. For this reason, in PSILCA this subcategory is measured by memberships in initiatives and foundations with a related focus, such as the existence and number of codes of conducts and contractual agreements with suppliers concerning social responsibility.
Regarding the quantification of the social responsibility promotion along the supply chain, which in this work is the most important, the UN Global Compact Initiative association is considered. It provides supports for companies to align their strategies and businesses with the ten principles of social responsibility, which are highly related to the one cited previously: human rights, labor, environment and anti-corruption. The UN Global Compact Initiative defines a list of participants classified by sector and location. For the quantification of this subcategory in PSILCA, this list is normalized with the number of employees and mapped to the Eora sector. The risk scale for the evaluation by the program is shown in Tab.(4.4,[42]). Also this indicator is considered as positive.

y, %	Risk level
$110 \leq y$	very low risk
$70 \leq y < 100$	low risk
$5 \leq y < 70$	medium risk
$1 \leq y < 5$	high risk
y < 1	very high risk
-	no data

Table 4.4: *PSR impact assessment: risk of unsustainable business practice [42]*

Fair salary

The fair salary index is considered as a fair wage with respect to the service value offered by the company. The assessment of a given level of wage was created considering the following three main points:

- The minimum wage required by law;

- The local ‘prevailing industry wage’;
- The ‘living wage’ (also sometimes designated as a ‘floor wage’ or ‘non-poverty wage’).”

Following this framework developed by UNEP, the fair salary index is calculated considering the three following subcategories: “Living wage, per month”, “Minimum wage, per month”, and “Sector average wage, per month” Tab.(4.5,[42]).

y, [USD]	Risk level
y < 100	very low risk
$100 \leq y < 200$	low risk
$200 \leq y < 500$	medium risk
$500 \leq y < 1000$	high risk
$1000 \leq y$	very high risk
-	no data

Table 4.5: *FS impact assessment: risk that cost of living is high [42]*

Chapter 5

Results of the LCSA

In this section the most important results of the research carried out with openLCA are described and explained. The studies in this first section have been modeled to understand where the company stands in terms of sustainability, by analyzing the three aspects of the E-LCA, LCC and S-LCA separately. The aim of this section is to show the effects changes of scenarios have on the chosen indexes of the sustainability quantification.
The analysis for the E-LCA and LCC will be carried following this path: since the main business of the company is the car rental, the main differences are brought by changing the percentages of electric cars, diesel/petrol and refrigerator trucks. The three scenarios presented are as follows:

- Equally Distributed Vehicle Categories-Grid (EDVC-G): Through the change of the composition of the fleet of cars it will be possible to understand which typology of cars most contributes to the sustainability impacts. This will be obtained by selecting as an input the same percentages for each typology of cars. In this case electric cars are charged through the regional gird. The main differences will be in emissions, since the production of electricity accounts from about 60% from fossil fuels, topped by natural gas with 50% [46].

- Equally Distributed Vehicle Categories-Photovoltaic (EDVC-P): This case uses the same category percentages as the one of the grid case, but electric vehicles are charged through the electricity generated from the photovoltaic plant on the roof, which delivers a power of 120 kW.

- Current Distribution of Vehicle Categories-Photovoltaic (RDVC-P): In this scenario, the real percentages for each typology of cars of the company as of now is used. This will help studying the present sustainability performances of the company.

The analysis for the S-LCA will be carried addressing the two following scenarios. In this case only the manufacturing is considered, there is no distinction for the charging phase:

- Equally Distributed Vehicle Categories (EDVC): This case uses the same car category percentages in order to show how EV and ICE performs for each social indicator.

- Current Distributed Vehicle Categories (RDVC): In this scenario, the real percentages for each typology of cars of the company as of now is used. This will help studying the present sustainability performances of the company.

5.1 E-LCA

The first phase of the E-LCA consist in showing the main differences between the three scenarios. The study is divided in the two Fig.(5.1) and Fig.(5.2) that respectively represent the impacts for the Human Health (HH) and for the Environment (E). As can be noted, the first two cases mainly differ only for the impact of the EV category of vehicles. In fact, the one that presents a photovoltaic production shows an interesting decrease in impact for all the indexes. This result was quite expected since the PV production apart from the initial phase of manufacturing of the panels and structures does not produce emissions. The same cannot be said for the internal combustion engine cars. Nevertheless, the manufacturing of the electric cars still presents limitations. OpenLCA gives the possibility to dig into the roots of what increases the four indicators. This enables the company to work on each of the aspects of its service to improve its overall sustainability. All these aspects will be discussed in deep below.

The two most important indicators for the HH impacts are shown to be the human carcinogenic toxicity and the global warming. While the *Fine Particular Matter Formation* (FPMF) and the *Water Consumption* (WC) can be considered nearly irrelevant. For this reason, the company would have to work mainly on the causes that increase the first two values. Regarding *Global Warming* (GW), Fig.(5.1) mainly shows that diesel car and refrigerator truck are the two categories that contribute the most to the impact. The refrigerator tracks have higher impact both in the production of the vehicles and in the consumption, but this is mainly given by their bigger size. Petrol cars instead have the smallest contribution between internal engines, this is given by the use of petrol as fuel, but also to the smallest size of the vehicles used by the company. The average construction of the vehicle

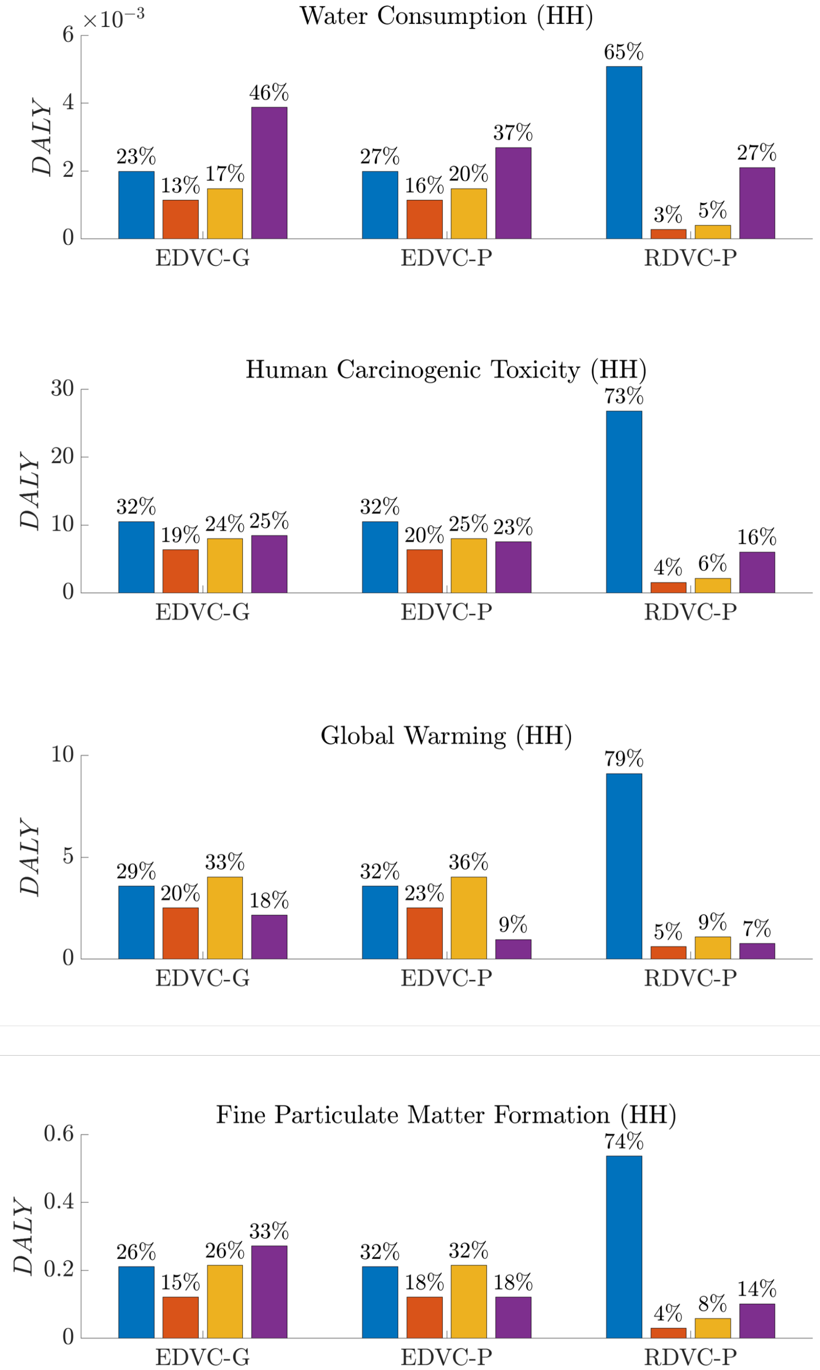

Figure 5.1: *Human Health value comparison (Blue=Diesel, Orange=Petrol, Yellow=Refrigerator truck, Purple=Electric vehicle)*

glider takes about three times the construction of the power-train of the internal combustion engine, but the interesting result is that the construction of the whole vehicle normally takes only 1/5 of the consumption of the total life-cycle impact of the car. The same cannot be said for the electric cars which have a much higher percentage since the vehicle usage takes much less in terms of everyday consumption. Electric vehicles have a similar building emission of internal engine cars, but in this case the battery takes about 46% of the total vehicle construction emissions. Less relevant in the life-cycle of the vehicle are the maintenance of the vehicles and the road maintenance/construction. Furthermore, in general it can be said that diesel vehicles tend to contribute more to global warming impact category, while electric cars with PV production much less. The differences between the first case and the second one, are only due to the supplying of electricity, but as can be seen it does not change the final result significantly. For the global warming there is a reduction of impact of 87.4% in the electricity supply. Moving forward to the second most relevant indicator, the *Human Carcinogenic Toxicity* (HCT) is mainly connected to the vehicle manufacturing, in fact looking at the first two cases of the HCT indicator, all categories have similar values, and the electric car does not change much. In this case the company can only choose vehicles that presents a lower impact in terms of car manufacturing, but it will not be able to do anything significant inside the company management to diminish the impact. The other two indicators follow a similar trend as the global warming one, but with higher values for the electric vehicles. These are anyway negligible since the values are way lower than in the other two cases.

The results of the impact on the ecosystem are shown in Fig.(5.2). As can be seen four are the indicators chosen for the quantification of the ecosystem sustainability, but as in the first case only two are more relevant. The first one is the *Marine Eco-toxicity* (ME), which in this case is higher for the electric vehicles. The reason why, is that it is strictly connected to the manufacture of the battery, which takes almost 60% of the total share of the impact. In fact, batteries do have a bad impact on the marine toxicity, but many are the possibilities to reduce it [55]. Nevertheless, this would not be a task for the company Iesse, but for the battery manufacturer. The remaining share of the impact is due to the manufacturing of the vehicles. The other relevant indicator is the global warming index, which as for the human health impact presents a much lower value for the electric vehicles with photovoltaic production. Here, as in the previous case the share is mostly dependent on the fuel used by the vehicles, in fact the trucks and diesel cars have the higher impact.

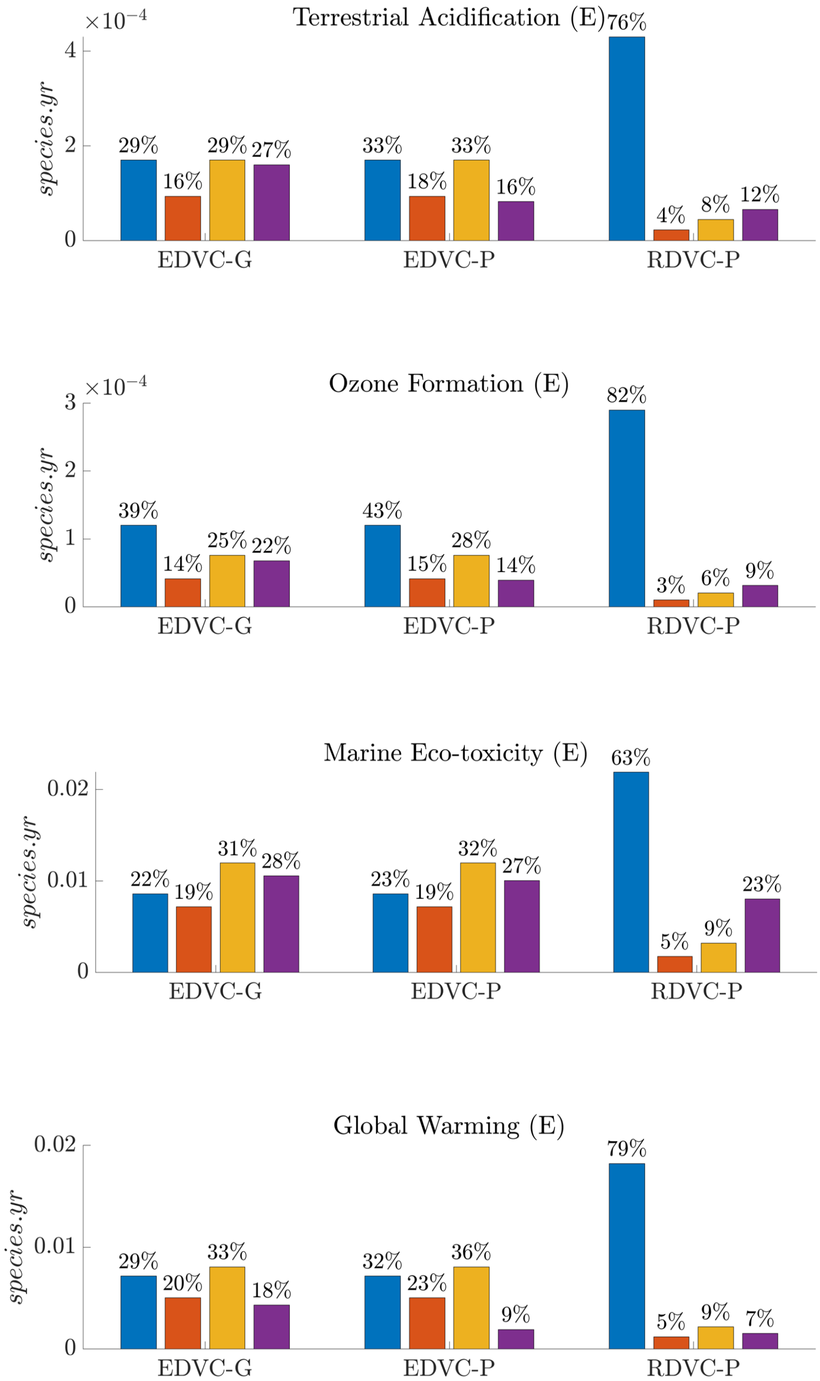

Figure 5.2: *Environmental values comparison (Blue=Diesel, Orange=Petrol, Yellow=Refrigerator truck, Purple=Electric vehicle)*

Lastly, it is interesting to have a look at the two graphs represented in Fig.(5.3), which show the total emission for each case and category, showing which is the final best category to provide the service in the most sustainable way. By looking at the first two cases, it is easy to see how the electric category with electricity photovoltaic production is the one that less arms the human health and the eco-system. Further, the petrol category has a really low impact in both HH and E, but this can be mainly explained by the fact that petrol vehicles have been selected as cars of small size, the one used by the company. This has effects on both the manufacturing of the cars and emission during their life-cycle. So electric cars charged by photovoltaic remain the best option. Unfortunately, as of now it would not be possible the complete substitution of internal combustion engine cars with EV since a good share of diesel vehicles is composed by vans and refrigerator trucks, categories of vehicles that have not been launched in the electric vehicle market. Furthermore, most clients are interested in ICE cars since the system in Sardegna is not yet ready to have an elevated number of electric cars. Most charging station would be alimented by the regional grid, falling in this way in the first case scenario (EDVC-G), that resulted much less sustainable. This enlightens how this study defines a decision-making process for investments in the long terms, that does not only asks for a transition in the company assets, but also in the overall grid system. As a matter of fact, the company Iesse already started the transition through a more sustainable approach by extending their fleet of vehicle with electric cars and by using photovoltaic panels for the electricity supply.

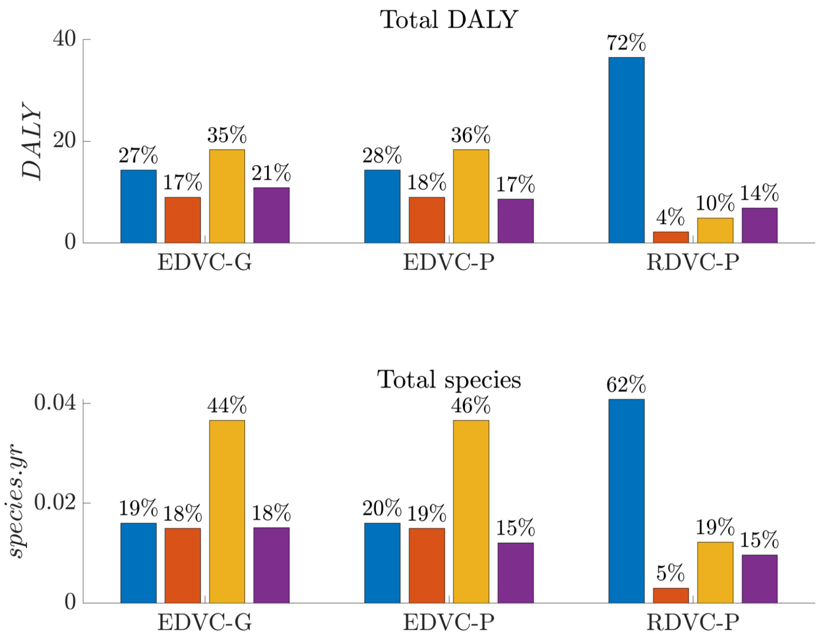

Figure 5.3: *Total impact values comparison (Blue=Diesel, Orange=Petrol, Yellow=Refrigerator truck, Purple=Electric vehicle)*

5.2 LCC

The LCC was performed with the use of only one indicator, the final results of the three cases are shown in Fig.(5.4). As explained before the impact calculated for this aspect of the sustainability assessment is the Net-cost, explained in section (4.1.2). This indicator helps us understand which are the categories that are more costly, which one can be cut or improved under an economical perspective. It is strictly connected to the E-LCA, in fact the flows used are the same. By looking at the first two cases of Fig.(5.4) it is easy to see that similarly as for the E-LCA aspect, the change in supply of energy has an incredible impact on the cost assessment. In fact, looking at the results more in-deep, the price of the electricity supply has 1/5 of the cost of the electricity from the grid. This has an incredible impact on the final overall price, which would be even more relevant with a higher number of electric vehicles. Nonetheless, fuels such as diesel and petrol have similar prices to the electricity supply. Furthermore, there is a big cost difference between the battery production and the manufacturing of the internal combustion engine. In fact, the former results in costing nearly 25% less. As expected again, the manufacturing

and usage of the refrigerator trucks and small size petrol cars represents the two extremes of the calculation. The first one being vehicles of large size with the addition of cold rooms and refrigerants, and the former being vehicles of smaller size.
Having now a closer look to the present status of the company, as can be seen from the difference in total net cost, the company has a good level of economical sustainability, and the transition to more electric vehicles would decrease sustainability performances.

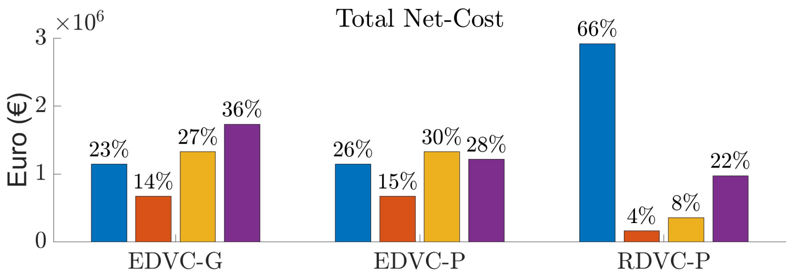

Figure 5.4: *Total net-cost (Blue=Diesel, Orange=Petrol, Yellow=Refrigerator truck, Purple=Electric vehicle)*

5.3 S-LCA

The social aspect of the sustainability was analyzed using four indicators, which were considered as the most significant for the car rental company service, and the ones better able to describe the social sustainability conditions with the available data. As previously explained, the social assessments tend to be expressed with more qualitative than quantitative measures. For this reason, the results in this section will be analyzed based only over the composition of the fleet of cars for the company, and by analyzing only the two main relevant categories: electric cars and diesel cars, for each indicator separately. These decisions are based also on the limitation brought by the lack of data. The Fig.(5.5) below represent the medium risk quantities for each of the four indexes selected. From the four graph it is easy to notice how the EV do have a stronger impact than ICE in terms of social impacts, both positive and negative. In most cases the main differences are relative to the production of the battery. For example, taking into account the indicator *Certified Environmental Management Systems* (CEMS), about 65% of the total share of the impact is taken by the battery manufacturing. This shows us how the manufacturing of batteries, which due to the use of more polluting materials, results in less EMS, even if slightly. In fact, the manufacturing of the vehicles' parts for EV and ICE takes about the same share for the two categories. Nonetheless, for the second indicator considered, *Contribution to the Sector Economic Development* (CSED), the highest share of the contribution is the manufacturing of the vehicles parts of the electric vehicle, that include the electric motor. Different behavior is found for the *Fair Salary* (FS) indicator. This highlights the salaries in the electric car manufacturing in France result in being less fair than the ICE vehicle manufacturing in Germany, with a significant gap between the two. Lastly, the *Promoting Social Responsibility* (PSR) indices presents a similar trend as the previous one, with the manufacturing of the EV parts that takes the highest share with 44%. Then the manufacturing of the ICE vehicles with 38%, and then the storage battery manufacturing with the lowest share, of about 18%. This indicator defines a negative impact, so diesel vehicles are the ones that mostly engage the promotion of social responsibility. This in deep analysis of the results can be applied to the current situation by shifting the purchasing of car to the more socially sustainable, but also by extending the research to different categories of vehicle in order to expand the decision-making process to other typologies of cars. This assessment can also help the manufacturer to improve or eliminate flows that decrease the social sustainability in their car manufacturing process.

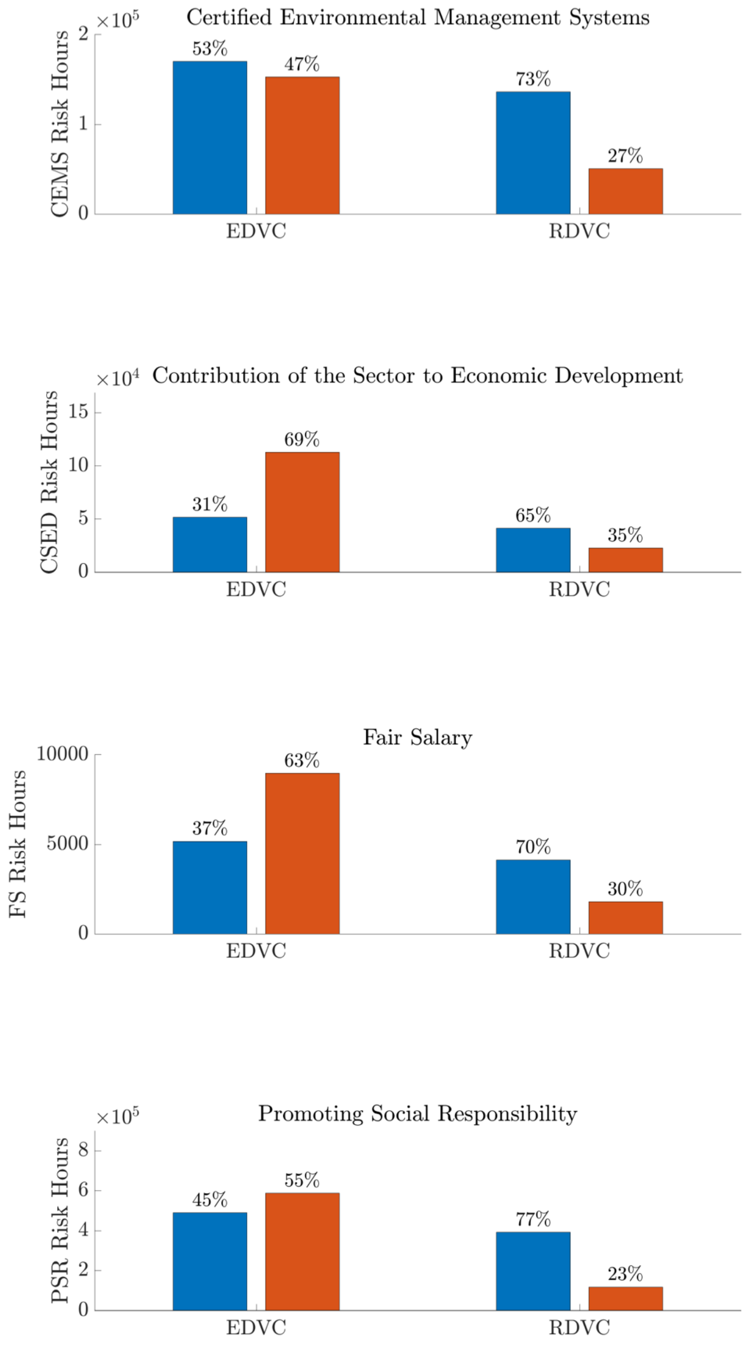

Figure 5.5: *Social indexes comparison (Blue=Diesel, Orange=Electric vehicle)*

Chapter 6

Multi-criteria decision analysis for the LCSA results interconnection

6.1 Multi-criteria decision analysis

The last part of the presented framework, consist in the interconnection of the results obtained from the life cycle impact assessment. A total of 13 indexes have been selected for the interpretation of the impact obtained from the life cycle sustainability analysis, 8 for the E-LCA, 1 for the LCC and 4 for the S-LCA. The total amount of units of measurements are 7, the DALY and species.yr for the E-LCA, the added value for the LCC and 4 different medium risk units for the S-LCA. Now that all the values have been defined, a methodology to interconnect them and see how they vary depending on the decision-making, needs to be selected. The in-deep analysis of the literature review of section (1.2) indicated that the scientific community relies mainly on the MCDA methodology, which seems to be highly used in conjunction with the LCSA methodology. The study performed by Cegan et al. [56] identified in the Web of Science database 3000 papers concerning MCDA in the environmental field. The analysis categorized the studies on the MCDA methodology used and on the field of research. The results show how the percentage of papers that introduced MCDA in their framework followed a constant increasing trend over the past 15 years. The mostly used methods are AHP/ANP and MAUT/MAVT, with 49% and 43% respectively. Less used are TOPSIS and outranking. The paper also showed how the three most appearing keyword were in order strategy, stakeholder and sustainability, this shows to which concepts the MCDA methods are mostly applied.

6.2 Multi Attribute Value Theory

This thesis applied the MCDA using the software DECENS [35], a program that enables the user to easily create product systems and apply 9 different MCDA methods. While defining this section, it was noticed that the chosen MCDA methodology mainly depends on the case study and final objective of the work. In this thesis the MAVT was chosen, which can be incorporated with other methodologies such as AHP to help the weighting selection. The MAVT method final objective is the creation of an integrated function able to represent the decision maker's preferential system. The function is built following the formula as follows:

$$V(a) = F(V_1(a_1), ..., (V_1(a_1)) \tag{6.1}$$

where a_j is a vector of the evaluation criteria, $V_j(a_j)$ is the score associated to all the values a_j can assume. The final objective of MAVT is the definition of a set of functions V, which summed up (sum is the most used method, also used in DECENS) after weighting, will have an optimal solution that can be identified. The formula of the final objective function is as follows:

$$V(a) = w_1 V_1(a_1) + ... + w_m V_m(a_m) \tag{6.2}$$

As can be seen, each function $V_j(a_j)$ is multiplied by a weight larger than 0, and the the sum of the weights must be equal to 1. This methodology gives the total power to the decision-maker to select the weights of the case. This method was chosen between the MCDA methodologies because it enables the creation of functions to establish how the final score of the company sustainability varies, modifying the weights. This function is highly important to understand the dependency the final score has on the weights given to the three different aspects, or to each one of the indexes that define the Product Systems. In this work case study the MAVT is used to create a function for each index and define two main functions, one for the diesel category and one for the electric vehicles. DECENS also allows the creation of exponential and piece-wise functions. For the considered case study, the indexes can be expressed through straight lines, and data are assumed to be taken without uncertainty. If uncertainty is considered, the Multi Attribute Utility Theory (MAUT) can be used. The created functions perfectly represent the trend of all the indexes of this case study. The product system's structure is shown in Fig.(6.1). The figure also helps understanding how the system was created in a figurative way. The program performs a normalization for each of the yellow boxes. Since depending on the indicator, the optimum value score needs to be maximized or minimized, for each of the boxes the minimum/maximum can be selected. In the end the final score will be a number between 0 and 1, where 0 is the worst-case scenario, and 1 is the best-case scenario. It is important to highlight that the choosing of the maximum values of each index is fundamental for the calculation of the final score. In fact, the score to each indicator is given based on the distance of the function's point to the maximum or minimum value, so it will depend on the range of chosen values. The best option would be the definition of a benchmark for this category of companies, that can be scaled based on the size of the company. In this study the sustainability assessment will be defined strictly on the company business, so the range will always go from 0 to the maximum value of the category that has the highest value.

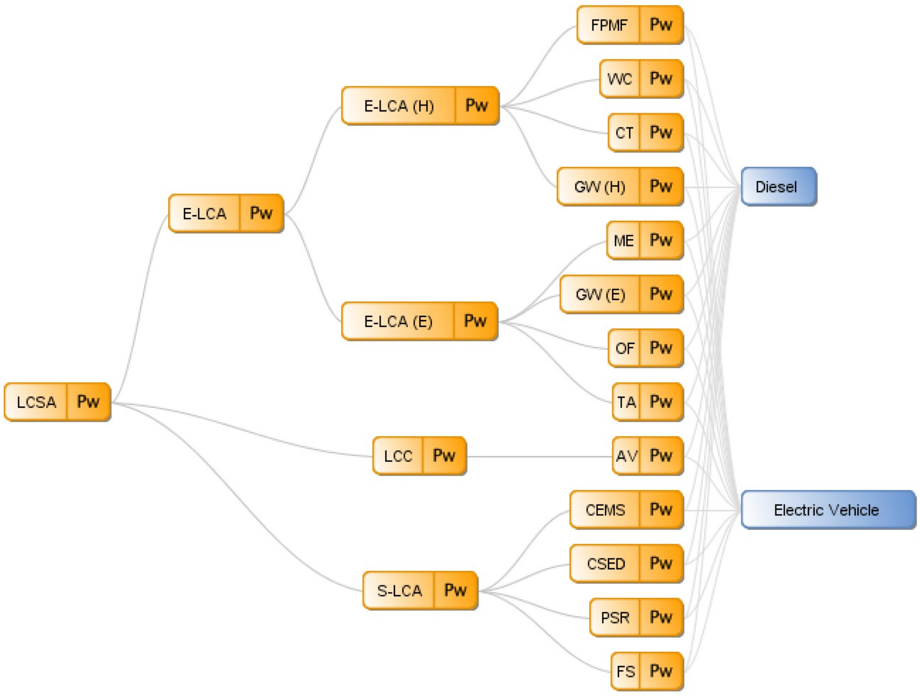

Figure 6.1: *Work-flow scheme for the MAVT application*

For example, if an indicator is 10 for the diesel and 7 for the EV, the following can occur:

1. Maximum is the optimum value: the diesel will score 1 and the EV will score 0.7;

2. Minimum is the optimum value: The diesel will score 0 and the EV will score 0.3.

Taking into consideration for example a benchmark that says that the range for this company goes from 0 to 20, the final score will be different:

1. Maximum is the optimum value: the diesel will score 0.5 and the EV will score 0.35;

2. Minimum is the optimum value: The diesel will score 0.5 and the EV will score 0.65.

This underlines the importance of the definition of a benchmark, that would enable the creation of a well-defined range of values to compare the companies of same, or even different sectors.

6.3 Analytic Hierarchy Process (AHP)

The analytic hierarchy process is a method created by Saaty TL et al. [57] in 1980. It is founded on the pairwise comparison between criteria, and it presents a different additive model with respect to Eq.(6.2), but with a different weight and decision matrix calculation. This method creates a matrix nxn, where each criterion is pairwise compared to the other. In the pairwise comparison, if one criterion takes the values s, the respective one will get the value $1/s$. The value of s can go from 1 to 9, meaning that in the pairwise comparison, one value can range from 1 to 9, the other from 1 to 1/9 respectively. The AHP model is based on the assumption that judges are better at taking relative than absolute decision, differently than in the MAVT method. This only expresses a different method for the weight system definition. Weights found with AHP can then be applied to the MAVT model, to perform a sensitivity analysis for a better weight selection. The use of both methodologies will be explained in section (7).

6.4 Sustainability function's framework

This unit is introduced to explain a possible alternative for the visualization of the interconnection of the impact assessment's results. The MATLAB code presents a similar framework to the MAVT method, but with a different final visualization of the data and range selection. The system's framework has an inverse development with respect to the MAVT system of Fig.(6.1), since it starts from the indexes' functions, and ends with the creation of the sustainability quantification function. The code starts with the definition of functions related to each of the indexes. Functions can be created interpolating points, or just by finding the equation of a straight line passing for two points, as in this case study since the indexes increase linearly with the variation of the vehicle's category percentages. Each indicator will have two functions, one for the diesel and one for the electric vehicles. The idea is to divide the two functions in 100 points, and sum them following the system shown in the equation (6.3).

$$\begin{cases} 0 \leq D \leq 100; \\ 0 \leq EV \leq 100; \\ D + EV = 100. \end{cases} \tag{6.3}$$

This defines a representation of the indicator measure when varying the composition of the fleet of cars. This process is repeated for each index. Subsequently, all the functions with the same unit of measurement are summed up, so the final value is obtained. Now four functions have been created, one for each one of the units of measurements ($DALY$, $species.yr$, $Net - cost$, $medium\ risk\ hour$). The workflow, once the functions are in the system, is presented in Fig.(6.2). Then, each function is normalized with respect to the maximum and minimum. Now scores are assigned to each of the points defined previously. As discussed before, indexes can be positive or negative in the sustainability quantification, so the maximum can represent the optimal level, or vice versa for the minimum. Two are the possibilities:

- Maximum: the score will be equal to the values assigned to the normalized function;

- Minimum: the score will be equal to 1 minus the values assigned to the normalized function.

Next, a weight is applied to the four functions. Once the functions are normalized and weighted, they can be summed up to obtain the final function that express the sustainability of the company. The function is denominated as "*Sustainability function*", and it will range from 0 to 1. The interesting aspect of this visualization is the possibility to understand how far the analyzed company is to the optimal system, and how the sustainability varies for every slight change in the fleet composition.

This methodology differently from the MAVT and AHP methods does not give any insights on how to model the weights in the analysis, but MAVT and AHP from their side are not able to represent in a clear and easy way the sustainability trend for the company, being two complementary approaches. Furthermore, this method is easily scalable for case studies that present more variables and indicators. Of course, increasing the variables, the iterations will increase exponentially, so variables need to be chosen carefully.

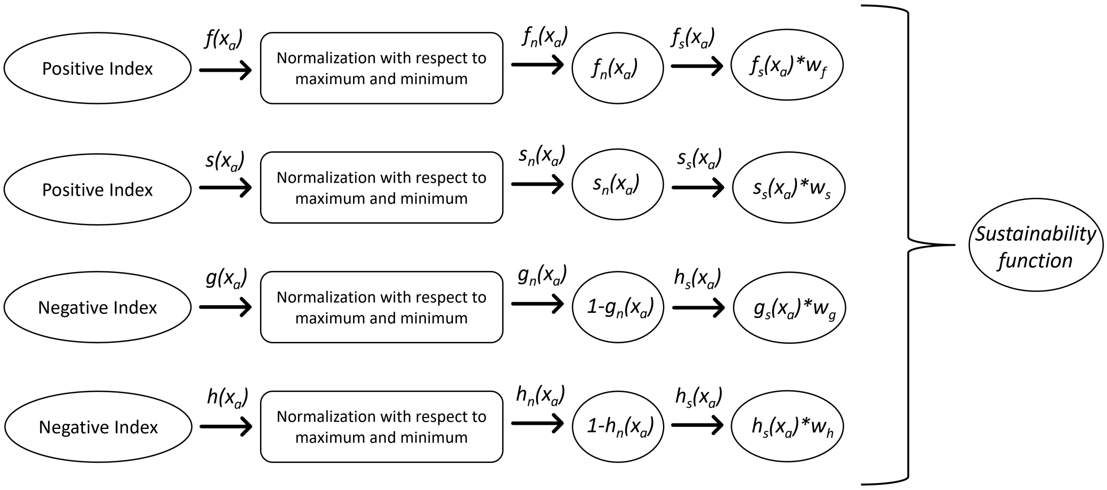

Figure 6.2: *Block scheme of the MATLAB code for the sustainability function creation*

Chapter 7

Framework results presentation

This section is dedicated to the description of the results obtained from the interconnection of the three pillars of sustainability. The results will be presented following the same order used in section (6).

7.1 Multi criteria decision analysis results

7.1.1 MAVT Results

The multi attribute value theory method was used in the framework to model the weighting scale and to obtain a final score for the company. It allows the user to select an initial set of weights for each of the criteria and monitor the trend of the score based on a sensitivity analysis on the weights.
The initial case is presented with the same share of weights distributed to each criterion. This baseline case is used to understand how the model would behave if environmental, economic and social aspects were valued as equal. The score trend represented by this initial case can be seen in Fig.(7.1). The red bar represents the score of the company if it was composed 100% by electric vehicle, the purple bar if it would be 100% diesel and the green bar the current composition of the fleet of Iesse, which is made by 20% electric and 80% diesel. It is possible to see that the electric vehicle alimented by PV has higher score respect to the diesel. This will mean that in general the values of the EV are closer to the optimum maximum/minimum, depending on the indicator. The value of the company instead stands in between the two values, much closer to the diesel given the composition. The behavior of the variation of the score by changing the percentages was found to be linear and oscillating between the two maximum and minimum scores.

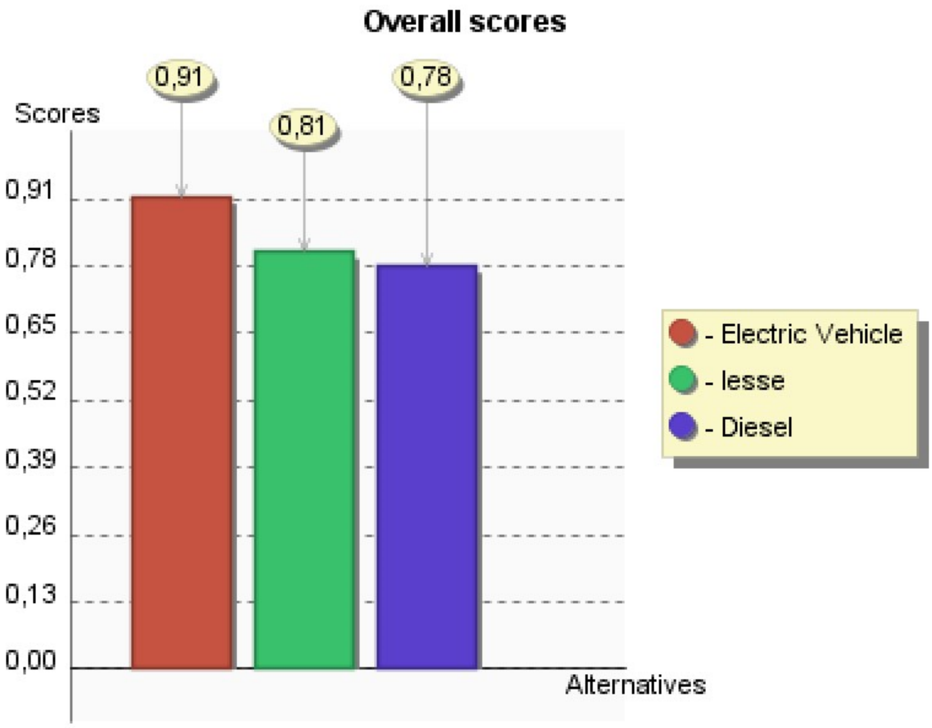

Figure 7.1: *Overall score using the MAVT method, scenario with equal share for each car category*

Now it is possible to perform a sensitivity analysis (SA) based on this weighting scale. The SA is shown in the three graphs represented in Fig.(7.2). The graphs are representing the variation of the E-LCA weight, LCC weight and S-LCA weight respectively. The x-axis represents the variation of the weight, from 0 to 1; The y-axis is referred to the score of the company, which as can be seen has a linear dependence to the weight variation.

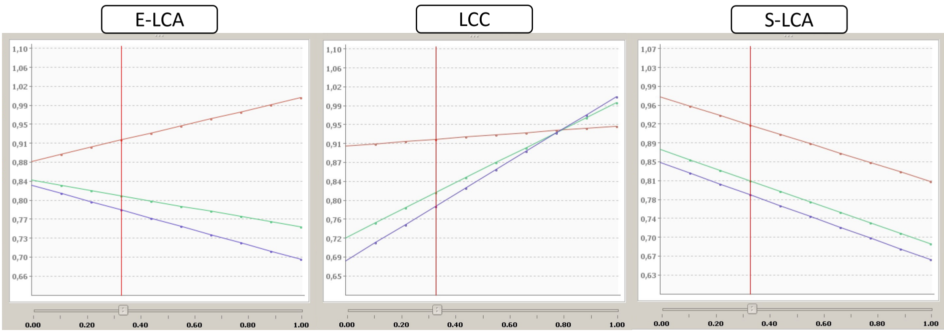

Figure 7.2: *Weight SA using the MAVT method, scenario with equal share for each car category (x-axis=% vehicles share) (y-axis=score)*

Analyzing the three graphs of Fig.(7.2) and looking at the slope of the three curves, it can be noticed that the EV and Diesel vehicles have opposite behavior for the environmental and economic aspects, while socially do not differ much. In fact, considering both the extreme cases of the E-LCA and LCC, it can be seen how in the first image scores tend to diverge, while in the second one to converge. This was expected, since environmentally EV performs better than diesel, and vice versa for the economic aspect. Socially instead the two scores behave nearly equally, in fact the slope is almost the same.

Having now a closer look to the current case study, it is possible to state that the weaker aspect in terms of data and indexes is the life-cycle costing. Taking this into consideration, the assumption that the LCC has a lower impact on the sustainability assessment can be taken. Furthermore, even though the S-LCA was performed with an acceptable set of data and the chosen indexes represent the social aspect with a good approximation, only the global aspect was considered, not taking into account the impact on the local community. For this reason, also the assumption that S-LCA has a lower relevance on the LCSA than the E-LCA but higher than the LCC, is considered. The value assigned to the weights of the E-LCA, LCC and S-LCA are 0.5, 0.15 and 0.35 respectively.

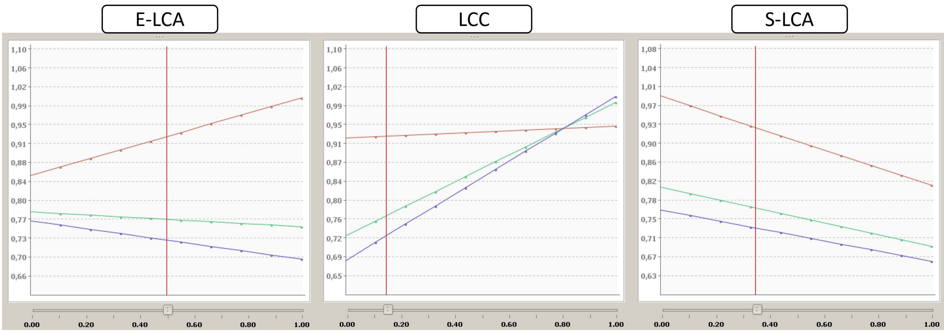

Figure 7.3: *Weight SA using the MAVT method, scenario adapted to case study (x-axis=% vehicles share) (y-axis=score)*

In Fif.(7.3) the results of the previously stated assumptions are presented. Having a general look at the graphs it can be noticed that even though the score results higher for the EV, the trend of the scores tends to be almost equal to the one of the previous case. The score of EV for this scenario is 0.92 while the diesel one is 0.73. Between the two cases this should be the more reliable one.

The program also allows to edit weights internally for the E-LCA, LCC and S-LCA. Obviously, the variations in these cases of the score functions will be less significant with respect to the three aspects weight variation, but it still may be important for a more precise final solution. In this case study, the unit of measurement are only four, "*DALY*", "*species.yr*", "*Euros*" and "*mediumrisk*", and the only ones belonging to the same category are the first two, since the "*medium risk*" has been factorized with the PSILCA impact assessment [40, 42]. For this reason, the current case study does not require a sensitive analysis of the units of measurements, but the study can be applied also to assessments with different units of measurement inside the same sustainability aspect.

It can be noticed how the score of the company stands in between the two lines (green line). This behavior was expected, in fact the results of the LCSA analysis vary linearly with the variation of the composition of car fleet, as previously explained. Of course, the company weight function with respect to the score will be closer to the diesel one. The more the percentage of EV increases, the more the slope of the company's function will get closer to the slope of the EV category, hence improving its score. This analysis may be an interesting framework for experts to be followed. It could help to better define weights in sustainability analysis. This method represents an easy and clear way to show how scores behave when depending on weights.

7.1.2 Analytic Hierarchy Process Results

The AHP can be used in this framework as an alternative method to calculate the weights. As previously anticipated, AHP allows the calculation of weights through more relative than absolute judgments. In this section the assumptions of the second case used in section (7.1.1) will be assessed, but using the AHP method. As previously E-LCA is the aspect considered more complete and with the most reliable data, for this reason it will have a higher importance than the economic and social case. Similarly, also the S-LCA aspect presents more reliable data and indexes, so it will be treated as more relevant than the LCC. The decision table is presented in Fig.(7.4). The weights assigned after this pairwise comparison are 0.558, 0.122 and 0.319 to the E-LCA, LCC and S-LCA respectively.

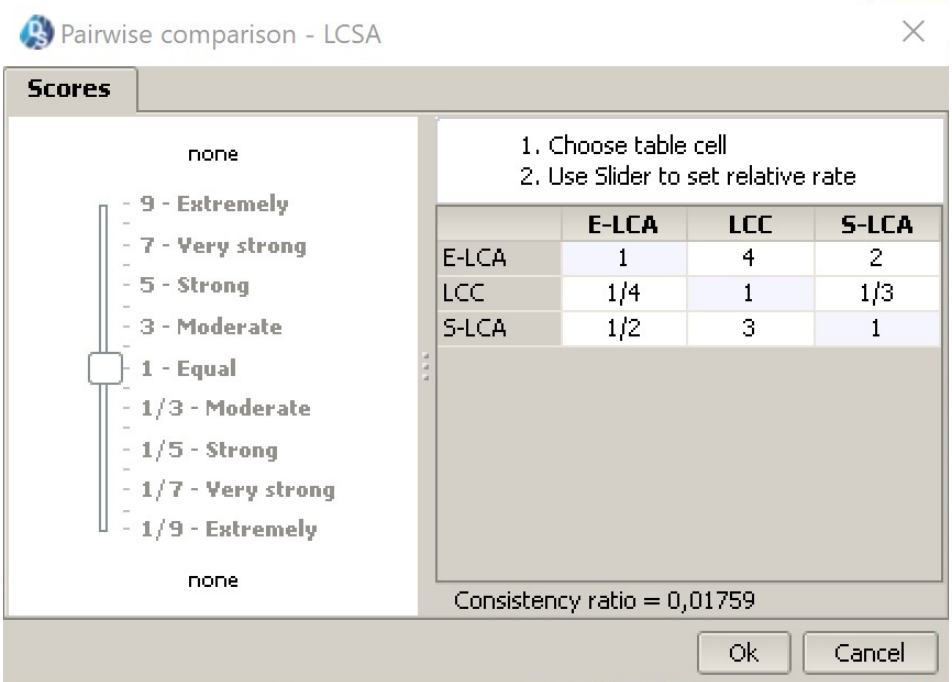

Figure 7.4: *Weight calculation using the AHP method, scenario adapted to case study*

Shown in figure Fig.(7.4) the values chosen to reflect the assumption made are represented. It is important to highlight that this is just a simple case where the weight are assigned only to the three aspect of the sustainability, but to develop a more precise system of weighting, the same pairwise comparison should be applied to each one of the boxes of Fig.(6.1), especially for the S-LCA aspects, that as previously explained, presents more qualitative then measurements. Applying these weights to the MAVT method then a sensitivity analysis can be applied again to perform a more accurate study on the weights.

7.2 Sustainability function calculation & results

The MATLAB code represents a different approach for the visualization of the final score of the sustainability quantification. The main differences between this methodology and the previously mentioned ones, are the flexibility and clearness, since it was developed based on the final objective of the Iesse case study. This gave the possibility to create a model to represent the value of the sustainability performance as a function dependent to the variation in category's car share. The behavior of the company sustainability, as expected is represented by a straight line (given the previously explained linearity dependence on the indexes in section (7.1.1)). The same behavior was found using the MAVT method in section (7.1.1), but a different weighting range was applied. In fact, in DECENS the score increased linearly with the increase of EV share, drawing an imaginary straight line. This shows that the program behave correctly for the current case. The sustainability function of the given case is shown in Fig.(7.5).

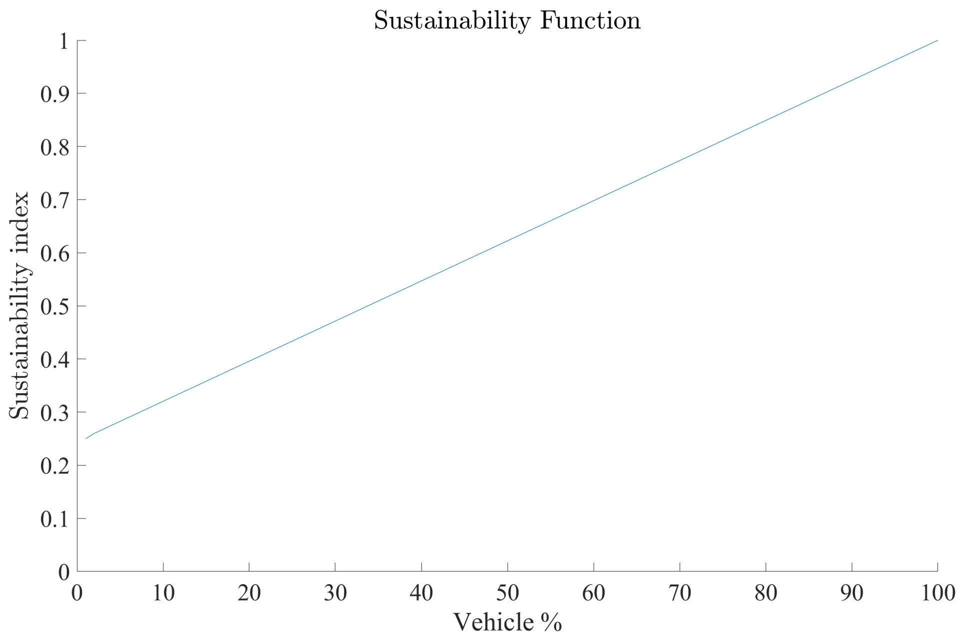

Figure 7.5: *Sustainability function representation of the company's case study*

It is important also to highlight that the current work is dependent on the company information. The case study was selected to monitor the behavior of the framework in the real world. This model would be interesting if implemented for a more complex case study that present a non-linear distribution of the data. In the former case, the optimum may be found anywhere along the sustainability function,

presenting a more complex result to be found. Furthermore, in the Iesse case study, because of the lack of data and to make the overall calculation easier, only two variables (EV and Diesel) were defined. On the contrary, a case study with more variables would create a calculation with a significant number of variables. This would define a much more difficult solution to be found, making the program incredibly valuable for the sustainability calculation.
To show the intended outcome, a system with four indicator represented by four piece-wise functions randomly assembled was created, the first two seeking to find the maximum, and the other two the minimum. The number of variables is kept constant, and it reflect the same situation of the case study, the variability of the car category's share for the company. The result is presented in Fig.(7.6). As can be noticed the sustainability function is irregular and presents two maximums and two minimums. The function reflects the sustainability of the company, showing for each percentage of car fleet, which is the performance value. For example, in this random case two maximum points with nearly the same values are observed. If the company finds itself at a percentage value of 20%, and seek to optimize its sustainability, the most convenient choice is to move to the closest maximum, since moving to the further one would create nearly the same improvements, but with much more effort.

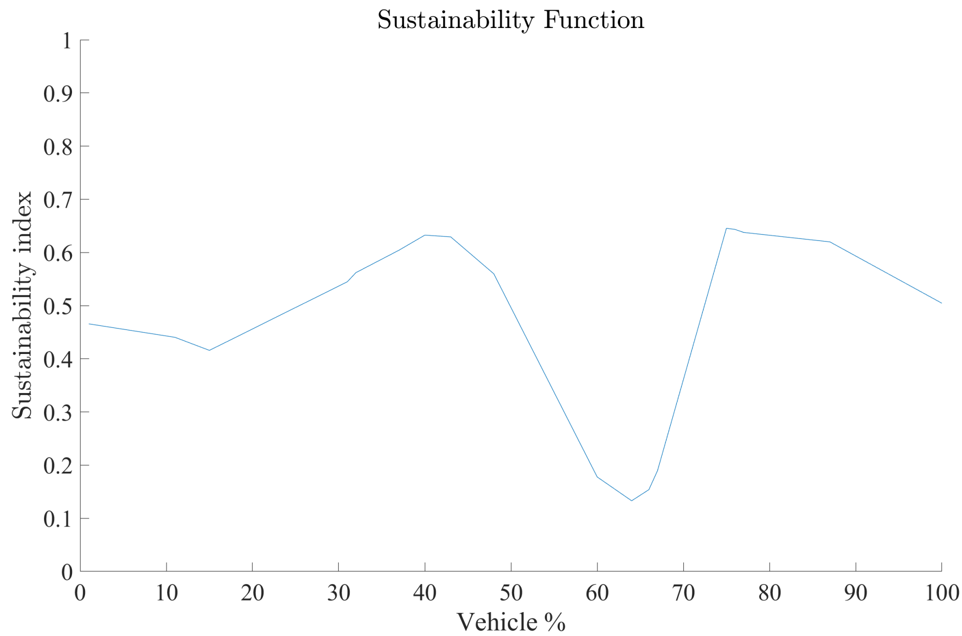

Figure 7.6: *Sustainability function representation of test case*

The last example explains how this framework could help in the decision-making for the company, by showing in a simple way how and where to direct future investments.

7.3 Suggested framework for the weight calculation

In this section a general framework for the interconnection of the three sustainability aspects will be explained. The method can comprehend all three methodologies described in the previous sections of this chapter. The sequence of chronological steps is presented in Fig.(7.7). The bold arrows represent mandatory choices, dashed arrows represent choices that can have more than one possibility. The method is iterative and should be repeated until the optimal solution is found.

1. Calculation of the LCSA impacts;
2. The first method to be used is the MAVT. Once the results are implemented into the system, the score functions relative to the weights are created by the program (DECENS), and the first evaluations are implemented in the system weight selection.
3. This step is composed of two possibilities: the first one is the use of the AHP method to define a more relative judgment on the weights, taking into consideration the assumptions and insight found in step n°2. The second possibility is the direct use of the sustainability function method for a better visualization of the data.
4. The process is repeated iteratively until the optimal solution is found.

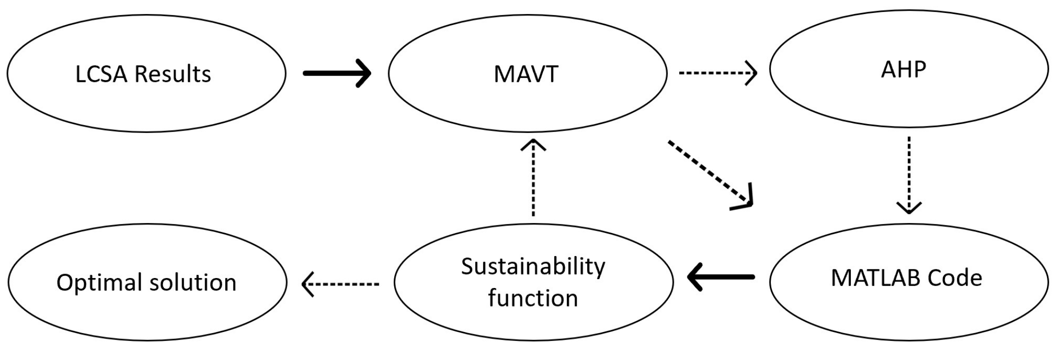

Figure 7.7: *Work-flow of the framework for the weight decision-making process*

Chapter 8

Conclusion

8.1 Discussion & perspectives

Throughout this work, a framework for the weighting selection in sustainability analysis was created. In the framework, a set of weights is created for each sector/sub-sector. The weighting of the three aspects can be given based on different criteria starting from the completeness of the sustainability analysis to the availability of data, the importance of the aspect in the sector, the range of values for each unit of measurement that is normally found in the sector, the importance of the indexes in the given sector, the size of the company (in terms of assets, employers, etc). This framework is thought to be implemented with the knowledge of experts from each of the three aspects of sustainability. It would require a common share both of data and knowledge from companies and sustainability professionals. The completion of a well-defined framework would have different positive outcome, that were anticipated shortly in section (2.2) and that will be treated in relation to the proposed framework shortly.

This thesis presented as example a real-world case study of the business built by Iesse, which presented only two variables. This decision, as previously explained was taken consciously to well describe the framework through a non-complex case study. The same approach that has been used for the optimum composition of the fleet of vehicles, can be applied to different aspects of the company. For example, an analysis of the steps, products and wastes for the car cleaning process, or the rental spaces offered by the company, that would take into account the energy used for the air conditioning, the comfort of the employee etc. The more information is furnished, the more the sustainability analysis will be complete. For this to be possible further digitalization is essential to keep track of data, and commitment and transparency of the company would be even more crucial.

Furthermore, even more interesting is the possibility to apply the same framework, following well defined criteria and parameters to companies belonging to same sectors/sub-sectors, but with different sizes. This distinctive characteristic, as previously anticipated, allows the creation of a benchmark. Once this stage has been reached, defining the sustainability performance of the company will not be as difficult as it is now. The only requirement will be to provide the data to the system that will automatically not only calculate the sustainability of the company, but also rank the company with respect to others. This will help stakeholders, public and private investors in selecting companies based on a new fundamental parameter, the sustainability performance. The interests of stakeholders and companies into a sustainability performance label is positively dualistic, since the first one positively impacts the other. In fact, the interests of stakeholders will increase with the improvement of sustainability assessment, and companies will provide complete and more reliable sustainability assessments to be more desirable in the eyes of stakeholders.

Moreover, the analysis of the provided data from many companies of similar sectors/sub-sectors, by defining better performing companies and by detecting how far is the company from the optimal solution, will be able to give insights on where to improve, limit or delete given processes of the business model, helping managers for future decision-making. Another booster for companies to carry sustainability studies is the significance it has reached to public viewers, as explained in section (1.2.1).

Lastly, given the issues our world has been facing, the final and most important outcome would be the overall improvements at a macro-level in the field of corporate sustainability. A concept that is growing but that needs a precise path to be followed, given the complexity of its success. From one side, the huge impact of the corporate sector would be positively reduced. From the other, the introduction of sustainability would have incredible indirect benefits. Firstly for entire communities, that would finally have guidelines on how to be more eco-friendly. Secondly for individuals, since the introduction of sustainability measures into companies would also instruct and boost workers to be more sustainable in their every-day life. In fact, this issue touches all of us, and small actions taken by everyone could bring massive changes.

8.2 Limitations & further studies

This work presented the definition of a general sectoral framework for the corporate sustainability quantification of a service company. It merged two major methodologies, LCSA for the sustainability quantification and MCDA for the results interconnection. While the former one can be considered as quite mature, LCSA is still under development. The reason why, is that it is composed of three aspects that reflect different ways and units of measurements. The E-LCA, which has reached maturity and reliability, LCC that has improved a lot in past years and S-LCA which is under constant development. For the current case:

- E-LCA was provided with almost all the data required for its calculation;
- LCC difficulties instead were found mainly in the lack of data furnished by the company, that did not allow the calculation of more precise indexes;
- S-LCA found its difficulties in the lack of data in the vehicles industry for a more precise calculation of the indexes.

Furthermore, LCSA is a framework that is primarily used to assess products and not services. The lack of literature on this topic required the adaptation of this methodology to a sustainability quantification of a service, being one of the first of its kind. Another limitation related to the lack of data, is that sustainability has not entered yet the corporate sector, for this reason it is difficult to find companies able to provide data for a complete benchmark creation. These issues are relevant for the interconnection of the results and for the creation of a more reliable sustainability performance score. The possibility to address the quantification using different examples would make the final result more consistent. Then, to apply the framework it is fundamental to gather experts, who need to discuss deeply the different aspects of sustainability in order to be able to perform a good measurement. Furthermore, because of the lack of data the framework was not applied to the maximum of its capabilities.
As predicted, the limitations are a great deal to be overcome, and in some cases may still need time, such as for example the digitalization of companies or the improvement of databases. Nevertheless, some ideas may be helpful for the application of the developed framework in future research. For example, an interesting possibility could be the use of machine learning to simulate sustainability measures and create an initial benchmark. Even more interesting would be the possibility to use companies of different sizes but from same sectors/sub-sectors and simulate measures from other companies to fill the gaps, following the increasing trend of the real-world companies selected, by using a number generator with mean standard deviation. This would help defining a sustainability benchmark that can variate its range together with the size of the company. Future research could focus on the application of the proposed machine learning creation benchmark to fill the gaps dictated by the lack of data, the not yet completed digitalization of companies, test the methodology on different sectors and gather experts of the three aspects of sustainability to better define the weights system.

Bibliography

[1] *2030 climate & energy framework*. URL: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy-framework_en (cit. on p. 1).

[2] Brundtland commission. «Report of the World Commission on Environment and Development: Our Common Future». In: (1987) (cit. on p. 1).

[3] Martina K. Linnenluecke and Andrew Griffiths. «Corporate sustainability and organizational culture». In: *Journal of World Business* 45.4 (Oct. 2010), pp. 357–366. DOI: 10.1016/j.jwb.2009.08.006 (cit. on p. 2).

[4] Agnieszka Żak. «Triple bottom line concept in theory and practice». In: *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu* 387 (2015). DOI: 10.15611/pn.2015.387.21 (cit. on p. 2).

[5] Joonhyun Kim and Jinsoo Kim. «Corporate Sustainability Management and Its Market Benefits». In: *Sustainability* 10.5 (May 2018), p. 1455. DOI: 10.3390/su10051455 (cit. on p. 2).

[6] Justyna Przychodzen and Wojciech Przychodzen. «Corporate sustainability and shareholder wealth». In: *Journal of Environmental Planning and Management* 56.4 (May 2013), pp. 474–493. DOI: 10.1080/09640568.2012.685927 (cit. on p. 2).

[7] *A European Green Deal | European Commission*. URL: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (cit. on pp. 3, 11).

[8] Julia Wolf. «The Relationship Between Sustainable Supply Chain Management, Stakeholder Pressure and Corporate Sustainability Performance». In: *Journal of Business Ethics* 119.3 (Feb. 2014), pp. 317–328. DOI: 10.1007/s10551-012-1603-0 (cit. on p. 3).

[9] Mark Anthony Camilleri. «Corporate sustainability and responsibility: creating value for business, society and the environment». In: *Asian Journal of Sustainability and Social Responsibility* 2.1 (Sept. 2017), pp. 59–74. DOI: 10.1186/s41180-017-0016-5 (cit. on p. 3).

[10] A U Mentsiev, M V Engel, A M Tsamaev, M V Abubakarov, and R S-E Yushaeva. «The Concept of Digitalization and Its Impact on the Modern Economy:» in: Vladivostok, Russia, 2020. DOI: `10.2991/aebmr.k.200312.422`. URL: `https://www.atlantis-press.com/article/125936542` (cit. on pp. 3, 14).

[11] Michael Rachinger, Romana Rauter, Christiana Müller, Wolfgang Vorraber, and Eva Schirgi. «Digitalization and its influence on business model innovation». In: *Journal of Manufacturing Technology Management* 30.8 (Dicember 2019), pp. 1143–1160. DOI: `10.1108/JMTM-01-2018-0020` (cit. on p. 3).

[12] Fernando Almeida, Jose Duarte Santos, and Jose Augusto Monteiro. «The Challenges and Opportunities in the Digitalization of Companies in a Post-COVID-19 World». In: *IEEE Engineering Management Review* 48.3 (Sept. 2020), pp. 97–103. DOI: `10.1109/EMR.2020.3013206` (cit. on p. 3).

[13] Ana Rodríguez-Olalla and Carmen Avilés-Palacios. «Integrating Sustainability in Organisations: An Activity-Based Sustainability Model». In: *Sustainability* 9.6 (June 2017), p. 1072. DOI: `10.3390/su9061072` (cit. on p. 4).

[14] S. Vinodh, K. Jayakrishna, Vishwajeet Kumar, and Ranajyoti Dutta. «Development of decision support system for sustainability evaluation: a case study». In: *Clean Technologies and Environmental Policy* 16.1 (Jan. 2014), pp. 163–174. DOI: `10.1007/s10098-013-0613-7` (cit. on p. 4).

[15] Blanca Corona and Guillermo San Miguel. «Life cycle sustainability analysis applied to an innovative configuration of concentrated solar power». In: *The International Journal of Life Cycle Assessment* 24.8 (Aug. 2019), pp. 1444–1460. DOI: `10.1007/s11367-018-1568-z` (cit. on p. 5).

[16] Sonia Valdivia and Cássia Maria Lie. «Towards a Life Cycle Sustainability Assessment». In: *Sustainability Assessment* (), p. 86 (cit. on pp. 5, 8, 14).

[17] CALCAS. «D20 Blue Paper on Life Cycle Sustainability Analysis». In: (Aug. 2009) (cit. on p. 5).

[18] Nuri Onat, Murat Kucukvar, Anthony Halog, and Scott Cloutier. «Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives». In: *Sustainability* 9.5 (Apr. 2017), p. 706. DOI: `10.3390/su9050706` (cit. on p. 5).

[19] D. Costa, P. Quinteiro, and A.C. Dias. «A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues». In: *Science of The Total Environment* 686 (Oct. 2019), pp. 774–787. ISSN: 00489697. DOI: `10.1016/j.scitotenv.2019.05.435`. URL: `https://linkinghub.elsevier.com/retrieve/pii/S0048969719324891` (cit. on p. 5).

[20] Bin Lu, Bo Li, Lihui Wang, Jianxin Yang, Jingru Liu, and Xi Vincent Wang. «Reusability based on Life Cycle Sustainability Assessment: Case Study on WEEE». In: *Procedia CIRP* 15 (2014), pp. 473–478. DOI: `10.1016/j.procir.2014.06.046` (cit. on p. 5).

[21] Xiaoyan Zheng, Said M. Easa, Zhengxian Yang, Tao Ji, and Zhenliang Jiang. «Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study». In: *Journal of Cleaner Production* 213 (Mar. 2019), pp. 659–672. DOI: `10.1016/j.jclepro.2018.12.227` (cit. on p. 6).

[22] Julia Martínez-Blanco, Annekatrin Lehmann, Pere Muñoz, Assumpció Antón, Marzia Traverso, Joan Rieradevall, and Matthias Finkbeiner. «Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment». In: *Journal of Cleaner Production* 69 (Apr. 2014), pp. 34–48. DOI: `10.1016/j.jclepro.2014.01.044` (cit. on p. 6).

[23] Argiro Roinioti and Christopher Koroneos. «Integrated life cycle sustainability assessment of the Greek interconnected electricity system». In: *Sustainable Energy Technologies and Assessments* 32 (Apr. 2019), pp. 29–46. DOI: `10.1016/j.seta.2019.01.003` (cit. on p. 6).

[24] Nuri Onat, Murat Kucukvar, and Omer Tatari. «Towards Life Cycle Sustainability Assessment of Alternative Passenger Vehicles». In: *Sustainability* 6.12 (Dec. 16, 2014), pp. 9305–9342. DOI: `10.3390/su6129305` (cit. on p. 6).

[25] Rizal Taufiq Fauzi, Patrick Lavoie, Luca Sorelli, Mohammad Davoud Heidari, and Ben Amor. «Exploring the Current Challenges and Opportunities of Life Cycle Sustainability Assessment». In: *Sustainability* 11.3 (Jan. 25, 2019), p. 636. DOI: `10.3390/su11030636` (cit. on pp. 6, 7).

[26] Ana Carolina Maia Angelo and Lino Guimarães Marujo. «Life cycle sustainability assessment and decision-making under uncertainties». In: *Life Cycle Sustainability Assessment for Decision-Making*. Elsevier, 2020, pp. 253–268. DOI: `10.1016/B978-0-12-818355-7.00012-9` (cit. on p. 7).

[27] Kannan Govindan and Martin Brandt Jepsen. «ELECTRE: A comprehensive literature review on methodologies and applications». In: *European Journal of Operational Research* 250.1 (Apr. 2016), pp. 1–29. DOI: `10.1016/j.ejor.2015.07.019` (cit. on p. 7).

[28] Aviad Shapira Tamar Opher Eran Friedler. «Comparative life cycle sustainability assessment of urban water reuse at various centralization scales». In: (Apr. 2018) (cit. on p. 7).

[29] Di Xu, Liping Lv, Jingzheng Ren, Weifeng Shen, Shun'an Wei, and Lichun Dong. «Life Cycle Sustainability Assessment of Chemical Processes: A Vector-Based Three-Dimensional Algorithm Coupled with AHP». In: *Industrial & Engineering Chemistry Research* 56.39 (Oct. 2017), pp. 11216–11227. DOI: 10.1021/acs.iecr.7b02041 (cit. on p. 7).

[30] Emily Grubert. «The Need for a Preference-Based Multicriteria Prioritization Framework in Life Cycle Sustainability Assessment». In: *Journal of Industrial Ecology* 21.6 (Dec. 2017), pp. 1522–1535. DOI: 10.1111/jiec.12631 (cit. on p. 7).

[31] Nuri Cihat Onat, Murat Kucukvar, Omer Tatari, and Qipeng Phil Zheng. «Combined application of multi-criteria optimization and life-cycle sustainability assessment for optimal distribution of alternative passenger cars in U.S.» In: *Journal of Cleaner Production* 112 (Jan. 2016), pp. 291–307. DOI: 10.1016/j.jclepro.2015.09.021 (cit. on p. 7).

[32] Marwa Hannouf and Getachew Assefa. «A Life Cycle Sustainability Assessment-Based Decision-Analysis Framework». In: *Sustainability* 10.11 (Oct. 2018), p. 3863. DOI: 10.3390/su10113863 (cit. on p. 7).

[33] Yvonne Vogt Gwerder, Pedro Marques, Luis C. Dias, and Fausto Freire. «Life beyond the grid: A Life-Cycle Sustainability Assessment of household energy needs». In: *Applied Energy* 255 (Dec. 2019), p. 113881. DOI: 10.1016/j.apenergy.2019.113881 (cit. on p. 7).

[34] Peter Tarne, Annekatrin Lehmann, and Matthias Finkbeiner. «Introducing weights to life cycle sustainability assessment—how do decision-makers weight sustainability dimensions?» In: *The International Journal of Life Cycle Assessment* 24.3 (Mar. 2019), pp. 530–542. DOI: 10.1007/s11367-018-1468-2 (cit. on p. 7).

[35] DECERNS. «DECERNS User Manual». In: () (cit. on pp. 8, 42).

[36] Boris Yatsalo, Vladimir Didenko, Sergey Gritsyuk, and Terry Sullivan. «Decerns: A Framework for Multi-Criteria Decision Analysis:» in: *International Journal of Computational Intelligence Systems* 8.3 (2015), p. 467. DOI: 10.1080/18756891.2015.1023586 (cit. on p. 8).

[37] Olivier Jolliet, Myriam Saadé-Sbeih, Shanna Shaked, Alexandre Jolliet, and Pierre Crettaz. «Environmental Life Cycle Assessment». In: (2016), p. 330 (cit. on p. 8).

[38] Claudia di Noi Andreas Ciroth. «OpenLCA Manual». In: (June 2020) (cit. on p. 9).

[39] *ecoinvent – ecoinvent.* URL: https://ecoinvent.org/ (cit. on p. 9).

[40] Franziska Eisfeldt Andreas Ciroth. «Database version 1 Documentation». In: (Mar. 2016) (cit. on pp. 9, 14, 26–28, 50).

[41] *System Models – ecoinvent*. URL: `https://ecoinvent.org/the-ecoinvent-database/system-models/` (cit. on pp. 14, 15).

[42] Kirill Maister. «Database version 3 Documentation». In: (), p. 124 (cit. on pp. 14, 18, 26–30, 50).

[43] Adrian König, Lorenzo Nicoletti, Daniel Schröder, Sebastian Wolff, Adam Waclaw, and Markus Lienkamp. «An Overview of Parameter and Cost for Battery Electric Vehicles». In: *World Electric Vehicle Journal* 12.1 (Feb. 2021), p. 21. DOI: `10.3390/wevj12010021` (cit. on pp. 16, 19).

[44] Fan Yang, Yuanyuan Xie, Yelin Deng, and Chris Yuan. «Predictive modeling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation». In: *Nature Communications* 9.1 (Dec. 2018), p. 2429. DOI: `10.1038/s41467-018-04826-0` (cit. on p. 17).

[45] *Telematics*. URL: `https://www.targatelematics.com/` (cit. on p. 17).

[46] *Italy - Countries & Regions - IEA*. URL: `https://www.iea.org/countries/italy` (cit. on pp. 18, 31).

[47] Mark Goedkoop, Reinout Heijungs, and Mark Huijbregts. «Report I: Characterisation». In: (), p. 133 (cit. on p. 20).

[48] M A J Huijbregts, Z J N Steinmann, P M F Elshout, G Stam, F Verones, M D M Vieira, A Hollander, M Zijp, and R van Zelm. «ReCiPe 1.1». In: (2016), p. 201 (cit. on pp. 20, 22–25).

[49] Jane C. Bare, Patrick Hofstetter, David W. Pennington, and Helias A. Udo de Haes. «Midpoints versus endpoints: The sacrifices and benefits». In: *The International Journal of Life Cycle Assessment* 5.6 (Nov. 2000), p. 319. DOI: `10.1007/BF02978665` (cit. on p. 21).

[50] Patrick Hofstetter. *Perspectives in Life Cycle Impact Assessment*. Boston, MA: Springer US, 1998. DOI: `10.1007/978-1-4615-5127-0` (cit. on p. 21).

[51] *The global burden of disease: summary; a comprehensive assessment of mortality and disability from diseases, injuries, and risk factors in 1990 and projected to 2020*. Geneve: World Health Organization [u.a.], 1996. 43 pp. (cit. on p. 21).

[52] «European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment». In: *Atmospheric Environment* 42.3 (Feb. 2008), pp. 441–453. DOI: `10.1016/j.atmosenv.2007.09.072` (cit. on p. 23).

[53] Pierre-Olivier Roy, Ligia B. Azevedo, Manuele Margni, Rosalie van Zelm, Louise Deschênes, and Mark A.J. Huijbregts. «Characterization factors for terrestrial acidification at the global scale: A systematic analysis of spatial variability and uncertainty». In: *Science of The Total Environment* 500-501 (Dec. 2014), pp. 270–276. DOI: 10.1016/j.scitotenv.2014.08.099 (cit. on p. 25).

[54] Andreas Ciroth. «Life Cycle Costing and calculation of Value Added in openLCA». In: (Mar. 2016) (cit. on p. 26).

[55] Christian Aichberger and Gerfried Jungmeier. «Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review». In: *Energies* 13.23 (Dec. 2020), p. 6345. DOI: 10.3390/en13236345 (cit. on p. 34).

[56] Jeffrey C. Cegan, Ashley M. Filion, Jeffrey M. Keisler, and Igor Linkov. «Trends and applications of multi-criteria decision analysis in environmental sciences: literature review». In: *Environment Systems and Decisions* 37.2 (June 2017), pp. 123–133. DOI: 10.1007/s10669-017-9642-9 (cit. on p. 41).

[57] Saaty TL. «The Analytic Hierarchy Process». In: (1980) (cit. on p. 44).