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## A new model to improve the life cycle of products since early design phase.

Manel Sansa

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Ministère de l'Enseignement Supérieur  
et de la Recherche Scientifique

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Université de Carthage

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Institut National des Sciences  
Appliquées et de Technologie



# THESE DE DOCTORAT

Discipline : Electronique

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**A NEW MODEL TO IMPROVE THE LIFE CYCLE OF PRODUCTS SINCE EARLY DESIGN  
PHASE**

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Présentée par

**Manel SANSA**

**A Tunis, le 27/07/ 2020 devant le jury composé de :**

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# Dedication

*I dedicate this thesis to  
My late grandparents  
My dearest grandmother  
My beloved parents and siblings  
My uncles, aunts, and cousins  
My precious friends  
And to anyone who believed in me and contributed directly or indirectly to the  
accomplishment of this Thesis*

*Everything is theoretically impossible,  
until it is done*

---

*Robert A. Heinlein*

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**Thank you all for your encouragement!**

## **Abstract**

From a sustainable product design perspective, we propose a new multi-criteria decision support approach for the choice of an optimal scenario that aims to minimize environmental, social and economic impacts. The model combines the system approach and the product approach from a life cycle perspective. It is structured around three significant levels, namely; the strategic, tactical and operational levels applied in the design of new products or services. Our contribution is distinguished by treating two issues. The first concerns the proposal of a mechanism that allows the generation of sustainable design scenarios that are consistent with organizations' context. This latter is characterized by taking into account internal and external issues and stakeholders requirements. These scenarios are not limited to traditional technological or component choice options. In fact, they are considered value chain oriented sustainable design strategies. To this end, we use strategic analysis tools such as SWOT, PESTEL, and 7S techniques to identify a multitude of criteria. These criteria form tactics to determine design alternatives by life cycle phase. Design alternatives are then combined to generate design scenarios that are not generic, but meaningful in the context of organizations. The second issue deals with the complexity of life cycle analysis methods and the uncertainty of data and experts' judgments in order to select an optimal scenario satisfying numerous and often dependent criteria. To this end, we propose to implement a decision support system based on the modelling of environmental, social and economic assessment for each scenario by life cycle phase. Hence, we calculate the impact indicators related to each assessment. The decision support system is based on control and influence criteria set by organizations as well as the Choquet integral for reducing the number of scenarios. The ANP (Analytic Network Process) method is then deployed to select the optimal design scenario. The validation of the model is tested on a real case study for a company designing, manufacturing and distributing batteries for motorcycles. The application of the model has effectively generated significant strategic scenarios for the company. The adopted tactical variables are summarized in technology options (AGM, Gel), logistics options (Land transport / Sea transport), manufacturing site options (Tunisia / Tanzania) and distribution options (Local

/ Exports) with logistics sub-options.

On the basis of simulations and impact calculations, we have established environmental, social and economic assessments of each scenario by highlighting the influence of options by scenario and by phase of the life cycle. Among the most impacting scenarios, we have demonstrated that the choice of AGM technology, manufacturing in Tanzania and maritime logistics generate the most environmental impacts (affecting ecosystem quality and degrading human health), the most important social aspects (labor rights, community and governance) and significant costs. The most advantageous scenarios are those using Gel technology, manufacturing at the Tunisian site and land transport. The resulting aspects have less impacts. However, the fourteen simulations showed that, although some scenarios are advantageous, they have different impacts per life cycle phase. Thus, the implementation of the fuzzy ANP and the Choquet integral has resolved interactions and dependencies between attributes and between phases of the product's life cycle. The implementation of this method led to the choice of the optimal scenario while addressing uncertainties of experts' judgments. The results obtained from this case study confirmed the relevance of the model to the company's expectations and demonstrated its applicability and ability to minimize environmental, social and economic impacts since early critical design phase.

## Resumé

Dans une perspective de conception durable des produits, nous proposons une nouvelle démarche d'aide à la décision multi-critères pour le choix d'un scénario optimal qui vise la minimisation des impacts environnementaux, sociaux et économiques. Le modèle conjugue l'approche système et l'approche produit dans une perspective de cycle de vie. Il est articulé autour de trois niveaux significatifs, à savoir les niveaux stratégique, tactique puis opérationnel appliqués dans un cadre de conception de nouveaux produits ou services. Notre contribution se distingue par le traitement de deux problématiques. La première, concerne la proposition d'un mécanisme qui permet la génération des scénarios de conception durable cohérents avec le contexte des organismes. Ce dernier se caractérise par la prise en compte des enjeux internes et externes et des exigences des parties intéressées. Ces scénarios sortent des cadres classiques des options technologiques ou de choix de composants pour migrer vers des stratégies de conception durable orientées chaînes de valeurs. A ce titre, nous employons des outils d'analyse stratégique tel que les techniques SWOT, PESTEL, et 7S pour identifier une multitude de critères. Ces derniers, forment des tactiques permettant de déterminer des alternatives de conception par phase du cycle de vie. Ces dernières sont combinées afin de formuler des scénarios de conception, non pas génériques, mais significatifs par rapport au contexte des organismes. La seconde problématique traite la complexité des méthodes d'analyse de cycle de vie et l'imprécision des données et des jugements des experts afin d'aboutir au choix optimal d'un scénario qui satisfait des critères souvent nombreux et interdépendants. A cet effet, nous mettons en œuvre un système d'aide à la décision qui se base sur la modélisation des profils environnementaux, sociaux et économiques par phase de cycle de vie et par scénario. A ce titre, nous calculons les différents indicateurs d'impacts de chaque scénario par phase de cycle de vie du produit à concevoir. Le système d'aide à la décision se base sur les critères de maîtrise et d'influence des organismes ainsi que sur l'intégrale de Choquet pour la réduction du nombre de scénarios.

La méthode ANP (Analytic Network Process) est déployée pour le choix du scénario de conception optimal. La validation du modèle a été testée sur un cas pratique réel pour une entreprise assurant la conception, fabrication et distribution de batteries. Le cas étudié concerne les batteries pour motocycles. L'application du modèle a permis effectivement de générer des scénarios stratégiques plausibles et significatifs pour l'entreprise. Les différentes variables tactiques adoptées se résument dans les options technologiques (AGM, Gel), les options logistiques (Transport terrestre / maritime), les options de site de fabrication (Tunisie / Tanzanie) et les options de distributions (Local / Exports) avec des sous options logistiques.

Suite aux simulations et aux calculs des impacts, nous avons établi les bilans environnementaux, sociaux et économiques de chaque scénario en mettant en évidence l'influence des options par scénario et par phase du cycle de vie. Parmi les scénarios les plus impactants, nous avons démontré que le choix de la technologie AGM, la fabrication en Tanzanie et la logistique maritime génèrent les plus grands impacts environnementaux (Affectation de la qualité de l'écosystème et dégradation de la santé humaine), les aspects sociaux les plus importants (Les droits du travail, la communauté et la gouvernance) et les coûts les plus importants. Les scénarios les plus avantageux sont ceux utilisant la technologie Gel, la fabrication au site tunisien et les transports terrestres. Les aspects qui en découlent sont moins impactants. Toutefois, les quatorze simulations ont montré que, bien que certains scénarios soient avantageux, ils présentent des différences d'impacts par phase de cycle de vie. C'est ainsi que la mise en œuvre de l'ANP floue et de l'intégrale de Choquet a permis de résoudre les interactions et les dépendances entre les attributs et entre les phases du cycle de vie. La mise en œuvre de cette méthode a conduit au choix du scénario optimal tout en traitant les incertitudes sur les jugements des experts. Les résultats obtenus à partir de ce cas pratique ont confirmé la pertinence du modèle par rapport aux attentes de l'entreprise et ont permis de démontrer son applicabilité et sa capacité à minimiser les impacts environnementaux, sociaux et économiques dès la phase critique de conception.

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# Abbreviations

<b>ABS</b>	Acrylonitrile Butadiene Styrene. 97–100, 104–106, 116
<b>AGM</b>	Absorbed Glass Mat. 97–102, 104–106, 113, 116, 125, 126
<b>AHP</b>	Analytic Hierarchy Process. 33–35, 43, 72, 76, 81
<b>ANP</b>	Analytic Network Process. viii, x, 27, 33, 34, 43, 72, 74, 80, 81, 83–86, 88, 110, 113, 122, 124, 126, 127
<b>APQP</b>	Advanced Product Quality Planning. 127
<b>CF</b>	Characterization Factors. 17, 71
<b>CSD</b>	Commission on Sustainable Development. 1
<b>CSS</b>	Country-Specific Sector. 107, 109, 110, 119
<b>EEE</b>	Electrical and Electronic Equipment. 15
<b>ELECTRE</b>	ELimination Et Choix Traduisant la REalité. 72
<b>FMEA</b>	Failure modes, their Effects and their Analysis. 127
<b>FU</b>	Functional Unit. 14, 15, 20, 23, 75, 102, 118, 144, 145
<b>GHG</b>	Greenhouse Gas. 12, 22, 70
<b>HLS</b>	High Level Structure. 29
<b>ISO</b>	International Organization for Standardization. 2, 10, 12
<b>LCA</b>	Life Cycle Assessment. 3, 4, 10, 12–18, 20, 30–36, 43, 46, 70, 74, 75, 94, 123, 124
<b>LCC</b>	Life Cycle Cost analysis. 18, 19, 102
<b>LCI</b>	Life Cycle Inventory. 16
<b>MAUT</b>	Multi-Attribute Utility Theory. 72, 74, 76
<b>MCDM</b>	Multi-Criteria Decision-Making. 71, 73, 74
<b>NSGA</b>	Non-dominated Sorting Genetic Algorithm. 35, 36

<b>OECD</b>	Organization for Economic Co-operation and development. 11
<b>PP</b>	Polypropylene. 97–100, 104, 106, 116, 126
<b>PROMETHEE</b>	Preference Ranking Organisation METHod for Enrichment Evaluations. 73
<b>PSILCA</b>	Product Social Impact Life Cycle Assessment. xii, 20, 21
<b>PSS</b>	Product-Service System. 35
<b>QFD</b>	Quality Function Deployment. 3, 27, 31, 33–36, 41, 127
<b>SAW</b>	Simple Additive Weighting. 73
<b>SDG</b>	Sustainable Development Goals. 8
<b>SHDB</b>	Social Hotspots DataBase. x, xii, 20, 21, 75, 102, 104, 107, 114
<b>SLCA</b>	Social Life Cycle Assessment. 19–21
<b>SMART</b>	Simple Multi-Attribute Rating Technique. 72
<b>TFN</b>	Triangular fuzzy Numbers. x, 84, 114
<b>TOPSIS</b>	Technique for Order of Preference by Similarity to Ideal Solution. 73
<b>TRACI</b>	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. 17
<b>UN</b>	United Nations. 1, 6, 8, 11
<b>VRLA</b>	Valve-Regulated Lead-Acid. viii, 89, 97
<b>WEEE</b>	Waste Electronic and Electrical Equipment. 124

# Introduction

Nowadays, the concept of sustainable development is becoming increasingly important on a global scale. Indeed, we are witnessing changes and transformations having significant impacts on people's lifestyles and well-being. The fast growth of technological development is impacting significantly the environment, the society and the economy. In addition, the growing consumer society has pushed for disproportionate development of energy-intensive products and systems, often in large quantities, whose benefits are channelled to minorities at the expense of other populations. This development context has led to a growth in the offer that creates the need for products and services. This vision of anticipation has contributed to the emergence of new systems and technologies that have led to positive and negative changes, not only affecting the natural environment, but also impacting the socio-economic environment (Dede, 1991; Frewer, 1999; Sui & Rejeski, 2002; Dreher, 2004; Borch, 2007). In environmental terms, this has resulted in the overexploitation of natural resources, climate change, the extinction of certain species and the impact on human health (Dreher, 2004). At the social level, the impacts are way more significant. Indeed, we are witnessing a significant increase in poverty, national and international migration, unemployment (West, 2015; Danaher, 2017) and child labor (Basu & Tzannatos, 2003). On the economic level, the impact has been observed in terms of price trends and inflation, which have contributed to the imbalance in economic rates and led to changes in politics and emergence of social movements (Bowman et al., 2017). On the basis of this global issue, the United Nations (UN) has established a Commission on Sustainable Development (CSD) in order to ensure an efficient follow-up of activities and conferences related to this topic. The UN has developed the Agenda 21 (Summit, 1992). It is an international improvement action plan that addresses the aforementioned problems. The main goal of Agenda 21 is to prepare the world and mankind for challenges facing future generations. Another Agenda has been developed by the UN entitled "*Transforming our world: The 2030 Agenda for Sus-*

*tainable Development*” (U. Nations, 2015). It offers a plan of actions for people, planet and prosperity with the aim to eradicate poverty in all forms and dimensions to ensure better living conditions for people. It also offers 17 Sustainable Development Goals and 169 targets to ensure a balance between the three pillars of sustainable development. As a result of this international awareness, we have witnessed the emergence of new standards established by the International Organization for Standardization (ISO) that cover products, systems and their impacts. We can mention in particular the standards for environmental management (ISO 14000 series) (ISO, 2015a, 2006a,b, 2011, 2002), sustainable development of cities (ISO 37101) (ISO, 2016b), environmental products’ labelling (ISO 14020 series) (ISO, 2000, 2016a, 2018a), and social responsibility (26001 series) (ISO, 2010).

Although this set of standards defines the requirements in this area, it does not provide methodologies to solve problems and challenges from a sustainable development perspective. In this context, scientific research has been held in order to develop tools and methods to control various environmental, social and economic impacts. This research focused on the life cycle of products from the extraction of natural resources to the end of life or reintegration of products. It can be divided into two categories. The first class focuses on products, their manufacturing processes and material components. The second focuses on their management systems.

In the first class, scientific research is very consistent. In addition to the operational safety aspect, a particular interest is attributed to the technological aspect, focusing mainly on environmental and economic criteria. It targets the minimization of costs, energy consumption (Seow et al., 2016; Sharif & Hammad, 2017), mass and volume of the products, and recycling possibilities (Paraskevas et al., 2015; Li et al., 2016; Unterreiner et al., 2016; Latunussa et al., 2016) in different fields and sectors such as nuclear energy, telecommunications, animal and plant transformations as well as their processes, construction materials, etc. This research axis has led to the creation of inventions that have revolutionized product quality and have contributed to economic development and human well-being. However, the main issue remains in the limited solutions in a particular field due to restrictive conditions. Indeed, the available solutions are able to reduce impacts in one phase of the life cycle. However, there is a high and common risk that the same adopted solution will contribute to the generation of other impacts in other phases of the life cycle of products and systems. We are thus witnessing a pollution transfer phenomena (Yu et al., 2013). For instance, photovoltaic panels reduce the consumption of natural resources, but at the end of their life, the management of their waste contributes to very significant environmental impacts (Sica et al., 2018). Another well-known significant example is the case of electronic bulbs. It is obvious that they contribute to minimizing energy

consumption, but their waste treatment is very critical since electronic waste is composed of hazard materials with very expensive treatment costs (Michaud & Belley, 2008; Ferrini, 2010). In the second class of scientific research, the researchers focused on the organizational and technical processes that contribute to minimize environmental, social and economic impacts. The processes essentially deal with design and the supply chain (Vollmann, 2005). In addition, the addressed issues are related to the implementation of tools and methods to optimize product and material flows in all stages of the life cycle. Among these researches, we mention those related to eco-design, the optimization of logistics' flows for the minimization of energy consumption, the control of manufacturing operations for waste minimization, the study of packaging units for volume reduction...etc (Zhu et al., 2005; Winkler, 2011; Brandenburg et al., 2014). These researches have mainly focused on aspects related to uncertainty, data imprecision and multi-criteria, multi-objective decision support targeting the optimization (Humphreys et al., 2003; F. Wang et al., 2011; Govindan et al., 2013). Among these researches, we mention those related to eco-design using the concepts of fuzzy logic and Quality Function Deployment (QFD) (Büyükoçkan & Berkol, 2011; Büyükoçkan & Çifçi, 2013; Lam, 2015). As mentioned above, research in this class focuses on the choice of technological or logistical options from a product life cycle perspective. The provided solutions are generic and cannot be applied to different varieties of industries. This is particularly relevant if we consider that the development of systems are adapted to the context of companies and it is highly recommended to consider the needs and expectations of their stakeholders. This recommendation has been supported in the latest published update of the quality, environment, health and safety management systems standards (ISO, 2015b,a, 2018b). These latter have also integrated the design of products and services. On the basis of the previous review of both research axes and related research opportunities, we were interested in the conjunction of the issues pointed out in both axes. Our work focuses on combining the product approach and the system approach at an early stage of the design process. Our objective is to propose a model that aims to optimize the life cycle of products with the goal to minimize the combined environmental, social and economic impacts. In order to achieve this aim, this thesis is outlined into five chapters as follows:

- In the first chapter, we will detail general issues and challenges facing the concept of sustainability and its objectives. We will review various tools and methods adopted in this field, for a clearer vision towards the main issues. A particular attention is given to the product life cycle, the Life Cycle Assessment (LCA) method (ISO, 2006a,b) and eco-design principles (ISO, 2002). We will also discuss the nature and characterization of impacts, their related indicators and international databases for their simulation.

- The second chapter is dedicated to a review study of research works in this field. Thus, we will focus on presenting issues specific to sustainable design and its contextualization. Based on this review, we will illustrate the idea of merging the system and product approaches in the design phase. In this perspective, we will proceed by proposing guidelines for the implementation of the model that addresses the problems of integrating environmental, social and economic criteria in a company-specific context with consideration of the stakeholders' needs and expectations. On the basis of these proposed guidelines, we will point out the research questions. At the end of this chapter, the complete model will be presented with a brief description of each step.
- The third chapter deals with the implementation of the first part of the model. In this chapter, we will present the methods and tools used to establish design strategies that are coherent with the requirements of sustainable development in each phase of the product life cycle. In particular, we will highlight the importance of considering the context and challenges of the company. In this perspective, we will detail the conjunction of the SWOT (i.e. Strengths, Weaknesses, Opportunities, and threats) (Brad & Brad, 2015), PESTEL (i.e. Political, economic, Social, Technological, environmental, Legal) (Kauškale & Geipele, 2017) and 7S (i.e. Skills, Staff, Style, Systems, Strategy, Structure, Shared values) (Ravanfar, 2015) methods. Also, we will present our proposal for the generation of multiple design scenarios that must meet the company's requirements in the various life cycle phases.
- In the fourth chapter, we will present our proposed multi-criteria decision system for the choice of a sustainable design scenario. This chapter illustrates the operational level of our model. We will then discuss the choice of an optimal scenario that addresses dependence, interaction and uncertainty issues based on sustainability impact indicators assessed using simplified LCA (C. Y. Ng & Chuah, 2014).
- The fifth chapter is dedicated to the implementation of the model on a real case study of a local company designing, manufacturing and marketing lead acid batteries. Thus, we will identify and detail the strategic, tactical and operational levels of our model. In this context, we will present, simulate and analyze the results of different design scenarios adapted to the local context and the requirements of the company's stakeholders. As such, we will highlight the advantages of the conjunction of the system / product approach and we will practically illustrate the accuracy of the optimal design scenario with regard to sustainability criteria.

Chapter **1**

**The context of the study and motive for improvements**

## **1.1 Introduction**

The purpose of this chapter is to point out the challenges of sustainable development and to illustrate the main tools and methods related to this concept. We begin by defining the concept of sustainable development and detailing its evolution and objectives. Then, we will present the concept of the product life cycle and the methods and approaches that can be used in order to minimize environmental, economic and social impacts that may affect the product's life cycle. A particular interest is given to the life cycle assessment tools and Eco-design approach since they cover all the life cycle phases and consider several impacts categories related to sustainable development. The last section of chapter 1 is dedicated to the motivation of our research in order to define its related challenges and research questions.

## **1.2 Sustainable development worldwide**

### **1.2.1 State of the art**

Sustainability is the satisfaction of the present's needs while guaranteeing future generations. It first appeared in 1980 in the World Conservation Strategy (UICN, 1980) as a concept of product development that takes into account three pillars: The environment, the economy, and the society. In fact, adopting the concept of sustainable development means ensuring the balance between environmental consciousness, economic growth, and social well-being. Later, the Brundtland Commission (Brundtland, 1987) defined it as “The development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In 1972, ecological management principles were adopted at the UN Conference on the environment. On the basis of these principles, awareness of sustainable development has begun to increase until it has become almost a necessity in all industrial and other sectors (Rosen & Kishawy, 2012), due to the significant environmental impacts damaging the population and ecosystems and which are caused by the fast economic and population growth.

The sustainable development concept is based on three pillars (i.e. Environment, economy, society) such as shown in Figure 1.1. In fact, the combination between the social and economic aspects leads to an equitable development that focuses on the social well-being of the citizens by reducing the gap between incomes and raising the standard of living conditions. The viable development is the combination between the economic growth and the protection of the environment from resources depletion in order to build sustainable economies. The third combination

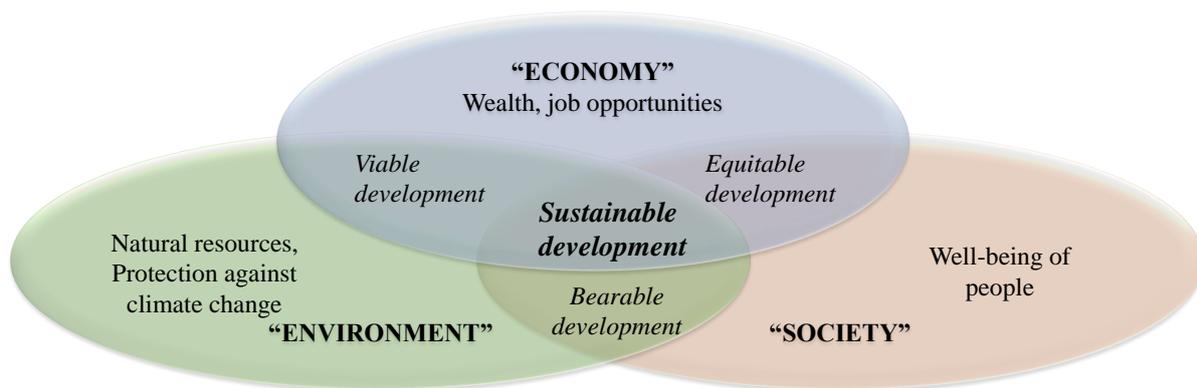


Figure 1.1: The concept of sustainable development

is the linkage between the society and the environment that forms the bearable environment which is ensuring a healthier environment for a better life style.

Lele (1991) had detailed through its critical review the main motives to link the pillars of sustainable development from a research perspective, we can mention in particular:

- **The environmental degradation:** This degradation is already affecting the population especially in underdeveloped countries which will significantly affect human well-being all over the planet for future generations. Environmental degradation is mainly caused by poverty due to excessive exploitation of natural resources for survival.
- **Basic development objectives:** The main motive to undertake improvement actions to promote sustainable development is the aim to provide basic needs by increasing the productivity of all human, natural and economic resources in the case of developing countries. For underdeveloped ones, the main goal is to maintain the standard of living and fix targets for improvement.

On the basis of these motives, during the earth summit in 1992, the Agenda 21 (Summit, 1992) has been elaborated in 40 chapters in order to address environmental concerns while ensuring economic growth. Later on, in 1995, the world summit on social development (T. U. Nations, 1995) has pointed out the role of sustainable development in ensuring social developments. Therefore, the third pillar has been officially integrated into the definition of sustainable development in 2002 during the world summit in Johannesburg (Laubner, 2002). By 2012, the social pillar has received full attention in the outcome document entitled “The future we want” (on the Post-2015 UN Development Agenda, 2012).

In addition, since the adaptation of the sustainable development concept, it has been pointed

out by Agenda 21 that quantitative indicators are a necessity to evaluate the goals defined for the achievement of sustainability. Since then, several indicators have been proposed, but despite these efforts by many organizations such as the European Commission, there are no clear methods that detail how to measure indicators related to sustainability and to the well-being of the citizens. To this end, Hák et al. (2016) have proposed an indicator-based approach that led to the identification of Sustainable Development Goals (SDG). These SDGs are a universal set of goals evaluated using relevant targets and indicators to frame the developed Agenda over the next future years. They have been proposed on the basis of nine sustainable development challenges. The following subsection presents the nine challenges and their relative SDGs.

### **1.2.2 Challenges and sustainable development goals**

In order to achieve and guarantee a better sustainable future, the UN has identified seventeen sustainable development goals. These goals address mainly nine global challenges facing the achievement of sustainable development as follows:

1. Establishing and ensuring sustainable consumption and production.
2. Promoting a high-performance economy, strengthening social equity and overcoming regional disparities.
3. Managing natural resources in terms of sustainability.
4. Promoting a balanced spatial planning on the basis of sustainable transport.
5. Guaranteeing a better quality of life for the citizens.
6. Improving energy's efficiency and promoting new and renewable energies.
7. Enhancing the capacity to adapt to climate change.
8. Promoting a society of knowledge.
9. Adapting the governance for a better promotion of sustainable development.

These challenges are defined in June 1992, during the Earth Summit in Rio de Janeiro, Brazil which more than 178 countries participated in the development and adaptation of the Agenda 21. On the basis of these challenges, a 2030 agenda for sustainable development (U. Nations, 2015) has been adopted by all United Nations in 2015 for each participating country, this agenda is a universal program applicable to all countries and which gives a vision for global development

for the next 15 years from 2016 to 2030. It details the seventeen objectives and presents 169 targets structured on the basis of 5 key domains called 5P (People, Planet, Prosperity, Peace , and Partnerships)(U. Nations, 2015). Below is the list of the seventeen identified sustainable goals as shown in Figure 1.2.



Figure 1.2: The sustainable development goals. Source: United Nations

1. No poverty : Ending all forms of poverty all over the world.
2. Zero hunger: Eliminating hunger, preserving security food and improving the nutrition for a sustainable agriculture.
3. Good health and well-being: Ensuring a healthy life for all mankind and promoting the well-being of citizens.
4. Quality education : Ensuring a better education system and promoting learning opportunities.
5. Gender equality: Empowering women to achieve gender equality.
6. Clean water and sanitation: Ensuring the continuous availability of water and sanitation for all citizens and promoting a sustainable water and sanitation management.

7. Affordable and clean energy: Ensuring the availability of affordable and sustainable energy for all citizens.
8. Decent work and economic growth: Promoting sustainable economic growth and decent work for all employees.
9. Industry, innovation and infrastructure: Building consistent infrastructure, promoting sustainable industrialization and investing in innovations.
10. Reduced inequalities: Reducing inequalities within countries and ensuring equal technological development.
11. Sustainable cities and communities: Ensuring safe and sustainable human settlements.
12. Responsible consumption and production: Ensuring a sustainable consumption and production and ensuring a balance between both of them.
13. Climate action: Acting urgently to fight against fast climate change and its related significant impacts.
14. Life below water: Conserving oceans, seas and marine resources from deterioration.
15. Life on land: Ensuring a sustainable use of terrestrial ecosystems and preventing land degradation.
16. Peace , justice and strong institutions: Ensuring peaceful societies and providing justice for all citizens.
17. Partnerships for the goals: Investing in the means of implementation of sustainable strategies and promoting global partnership for sustainable development.

It is obvious that aiming towards a more sustainable society is not an easy task. To this end, several tools are developed and implemented in order to apply the concept of sustainable development. Some of these tools do not deal with all three pillars such as methods and approaches that are related to climate change. Some are officially validated and normalised by the ISO such as the well-known LCA method (ISO, 2006a,b) and the eco-design principles (ISO, 2002). In most cases, to achieve sustainable development, tools are often combined to cover multiple dimensions. In the following section, we will present a variety of sustainable development tools with a particular focus on the life cycle assessment methods and their applicability in the context of eco-design.

## 1.3 Sustainable development tools

In order to deal with various challenges facing the achievement of sustainable design in different fields, many researches have been performed with the aim to propose a variety of tools adapted to this concept. In fact, Riffon & Villeneuve (2011) have classified these tools into categories according to their utility as follows:

- **Tools for strategic application of sustainable development:** These tools are dedicated to develop adequate strategies to achieve sustainable development. In fact, they target the current situation of the planet with regard to climate change and ozone depletion and aim to propose national and local improvement actions (Claval, 2006). We can mention in particular, the Agenda 21 and the 2030 Agenda that comprises the seventeen sustainable development goals elaborated by the UN. In addition, with regard to a regulatory perspective, laws and agreements were elaborated to guide the stakeholders with the process of adapting such strategies. These laws have been set and developed by countries' government in order to cope with the country's resources and abilities to progress through deploying this concept. Also, standards were available as guidelines for such practice such as ISO 26000 (ISO, 2010) relative to social responsibilities within companies and organizations, ISO 14000 series for environmental systems managements and eco-design practices (ISO, 2015a, 2002). Moreover, Taxes and penalties were set by the government especially for industries to limit their contribution to the impacts such as carbon tax due to the significant impacts of carbon emissions to the quality of ecosystems and the human health. In addition, sustainable development labels and ecolabels (Initiative et al., 2010) have been proposed to particularly guide consumers to be environmentally aware of the potential impacts generated from products they are willing to buy.
- **Tools dedicated to economic approach:** The economic approach focuses on ensuring sustainable economy. Many tools are proposed for this approach. The most known are the polluter pays and the user pays principles. According to the environmental law, the polluter pays principle is making companies responsible for producing pollution within their activities. They have to pay for the damage affecting the environment. This principle was adopted by the Organization for Economic Co-operation and development (OECD)<sup>1</sup> in 1972. The user pays principle is derived from the polluter principle which make the user responsible for consuming natural resources.

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<sup>1</sup><https://www.oecd.org/>

- **Tools dedicated to the techno-scientific approach:** This approach is mostly adapted to industries since the related tools are characterized by quantitative and concrete results. Many organizations are promoting projects and programs to constantly improve the quality of data and methods required for such tools. The most known are the life cycle approach, the life cycle assessment, and the eco-design approach.

To fall within the scope of this thesis, we will focus on the techno-scientific approach's tools, particularly, the life cycle assessment and the eco-design as both are widely used in most researches and works that adopted sustainable development concept.

### 1.3.1 Life cycle assessment

The life cycle assessment LCA (ISO, 2006a,b) is considered as the well-known tool for assessing product's life cycle impact, in all sectors and fields since it is a standardized method by the ISO organization. The LCA is based on the life cycle thinking approach which is an extended vision towards the whole stages of the product life cycle instead of focusing only on manufacturing processes' potential impacts. Indeed, in real cases, environmental, economic and social impacts might be generated also during the use phase and the end of life phase. For instance, Greenhouse Gas (GHG) emissions are not only generated from the factory's activities and manufacturing operations but also, GHG emissions generated from the production of raw material must be taken into account for accurate impact assessment results (Weisser, 2007). As illustrated in Figure 1.3, the life cycle of a product is composed of five main phases.

According to ISO (2006a), the life cycle is defined as the life span of the product from extraction of raw materials to the treatment of its waste. The main inputs of the life cycle are the prototype, manufacturing instructions and guidelines in order to manufacture compliant products on the basis of the defined requirements. It consists of five phases as follows:

1. **Extraction of raw materials:** Extracting and transforming the necessary natural resources for the manufacturing phase. We can mention in particular polymer, glass, and steel. These materials can be recycled from the end of life phase.
2. **Manufacturing:** The production and the assembly of raw materials into the final product. In most cases, waste is generated during this phase.
3. **Distribution:** The packaging and delivery of the final products to retailers or customers through a distribution process.

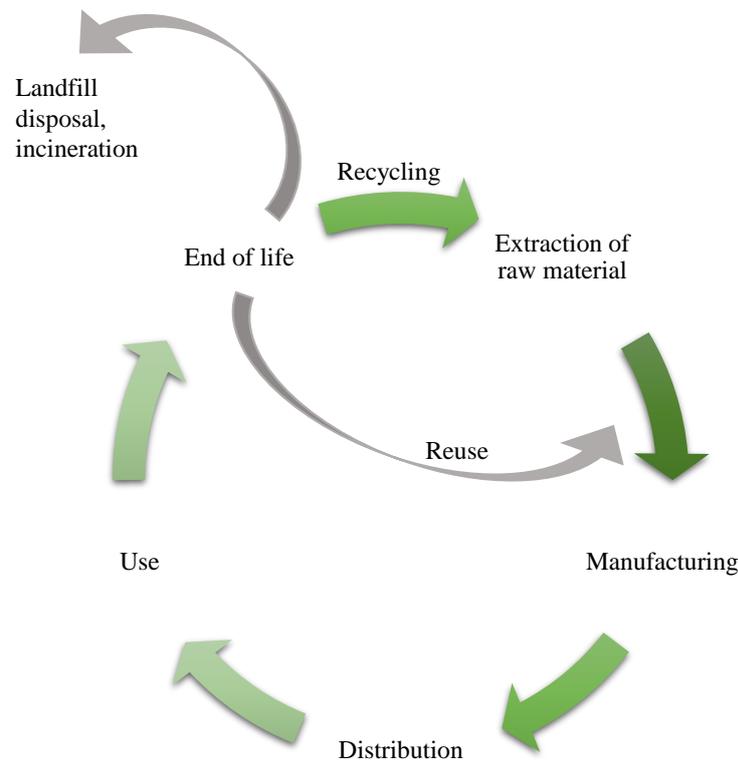


Figure 1.3: The life cycle phases of a product

4. **Use:** At this phase, the product is ensuring its main function. Maintenance interventions might be required to maintain its function until its end of life.
5. **End of life:** At this phase, the product is considered as waste which will be treated through various options. It can be recycled and used again as a material either for a similar product or different one after going through a transformation process. Also, it can be reused directly in the manufacturing process. The last option is the final destruction of components through incineration or landfill disposal.

Adopting the life cycle approach in the impact analysis especially at the design stage guides the decision makers to make choices for the long term (ISO, 2015a). In the following subsections, we will present the life cycle assessment methods that cover all three pillars of sustainability namely; Environmental LCA, Economic LCA and social LCA.

### 1.3.1.1 Environmental LCA

The environmental Life Cycle Assessment (ISO, 2006a,b) is a methodology that aims to quantify environmental impacts of a product during its life cycle. The results of the impacts assessment are deployed in most cases for decision making support to achieve sustainable development. The LCA is defined and its different steps are detailed by the ISO 14040 series (ISO, 2006a,b). The LCA consists of four main steps as shown in Figure 1.4.

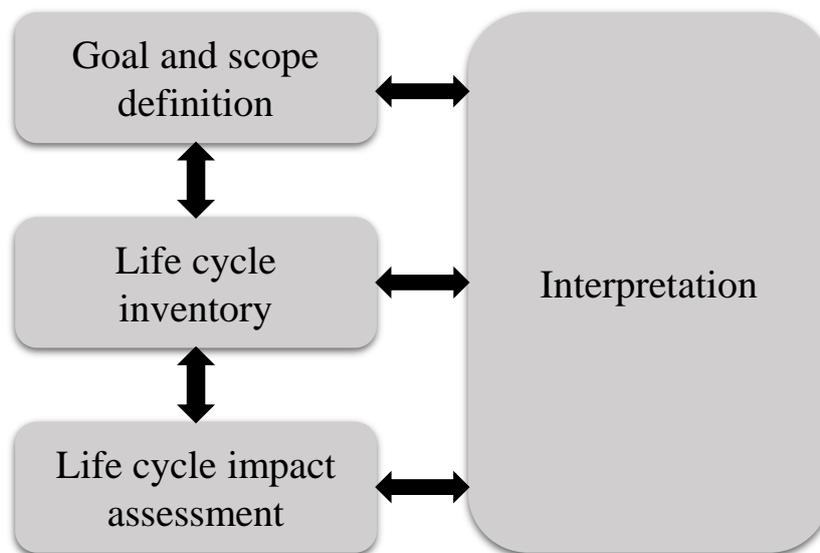


Figure 1.4: The life cycle assessment methodology as defined in ISO 14040 (ISO, 2006a)

**1.3.1.1.1 Goal and scope definition** According to ISO (2006a), in order to define the goal of the study. The LCA analyst should specify the main reason for carrying out the LCA study, the targeted audience to whom the analysis' results should be communicated, and the aim of the study (Rebitzer et al., 2004). For instance, the life cycle assessment is performed in order to compare products or scenarios for decision making. In addition, a LCA study is also used to define the environmental performance of a specific product for marketing or redesign purposes. Interested parties (i.e. Consumer, producer, government) are also defined at this step in order to set the scope. In this context, the scope of study is to highlight and define the function of the product/service or product scenario, the assumptions especially in case of a design scenario, Allocation, and data quality requirements. In fact, the Functional Unit (FU) is the most important step in the LCA since all the measures are referred and normalized according to the FU. ISO (2006a) defines the FU as a quantification of the function of the product. For example, a comparative LCA study has been performed to compare incandescent bulbs with fluorescent

lamps (Michaud & Belley, 2008). Since the two products do not have the same characteristics and have different functioning modes, It is not possible to compare both units. To this end, the FU must be related to the main function. For example “*Provide between 500 and 900 lumens for 10,000 hours*”. It is important to note that the results of the LCA depend on the choice of the Functional Unit. Indeed, all reference flows that will be computed in the inventory step must be adapted to the FU (Guinée, 2002). In this context, Jolliet et al. (2010) presented an example of a comparative life cycle assessment between two products with different material composition. This example have demonstrated the impact of the FU on the results. In fact, the results are reversed if we change the mass unit into the volume unit in the FU due to the difference in density of both materials.

Then, once the Functional Unit is defined, the system boundaries are carried out by selecting the life cycle phases and the elementary processes that will be included in the study. In fact, defining the boundaries of the study is to exclude any part of the product system through its life cycle that can not affect the simulations and the results of the study (Tillman, 2000). For example, in decision making, if we consider several alternatives for a battery design, on the basis of the collected data, we suppose that the packaging phase is the same for all alternatives in terms of material type and energy consumption, It is recommended to exclude this phase from the system since the results regarding this phase will be the same for all alternatives in terms of impacts’ generation. On the other hand, during the distribution phase, the alternatives do not provide the same transportation mode. Thus, the results are affected. Hence, the distribution phase must be included in the system boundaries.

After defining the boundaries, in some cases, allocation processes are required. In fact, the allocation is the partitioning of the collected inputs and outputs related to the product (ISO, 2006a). The allocation is only required for processes that produce more than one product. In this particular case, the materials inputs and the energy that are initially measured in total, should be allocated to each involved products produced by the same process.

Among the available allocation methods, we can mention in particular physical and economic allocation (Dolezal et al., 2014). Indeed, the physical allocation is based on the physical properties of the flows involved in the study while economic allocation is based on the given prices of the different flows. In fact, economic allocation can be observed as mass or volume allocation where the values are weighted economically.

In another context, especially in the case of Electrical and Electronic Equipment (EEE), reuse and recycling processes are very important. To this end, the ISO (2006b) has distinguished two main allocation procedures.

- Closed loop allocation procedure which can be used in case the inherent properties of the reused and recycled products remain the same.
- Open loop allocation procedure which can be used in case the component is recycled or reused into another product system where its inherent properties are changing consequently.

The last step of the goal and scope definition is to define the data quality requirements. In fact, the accuracy and the reliability of the obtained results of an LCA study mainly rely on the quality of the collected data. This latter is a full description of the processes involved in the product system. The data is mainly categorized into inputs (i.e. Material and resources flows) and outputs (i.e. emission, waste and product flows).

In this context, it is necessary to define requirements that will guarantee the quality of the data (Rebitzer et al., 2004). The ISO (2006b) has defined several quality aspects to be addressed. First, the data should represent a time period and a geographical coverage. Indeed, the life cycle of a product takes place in different parts of the world. For instance, raw material is produced in China while the assembly of the final product is achieved in Tunisia. To this end, the collected data should be related to a specific area. Second, it is highly recommended to use precise, complete and representative data and consistent methods throughout the LCA study. Most importantly, the source of the collected data should be defined. For example, data can be derived from research studies, previous LCA on a given product or generic databases. Finally, it is important to note that the issue of data uncertainty must be handled throughout the LCA study.

**1.3.1.1.2 Life Cycle Inventory Life Cycle Inventory (LCI)** This step identifies and quantifies the pollutant emissions in the air, water and soil along with renewable or non-renewable raw material extractions. As shown in Figure 1.5, the LCI inputs are elementary flows extracted from the environment such as energy, water and intermediate flows which are components outgoing from upstream processes.

One of the most-known LCI databases is the ecoinvent (Wernet et al., 2016) for environmental assessment. In fact, it was first published in 2003 (Frischknecht et al., 2005). Its main objective is to reduce the difficulty of LCA assessment by providing consistent generic background LCI data. At first, the data was only adapted to Switzerland, but the second version of the ecoinvent database released in 2007 included new economic sectors and covered more geographical area outside of Europe.

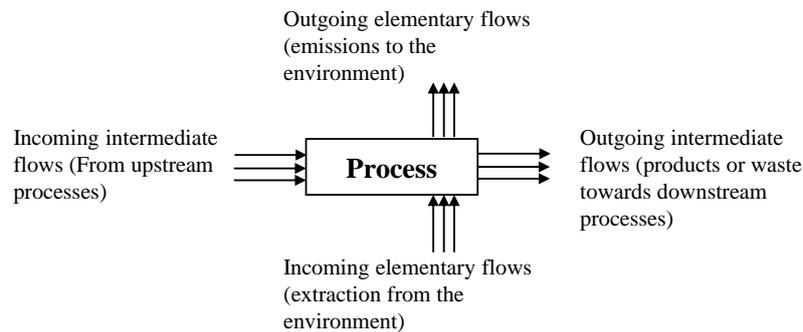


Figure 1.5: Inputs and outputs of the inventory

**1.3.1.1.3 Life cycle impact assessment** This phase aims at evaluating the impacts of calculated emissions in the inventory. It consists of three main steps: (i) Classification of emissions to impacts categories. (ii) Intermediary characterization of emissions in each impact category using Characterization Factors (CF) in order to convert the calculated flows into impacts. (iii) Damage characterization of impacts categories into damage categories (Jolliet et al., 2004). This step is realized using LCA softwares. The CF are already computed and set within the life cycle impact assessment tools. Several methods are available for the assessment of environmental impacts, namely: Eco-indicator 99 (M. J. Goedkoop, 1999), Impact 2002+ (Jolliet et al., 2003), ReCiPe (M. Goedkoop et al., 2009), LUCAS (Chan & Salustri, 2005), Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (Bare, 2002) and IMPACT World + (Bulle et al., 2012). These methods offer quantified impacts indicators. The most common indicators are: Human Health, ecosystem quality, climate change, resources, carbon footprint and water footprint.

**1.3.1.1.4 Interpretation** The results obtained from the impact assessment are analyzed in this step on the basis of the main goal of the LCA analysis. Uncertainty and sensitivity analysis are performed at this stage in order to check the reliability of the analysis results, interpretations and conclusions.

Although the LCA is basically the ultimate choice to quantify the environmental assessment, one of its major limitations is the uncertainty problem. In fact, three sources of uncertainty are identified as follows (Commission et al., 2010): The first one is related to the inventory data and to characterization methods. These uncertainties are taken into account by carrying out sensitivity analysis to compare multiple scenarios. The second one is related to decision makers' choices at the goal and scope definition step. Indeed, the choice of the processes included in the assessment, as well as the choice of data, allocation and characterization methods has a

significant influence on the assessment results. These uncertainties can be addressed by the consideration of scenarios concept. The last source is the uncertainty related to the lack of data. In fact, the full LCA requires a significant amount of data for the inventory analysis. Due to the lack of data, decision makers propose assumptions on the basis of the processes and flows considered. However, there is a high risk of carrying out an assessment on the basis of false or incoherent assumptions.

The uncertainty issue will be detailed in chapter 2. In the next subsection, we will give a brief recall on the life cycle cost analysis.

### 1.3.1.2 Life Cycle Cost analysis

The Life Cycle Cost analysis (LCC) (Woodward, 1997) is the computation of costs of a product or a system for each of its life cycle phases. The costs of a product depend on the nature of the product and the activity of the company. Yet, as illustrated in Figure 1.6, the common costs of a product may involve:

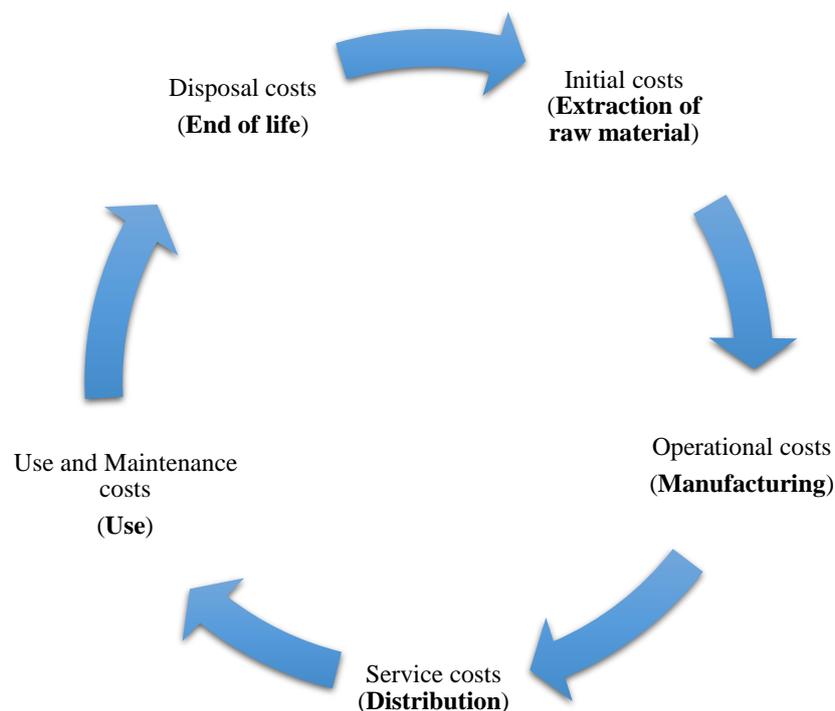


Figure 1.6: The life cycle costing framework

1. Initial costs or the acquisition costs: In fact, during the extraction of raw material phase, the initial costs are those related to the purchased material components required for the manufacturing phase. Also, the freight costs of the raw materials' import are included in the cost analysis.
2. Operational costs: These costs are relative to the manufacturing phase. For instance, cost of energy and water consumption are included in the study. Also, downtime costs due to failures or repair of equipment must be considered. In addition, the analysis included the costs of waste generated from the manufacturing process such as emissions and scrap. Moreover, all services provided for the staff and the cost of their labor hours are also taken into account within the cost analysis.
3. Service costs: These costs are relative to the charges of the distribution of the factory to the retailers.
4. Maintenance costs: During the use phase, there is always a risk of failure of the product. In this context, corrective and preventive maintenance are a necessity to ensure the reliability of the product in its use phase. To this end, costs relative to maintenance actions are included in the cost analysis.
5. Disposal costs: At the end of life, the treatment of waste is a set of operations of dis-assembly, recycling or disposal that requires equipment and therefore costs may apply within this phase. Analysts must consider all the possible generated costs.

Hence, the LCC analysis is considered as a decision making tool from an economic perspective with the aim to guide decision makers to select the best option among several investments plans on the basis of LCC results. In a design context, the LCC guides the decision makers to optimize the total costs by choosing more economic alternatives through comparing several design scenarios and selecting the optimal one according to the investment plan and the available resources set by the company.

In the next subsection, we will present the last pillar of the sustainable development concept. Indeed, a Social Life Cycle Assessment (SLCA) has been proposed to deal with the social aspect and its related impacts. It follows the same methodology as the environmental LCA. Yet, it has not reached the same maturity level and still under development for improvement.

### 1.3.1.3 Social Life Cycle Assessment

The social life cycle assessment SLCA is a life cycle assessment tool that aims at quantifying social potential impacts through all the life cycle of the product. The social impacts are the social interactions and relations of stakeholders that may affect their well-being due to activities held in the different life cycle phases. The main causes of such social impacts are mainly resulted from behaviors affecting the well-being of employees such as child labor or deprive of labor rights. Also, socio-economic decisions can generate significant social impacts such as investing in building an industrial zone near an urban zone (UNEP, 2009).

The framework of the SLCA is mainly based on subcategories that are classified according to a stakeholder category. These subcategories are themes related to significant social context and issues. They are assessed using inventory indicators adapted to the context of social analysis. The SLCA follows the same steps of the conventional LCA and has been considered as a complement since it provides an impact assessment from a social and a socio-economic perspective on the basis of generic and site specific data. In each social life cycle assessment category, five stakeholder categories might imply, namely; Staff, consumers, value chain actors, national society and local community. It is important to note that there is additional stakeholders' categories. The identification of such categories depends on the context of the social analysis. Compared to the LCA method, the SLCA also requires a significant amount of data and based on iterative procedure. This method can be implemented for decision making purpose. The steps of a social life cycle assessment are as follows:

- **Goal and scope definition:** In this step, the stakeholders involved within the study are identified along with the specification of data that will be collected in the next step on the basis of the objective of the study and the defined Functional Unit FU.
- **Life cycle inventory analysis:** On the basis of the outputs of the first step, data are collected for impact assessment. Life cycle inventory data are expressed in worker hours that are classified by country. The most well-known social databases are the SHDB (Norris et al., 2013) and PSILCA (Ciroth & Eisfeldt, 2016). Table 1.1 highlights the main characteristics of both databases.
- **Social impact assessment:** Impact categories, subcategories and characterization models are selected. The impacts categories are relative to the well-being of stakeholders such as health and safety, human and labor rights, conditions of the working environment..etc. The available social impact assessment method is different from environmental ones. In

Table 1.1: Characteristics of PSILCA and SHDB

Characteristics	SHDB	PSILCA
Launch year	2005 by the new earth organization	2016 by Green Delta
Main objective	Analyzing generic social data categorized in countries and sectors in order to quantify potential social impacts during the life cycle of products	
Structure	Social data tables: Qualitative and quantitative data, worker-hours model, input-output model	
Risk levels associated to the social issues	Four levels: Low, Medium, High, Very High. Scale: From 0.1 to 10	5 Levels: Very Low, Low, Medium, High, Very High. Scale: From 0.25 to 5
Number of indicators	123 indicators (Only 23 analyzed by the impact assessment method)	53 indicators
Stakeholder categories	Five categories: Workers, Consumers, Local community, society, Value chain	Four categories: Workers, Value chain actors, Local community, Society.
Aggregation in impact methods	Aggregation through themes and social categories	Limited aggregation

fact, it evaluates the risk level of each element while environmental impact assessment methods aim to model the cause and effect chain (Midpoint and endpoint impact categories).

- **Interpretation:** This step is dedicated to the evaluation of results by identifying the significant issues resulted from the impact assessment. Recommendations for improvement are proposed in order to minimize the impacts taking into consideration the uncertainty issues related to the assessment results.

The SLCA is applicable in several researches. However, it is still a recent proposed technique and the available databases are under development. The background data is still incomplete. Therefore, the collection of required data is time-consuming and needs significant investments to obtain robust assessment.

Moreover, one of the major challenges is the application of these tools at an early stage of the design process. In fact, most of companies aim to detect potential environmental, economic and social impacts since the design phase in order to compare between several scenarios and select the optimal one. Indeed, it is easier to optimize the impacts and improve the performance of the product from a sustainability perspective when the product is not developed yet. At a later stage, improvement actions for redesign and development are significant. Thus, our objective is to conduct life cycle assessment at the design stage and integrate the consideration of environmental, economic and social issues within the process of design. In the following subsection, we will recall the steps of the eco-design process as defined in the ISO 14062 (ISO, 2002).

### 1.3.2 Eco-design process

The term Eco-design is short for ecological design. The design process, as defined in the ISO (2002), is a set of processes that transforms requirements into product or system specification. Usually, the design of a product takes into account several factors such as the main function of the product, the quality, the ergonomic, the safety and the cost. However, the environmental aspects that may occur during the life cycle of the product are not considered. Conventional regulation focuses mostly on the GHG emissions during the manufacturing phase. Yet, the product, in all its stages, may contribute to the generation of environmental impacts. To this end, the concept of eco-design has evolved through recent years in order to minimize potential impacts since early design phase to optimize the life cycle of a product from an environmental perspective.

ISO (2002) has defined the eco-design as the integration of environmental aspects within the design and development process as illustrated in Figure 1.7.

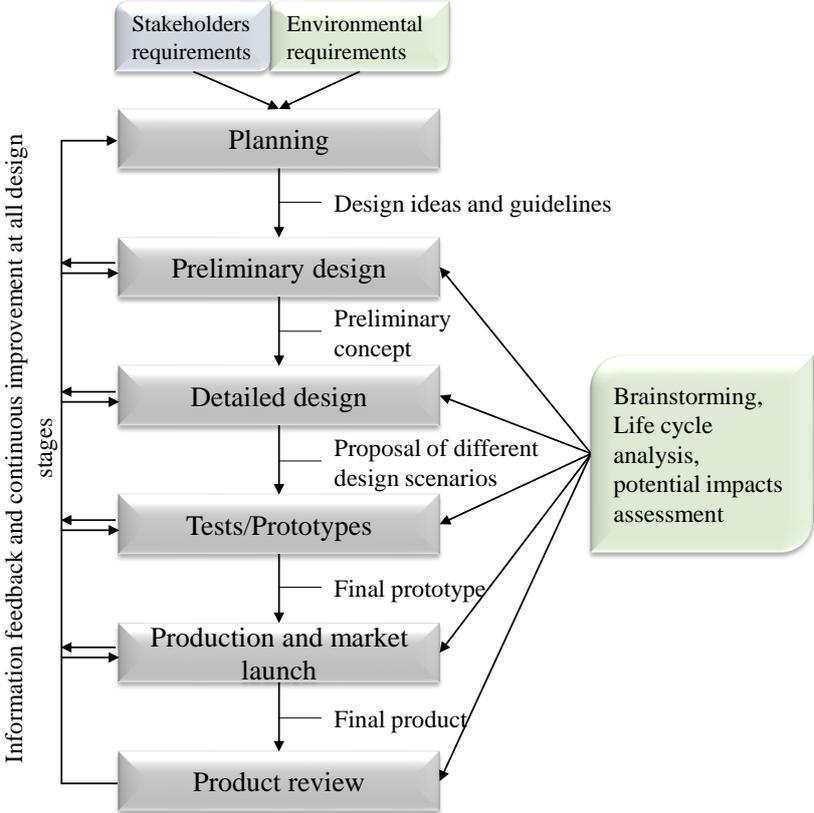


Figure 1.7: Generic framework of an Eco-design process (ISO, 2002)

- **Planning:** This phase sets the characteristics of the product and its principle aspects. The

inputs of this phase are mainly the requirements of customers and the stakeholders, data relative to the market situation, the organization's image and competitors, environmental and regulatory requirements and data relative to financial resources available for design activities. The life cycle approach is included since the planning of design by analyzing life cycle phases of a similar product in order to detect potential impacts related to environmental issues such as global warming, human toxicity, ozone depletion..etc. The results of impacts assessment have a significant influence on the design decisions. The output related to this step is a set of design ideas and relevant requirements identified on the basis of collected data inputs.

- **Preliminary design:** During this step, design ideas are converted into several concepts satisfying the identified requirements. These ideas also give hints on environmental objectives relative to the product. Therefore, the next step is data collection in order to create an inventory of elementary and intermediate flows (inputs: environment extractions/ outputs: emissions to the environment) for each elementary process of the product system. The output is the final specifications and the selected concepts.
- **Detailed design:** This phase consists of detailing more the selected concept to specify the product. The collected data relative to the elementary processes and to the reference flow of the FU are then validated. The potential impacts are identified from the different phases of the life cycle. At this stage, we are able to assess the identified impacts. The assessment is composed of six steps. The first is the selection of impact categories, indicator categories and characterization models. The second step is the classification of inventory results. The third step is the characterization which consists of calculating the results of category indicators. The fourth step is normalizing the results of the indicators' category considering the information of the reference. The fifth step is grouping which is sorting and ranking impact categories. The sixth step is weighting which is reducing the results to a unique score. Usually the weighting is used in the case of endpoints (i.e. human health, ecosystem quality, climate change and resources). The outputs are the proposed solutions for the final product design.
- **Tests/ Prototype:** This phase consists of checking the detailed design by comparing it to the required specifications. The interpretation of the life cycle analysis includes 3 types of checks (i.e. Completeness, sensitivity and consistency checks) (ISO, 2006a). Tests on the prototype are made to check some specifications such as material properties, resistance to wear, main functionality and lifespan. At this stage, the prototype is ready

to be manufactured and to be launched in the market.

- **Production and market launch:** The product goes through an assembly process until the final product. The market launch consists of communicating information relative to the characteristics of the product in order to encourage customers to buy and use the product.
- **Product review:** This phase allows the designers to find sources of improvements from the critiques of users and interested parties. These recommendations allow us to set improvement actions and in some cases reviewing the objectives and the scope.

In chapter 2, we will review recent related works to sustainable design and we will detail the hindrances that might face the application of life cycle assessment at the design stage. In the last section, we will outline the motivation for the elaboration of this thesis.

## 1.4 Motivation

The main motivation for our research is to anticipate environmental, social and economic impacts at an advanced stage of the life cycle of a product or service. Thus, we will focus on the design phase where choices and strategies are decisive and sometimes irrevocable. This interest is most relevant if the issues related to the product's implementation or improvement affect the sustainability criteria in environmental, social and economic dimensions. For instance, designers often redesign intelligent electronic systems (i.e. Smartphones, remote monitoring systems.. etc.) based on their performance and their operational safety aspects. In several cases, the environmental dimension is taken into account to minimize pollution. However, from an industrialization and manufacturing perspective, there are impacts that are not considered, such as the impacts related to the decomposition and relocation of manufacturing processes in developing countries, which favours child labor and additional work hours at night. Moreover, these impacts might affect the culture and values of societies and economies in the use phase. It could affect human relations, over-consumption and waste leading to conflict and poverty aspects.

In this context, there are many examples. The most important thing is to consider all the phases of the product's life cycle from the extraction of natural resources to the end of life. This consideration during the design phase is very critical, given the lack and imprecision of design input data and the uncertainty about possible impacts of output data that may affect sustainability from an environmental, social and economic perspective. Sustainable design scenarios are numerous and sometimes complementary. They are based on dependent and interacting criteria.

Certainly, there are already multi-criteria and multi-objective methods in the literature that can solve this problem. However, without a coherent approach and a structured design model, they could not be meaningful and could not fully achieve the expected results.

Our idea is to build an innovative and generic model that could address the impacts of the product life cycle and that could guide designers to select an optimal design scenario from a sustainability point of view. Its generic aspect will be characterized by taking into account other factors related to business contexts and strategies. Moreover, the interest of this work is not only limited to research methods and tools. It is extended to their conjunctions and in the construction of a model that can be used by designers, engineers, researchers and managers to effectively implement requirements and objectives of sustainable development in all phases of the product and system life cycles.

## **1.5 Conclusion**

In this chapter, we have presented the concept of sustainable development and its related challenges and objectives on the international level. Then, we have presented the life cycle assessment tools and the Eco-design principles that cover all life cycle phases and provide a clear vision on the potential impacts that may occur during the product's life cycle. We have also outlined the motive of the elaboration of this thesis and the main focus of the research on the design of industrial products. In the following chapter, we will present the proposed approach and we will detail the guidelines that led to the construction of the model's framework based on previous scientific publications that proposed innovative models and frameworks for sustainable design of products.

Chapter **2**

**A new approach for sustainable design  
scenario selection: Methodology and  
model's construction**

## **2.1 Introduction**

On the basis of the state of the art detailed in Chapter 1. We have analyzed different principles that guide to sustainable design strategies. This Chapter focuses on introducing the methodology that led to the proposal of a new approach for sustainable design of a given product on the basis of a review of recent related works.

## **2.2 Challenges facing sustainable design**

### **2.2.1 Strategic vision and contextualization of design**

Within the first axis and from a multidimensional perspective, we note that internal and external issues of organizations can significantly affect initial choices of design alternatives. For example, we can mention the consideration of financial opportunities, the existence of an environmental tax, supply chains, process capability for similar products, the qualification and nature of employees, factories' locations and many other issues that depend on the activity of the enterprise. These issues can be internal or external and the choice of a sustainable design scenario can be changed due to these issues. Moreover, without considering them, it is highly possible that the chosen design scenario can not be adapted to the needs of the company in terms of resources. To this matter, the design process is not only limited to the design of the products in terms of material choices but a whole value chain design. In fact, the choice of a best scenario can not be generic but must be necessarily contextualized on the basis of each company's objectives, strategic direction and capabilities.

In this study, design scenarios are identified from stakeholders' requirements and the company's internal and external issues. Tyl et al. (2015) have identified only strategic scenarios based on the integration of the stakeholders' concept into eco-innovative opportunities. Bereketli & Genevois (2013) have implemented the QFD tool to identify the needs and expectations of the stakeholders that are mainly related to costs, quality of the product and environmental criteria. Their framework did not involve internal and external issues of the organization. Moreover, we have proposed in Sansa et al. (2017) a framework that select an optimal scenario from a list of predefined ones. The choice of the best scenario is based on the assessment of sustainability potential impacts and the fuzzy ANP (Mikhailov & Singh, 2003) in order to compute a single score for each option. The proposed model is illustrated in Figure 2.1.

This model was applied to select the best technologies among four different batteries. The

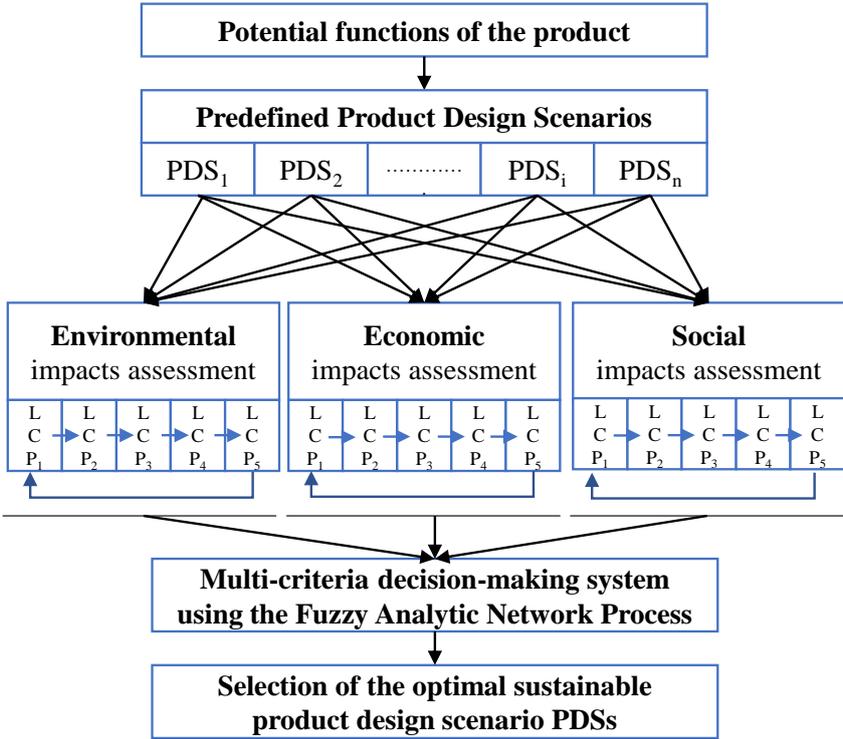


Figure 2.1: Sansa et al. (2017) proposed framework for sustainable product design selection

Multi-criteria decision system was based on sustainability perspectives. However, the options were already predefined without a previous analysis of the company’s context. The assessment of impacts of each option was preformed using environmental (ISO, 2006a,b), economic (Neugebauer et al., 2016) and social life cycle assessments (Dreyer et al., 2006). Hence, the risk of selecting a non adequate scenario is very high due to the lack of context analysis that must be integrated within the first phase of the selection process for more accurate results. In fact, the contextualization concept was first introduced in the ISO9001 (ISO, 2015b) standard for quality management systems and ISO14001 (ISO, 2015a) for environmental management systems in their latest versions published in 2015. Both standards required the coherence of system planning and development with regard to the issues of the company and the stakeholders’ requirements in order to achieve the desired goals efficiently.

Design and development activities are fully integrated into the requirements of management systems. In a particular context of Eco-design (ISO, 2002), ISO14006 (ISO, 2011) in its 2011 version has combined design, environment and management system requirements to provide the necessary guidelines for the implementation of Eco-design approaches. This combination is based on merging the requirements of ISO9001:2008 (ISO, 2008), ISO14001:2004 (ISO, 2004)

and ISO14062:2003 (ISO, 2002) as shown in Figure 2.2.

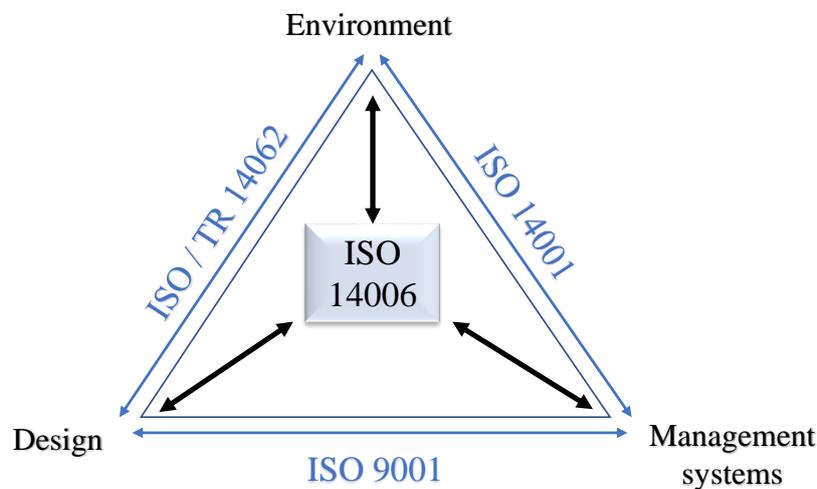


Figure 2.2: Links between the ISO14001, ISO9001, ISO14062 and ISO14006

In fact, ISO14006:2011 offers guidelines to help companies through the implementation process of their Eco-design management on the basis of an environmental management system. These guidelines are generic and comply with any company, regardless its activity or its size. In addition, this standard points out the importance of considering external issues when defining Eco-design strategies. It is highly recommended that factors which may influence the design process should be addressed at an early stage to deal with this influence through defined strategies.

In 2015, a new version of both standards; the ISO9001 (ISO, 2015b) and 14001 (ISO, 2015a) standards has been published. The new up-dated versions have evolved towards a High Level Structure (HLS). In fact, it is a harmonized structure based on including the context of organization in order to set the adequate strategies and the appropriate management of all processes. To this end, the HLS recommends the integration of internal and external issues of the organization as well as the needs and expectations of its stakeholders. However, it should be noted that up to this day, the ISO14006 has not fully evolved yet towards the HLS perspective.

Regarding the social pillar, the latest version of ISO26000 (ISO, 2010) published in 2010, includes recommendations to better address environmental, economic and social aspects with the aim to provide guidelines within the context of sustainable development. This standard highlights the necessity and the importance of considering the context of the organization to ensure the human health and the social well-being by analyzing and addressing factors that might affect both pillars. In the same perspective, ISO 37101 (ISO, 2016b), published in 2016, presents requirements and guidelines for a sustainable management system with regard to the territorial

communities. This standard recommended the use of the context analysis for planning. On the basis of the known design mechanisms and considering the context of the enterprise, it is possible to identify a multitude of criteria that, when combined, can form a high number of operational design scenarios adapted to the current state of the organization. At this level, the main difficulty is to address this set of scenarios and to choose an optimal option among them. In the following subsection, we will detail different challenges that face the selection of the best scenario.

### **2.2.2 Issues facing the choice of the optimal design scenario**

based on the literature and related works in the field of sustainable design and development, we can identify and address five main issues facing the accurate choice of an optimal design scenario, namely:

1. The difficulty of applying the LCA at an early stage of design process: In fact, LCA (ISO, 2006a,b) is the best known tool to treat environmental impacts (Kobayashi, 2005). Most of related works are based on the use of this tool. We can mention in particular the works of (Ostad-Ahmad-Ghorabi & Collado-Ruiz, 2011; Herva et al., 2012; Arena et al., 2013; X. Wang et al., 2014; Romli et al., 2015) where their proposed models and frameworks are essentially based on the principles of LCA. However, barriers still holding it back from being a common tool in industries, especially due to its difficulty and data requirements. Usually, LCA is time-consuming which have motivated researchers to attempt to simplify the process of applying LCA such as the use of generic databases, we can mention in particular the Ecoinvent database (Wernet et al., 2016) that provides a huge amount of assessed data that shortens the required time to get desired results. Also, early stages of design have to most potential for improvement, thus, many researchers have focused on assessing environmental issues at these stages
2. The uncertainty issues: Impact assessment methods in the different life cycle phases are based on simplification assumptions that are related to data quality and availability. In the context of sustainable design, product data are often generic and relative. Various assessment methods are used in order to measure and address environmental, economic, and social impacts. Each method has its own parameters and its specific classification of indicators that can be oriented problems or damages (i.e. Midpoint or Endpoint categories). They are mainly based on aggregating different categories of impacts using characterization factors. Hence, the aggregation leads to imprecision in the obtained results. It is

important to note that these results are used as a decision support for decision makers through the selection process of design or improvement scenarios. In addition, the judgments of experts are not fully objective. The preferences of decision makers are often based on collected data but still subjective according to experts' logic and interpretation.

3. The maturity level of the economic and social aspects: Both aspects have been always measured with single indicators that are limited usually to the employees' health and safety or the product's costs. For instance, Fagnoli et al. (2014) have dealt with social aspect by considering the safety of consumers and employees. In the other hand, Younesi & Roghanian (2015) have measured the quality of the product as a social parameter. Ahmad et al. (2018) have conducted a critical review of tools used within sustainable products' design and development. They have classified these tools into two categories; tools that are limited to addressing two aspects such as eco-design tools. the authors named them Partial sustainable product design tools. The second category includes all three aspects of sustainability. This classification is based on scientific papers published between 2007 and 2017. Hence, the authors have revealed through this review that most of researchers have focused on partial sustainable product design tools. In particular, eco-design tools have reached a maturity level since they are mostly based on standards and well-known models and frameworks such as the QFD model.

As a conclusion, tools that integrated three aspects are still not mature compared to Eco-design tools. In fact, many of them are simple proposals or conceptual frameworks. The authors have recommended in-depth researches to improve such tools. They also pointed out the drawbacks of using these tools at a later stage of the design process. In this context, an attempt has been made to extend LCA method to the economic and social dimensions. The most recent proposed frameworks are the economic life cycle assessment (Neugebauer et al., 2016) and the social life cycle assessment (Dreyer et al., 2006). Indeed, Neugebauer et al. (2016) have proposed an economic life cycle assessment approach based on the common Life Cycle Costing method (Woodward, 1997). The Economic Life Cycle offers impacts categories that follow an impact pathway composed of Mid-point category (i.e. Five economic indicators), Endpoint category (i.e. Two indicators) and area of protection (i.e. Two indicators). This framework is still require validation as it is still undergoing practical implementation within different fields in order to provide consistent economic assessment.

For the social pillar, Dreyer et al. (2006) proposed a social life cycle assessment that provides, compared to the environmental LCA, a new area of protection (i.e. Human

Well-being and Dignity). The social LCA includes all phases of the product's life cycle and provide two impact categories' layers that offer a variety of social impacts indicators. Databases have been developed for social assessment. The social life cycle assessment is under continuous improvement and many researchers in this field are focusing on reaching the same maturity level as the environmental LCA.

4. The dependency between Life cycle phases and the interaction between the sustainability pillars. In this context, during the design process, design choices and criteria of a given product are subject to create dependency between the life cycle phases of this product (X. Wang et al., 2014). For instance, the manufacturing process, the method of delivery of the product, its use phase and the type of its waste treatment depend mostly on the choice of raw materials' nature and quantity. on the other hand, the environmental, economic and social aspects and impacts interact according to the behaviour of the product's life cycle. For example, the generated waste during the manufacturing phase is able to contribute to an exodus of population that lead to unbalance between the cities. These impacts have an influence on the economic development and on the quality of life. Moreover, economic development boosts the creation of job opportunities but simultaneously, increases the consumption rate and contributes to the increase of the amount of generated waste at the end of life phase. The waste, especially non-recyclable hazardous material has significant side effects to the human health.
5. The complexity of multi-criteria choice of scenarios: It is obvious that we are facing a multi-criteria choice problem since we are dealing with a selection process on the basis of a multitude of design criteria. The main challenge is reflected through the difficulty of changing decisions about a design scenario at a later stage (Earl et al., 2005). Changing or modifying criteria at a later stage is time-consuming and requires significant additional costs. It is highly recommended to implement adequate methods and tools that address a large number of design criteria and alternatives that form a variety of combinations with interactive impacts.

On the basis of these issues, we have preformed a review of recent works that have proposed models and frameworks to solve design problems. We have detailed for each work with regard to how the authors have dealt with each design issue as discussed in Table 2.1.

Table 2.1: Evaluation of related works with regard to the design issues

Related works	Issues					
	Complexity of LCA	Dependencies and interactions	Maturity level of economic and social aspects	Uncertainty issues	Complexity of multi-criteria choices/number of scenarios	Strategic vision and contextualization of design
Herva et al. (2012)	The complexity was not considered. LCA was already used. The indicators were global and they did not consider each life cycle phase	Only environmental indicators were used	The economic and social aspects were not considered	Use of fuzzy logic reasoning (Zadeh, 1965) for the aggregated data treatment (Ex. Ecological footprint, environmental risk assessment and LCA results.	No scenario concept. The proposed approach combined three assessment methods: mono-criteria Ecological footprint, environmental risk assessment and LCA results.	Organization strategies were not taken into account
Bereketli & Genevois (2013)	Not considered	Only quality and costs aspects and environmental impacts were taken into account	The social aspects were not considered	Use of Fuzzy logic to deal with imprecision of criteria and alternatives preferences	Use of Analytic Hierarchy Process (AHP) (T. Saaty, 1980) to limit the number of criteria and alternatives	Use of the QFD to identify stakeholders' needs and expectations considering the costs, the quality and the environment criteria
X. Wang et al. (2014)	An environmental assessment per life cycle phase was conducted	Consideration of dependencies between life cycle phases	Only environmental indicators were used	Use of fuzzy ANP to treat dependencies between life cycle phases and uncertainties of judgments	Use of predefined alternatives for product design	
Fargnoli et al. (2014)	Use of eco-indicator 99 for the impact assessment	Analysis of interactions between technical functions through morphological matrix	Only environmental and economic indicators were used	Use of Preliminary hazard analysis to treat uncertainties during the use phase	Use of "Intervention chat" to connect the requirements to the alternatives taking into account the product's functions	Bench-marking deployment for data collection related to the market and the competitiveness
Romli et al. (2015)	Computation of environmental indicators through the life cycle phases	Not considered	Only functional and environmental criteria were considered	Not considered	The QFD method was adapted for the choice of components and process parameters	Only customers' requirements were considered

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Table 2.1 – continued from previous page

Related works	Issues					
	Complexity of LCA	Dependencies and interactions	Maturity level of economic and social aspects	Uncertainty issues	Complexity of multi-criteria choices/number of scenarios	Strategic vision and contextualization of design
Younesi & Roghanian (2015)	The LCA was not used	The dependencies between customers' requirements, the environment, and quality criteria were addressed	Only environmental and cost criteria were considered	The use of QFD and fuzzy logic to deal with uncertainties of experts' judgments	The use of fuzzy ANP for multi-criteria decision making.	The use of fuzzy QFD to Consider customers' requirements, environment and quality factors
C. Ng & Chuah (2016)	The design alternatives were identified per life cycle phase	The dependency was not treated	Only environmental indicators were considered	The uncertainty was dealt with using the fuzzy logic to estimate two indicators related to natural resources' aspects and to emissions to water, air, and soil	The use of AHP combined with the fuzzy logic and evidential reasoning for the choice of the optimal alternative	No contextualization process was deployed within the proposed approach
Sansa et al. (2017)	The design criteria and the derived alternatives were identified per life cycle phase	The dependency was addressed by measuring the importance of each life cycle phase with regard to the remaining phases	All sustainability pillars were considered	The uncertainty was addressed using the fuzzy logic combined with ANP to deal with the subjectivity of experts' judgments	The use of the ANP method to select the best product design option on the basis of eight alternatives	No contextualization process was deployed within the proposed approach, the product design options were predefined as technological and technical characteristics

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Table 2.1 – continued from previous page

Related works	Issues					
	Complexity of LCA	Dependencies and interactions	Maturity level of economic and social aspects	Uncertainty issues	Complexity of multi-criteria choices/number of scenarios	Strategic vision and contextualization of design
Song & Sakao (2017)	Product life cycle information was considered as an input data of the design framework. The framework included a customer activity cycle	The dependency issue was addressed using Fuzzy graph-based clustering (Rosenfeld, 1975) to deal with dependencies and interactions between components	The social aspects were not considered	The uncertainty was dealt with using the Fuzzy graph-based clustering	The multi-objective optimization modeling and Non-dominated Sorting Genetic Algorithm (NSGA) II (Deb et al., 2002) were used to select the best product/service system configuration	The proposed framework included the stakeholders within the customer activity cycle in the identification of Product-Service System (PSS) requirements
Kim & Moon (2017)	The life cycle approach was employed to compute environmental and economic indicators during the first step of the proposed approach	The dependency issue was addressed using the design structure matrix to identify the dependencies between components and the Bayesian network (Rosenfeld, 1975) to model these dependencies and interactions between components	All sustainability pillars were considered	The uncertainty was dealt with using a fuzzy inference system	First, a multi-attribute decision making tool was used to rank the sustainability indicators. Later on, a fuzzy inference system for decision making was used on the basis of the collected results from previous steps of the proposed approach, to select the best design	The issues related to the company and its stakeholders requirements were ignored in the proposed framework
Rehman & Ryan (2018)	The Life cycle approach was considered in the proposed framework	The dependency issue was not considered	All sustainability aspects were considered	Use of future proofing within the proposed framework	Use of modified AHP to select a sustainable future-proof design	The stakeholders' preferences were considered
Tao & Yu (2018)	The Life cycle approach was considered in the proposed framework	The dependency issue was not addressed	All sustainability aspects were considered	Not considered	Use of QFD method to generate options	The stakeholders and the consumers' preferences and behaviours were considered

Continued on next page

Table 2.1 – continued from previous page

Related works	Issues					
	Complexity of LCA	Dependencies and interactions	Maturity level of economic and social aspects	Uncertainty issues	Complexity of multi-criteria choices/number of scenarios	Strategic vision and contextualization of design
Frizziero et al. (2018)	The LCA was not considered	Use of interaction matrix to compare technical requirements	The economic and social aspects were not considered	Not considered	Integration of TRIZ (Ahshuller, 1996) and QFD methods to optimize outputs derived from the product's requirements	A comparative study was performed between the company and 3 of its competitors
Gonzalez-Garay & Guillen-Gosalbez (2018)	Use of a complete life cycle assessment to assess environmental impacts	Dependencies and interactions were not considered	The social aspects were not considered	Not considered	Use of data development analysis to classify the alternatives without weights' computation. The use of multi-criteria and multi-objectives tools	Use of the multi-criteria decision tools to assist the stakeholders within their decision process
Badurdeen et al. (2018)	Use of Multi-life cycle approach to address the design problems	Use of a dependency diagram to assess dependencies and sustainability objectives	The social aspects were not considered	Not considered	Use of NSGA II for multi-criteria decision system	Not considered
Opon & Henry (2019)	Not considered	Use Causal network that included interrelationships between indicators	The economic and social indicators were considered in combination with the 17 sustainable objectives	Not considered	Use of causal network to analyze and aggregate a multitude of criteria	Not considered

### 2.2.3 Identification of design principles

In order to construct our model. This latter has to be based on design principles as references. First, principles are identified as basic references for model construction. These design principles were recommended by Marques et al. (2017) and the international standards (ISO, 2002, 2006a,b, 2011). In addition, Gould et al. (2019) have highlighted the needs required to achieve a sustainable design. As conclusion, on the basis of the above works, we have set five design principles, namely:

- **Early integration:** The assessment of different impacts generated from the product should target the early stages of the design process. In fact, the assessment of such impacts is not an easy task when the product has already been developed and it may cause significant costs. The advantage of the early integration of the sustainability concept is the significant influence of decisions on the contribution of life cycle phases to impacts related to the three pillars. In addition, decision-making at early stages has the ability to clear the vision with regard to the progress pattern of the project's success.
- **Life Cycle Approach:** The life cycle approach includes all stakeholders in a whole chain of a product's life cycle from the extraction of its raw materials to its end of life disposal. Identifying environmental, economic, and social impacts for each life cycle phase of the product drives the industry towards a more sustainable direction and targets better the significance of the identified impacts.
- **Multi-criteria concept:** The multi-criteria concept is the decision-making on the basis of several criteria. It helps decision makers to minimize the subjectivity of their judgments. Moreover, the decision to make is based on a diversity of criteria from different nature and types which lead to more accurate results.
- **Consideration of sustainability aspects:** All three aspects (i.e. environment, economy, and society) must be included to target the design of the product towards a sustainability concept and to take into account impacts related to each pillar.
- **Choice of an optimal design scenario:** The chosen solution must consider trade-offs between different scenarios and criteria. The choice of a most optimal design scenario is based on choosing one having the lowest environmental, economic and social impacts in terms of significance on the environment, the economic growth and the well-being of

citizens and future generations. On the other hand, the best scenario must generate high profitable impacts to the company for all life cycle phases.

In the following, we have evaluated the related works aforementioned in Table 2.1 with regard to the consideration of the design principles detailed above as shown in Table 2.2.

Table 2.2: Evaluation of related works with regard to the design principles

Related works	Design principles taken into account							
	Early gratification	inte-	Life cycle approach	ap-	Multi-criteria concept	Sustainability aspects	Optimal option	Contextualization
Herva et al. (2012)	✓						✓	
Bereketli & Genevois (2013)	✓				✓	✓	✓	✓
X. Wang et al. (2014)	✓		✓		✓		✓	
Fargnoli et al. (2014)	✓		✓		✓			✓
Romli et al. (2015)			✓					
Younesi & Roghanian (2015)	✓				✓		✓	
C. Ng & Chuah (2016)	✓		✓		✓		✓	
Sansa et al. (2017)	✓		✓		✓	✓	✓	
Song & Sakao (2017)	✓		✓		✓		✓	✓
Kim & Moon (2017)	✓		✓		✓	✓	✓	
Rehman & Ryan (2018)	✓		✓		✓	✓	✓	✓
Tao & Yu (2018)	✓		✓		✓	✓	✓	✓
Frizziero et al. (2018)	✓				✓		✓	✓
Gonzalez-Garay & Guillen-Gosalbez (2018)	✓		✓		✓		✓	✓
Badurdeen et al. (2018)	✓		✓		✓		✓	
Opon & Henry (2019)	✓				✓	✓	✓	

## **2.3 Guidelines for the construction of a sustainable design selection model**

On the basis of the design issues (subsection 2.2.2), the design principles (subsection 2.2.3), and the review of related recent proposed frameworks and models, we have synthesized these guidelines for the development of our model as illustrated in Figure 2.3. The originality of our idea relies on the combination between the organizational and product approaches to achieve sustainable design.

Within this conjunction, three levels that characterize the guidelines are identified. This characterization is based on interactions between the design problem, the design principles and the current standards. The three levels are identified as follows:

1. **Strategic level:** In this level, design strategies are determined on the basis of the contextualization' principles and taking into consideration the internal and external issues, and the needs and expectations of the organization's stakeholders. The strategic vision issue is addressed at this level.
2. **Tactical level:** In this level, the main objective is to define tactics that are adapted to the strategies identified in the strategic level. Design criteria are derived from these defined tactics and assigned to each life cycle phase of the product. At this stage, it is possible to set design alternatives specific to each design criteria. By combining them, multitude of scenarios can be generated.
3. **Operational level:** The last level considers the aspects of the sustainable development and their related impacts in each phase of the product's life cycle. The selection of the optimal operational design scenario is performed at this level.

In the following subsection, we will detail the three levels of the proposed approach with regard to the related works and we will identify the research questions for each level.

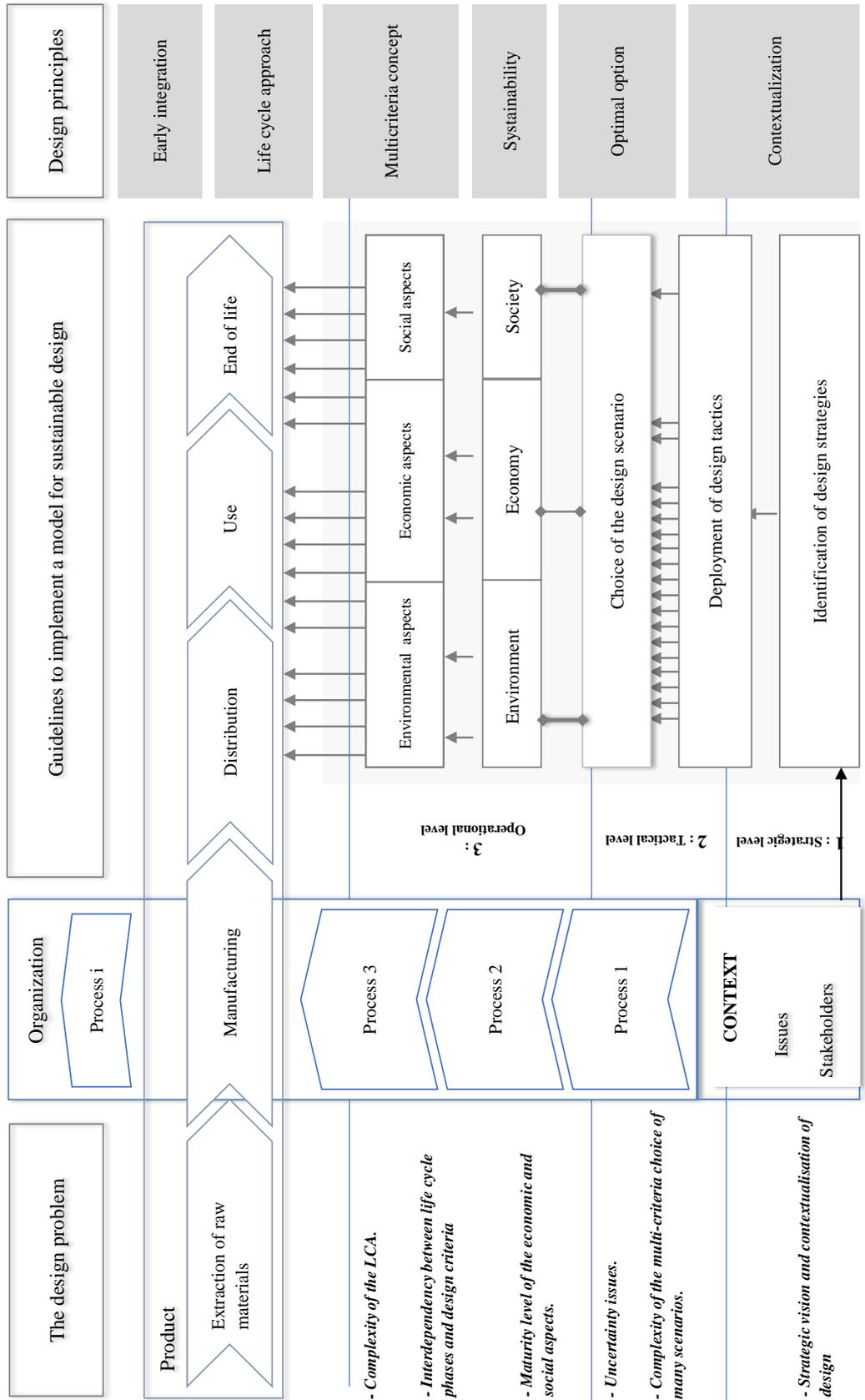


Figure 2.3: Product and system Conjunction - Principles of Sustainable Design (Sansa et al., 2019)

### 2.3.1 The three levels of the proposed approach and the Research questions

Below, we have classified the most relevant related works cited in Table 2.1 with regard to each of the three identified levels as follows:

1. **Strategic level:** At this level, some works considered only the requirements and expectations of stakeholders and did not include internal and external issues. We can mention in particular the works of Bereketli & Genevois (2013), the authors have used the QFD as a tool to identify their stakeholders' functional requirements in terms of costs, quality and environment. Fagnoli et al. (2014) have deployed a bench-marking to collect data related to the company's competitors. They did not consider all the company's stakeholders. In addition, Younesi & Roghanian (2015) have used the QFD to include customers' requirements as inputs to their proposed framework. Moreover, B. He et al. (2018) have identified and assigned the functional needs of the stakeholders into four levels based on a unique goal, categories, attributes and examples. The stakeholders' needs have been focused only on a sustainability perspective without considering the company's issues. Rehman & Ryan (2018) have integrated future proofing and sustainability principles in order to form a database that aimed to estimate future requirements and to project solutions. Also, Tao & Yu (2018) have used the QFD to define the strategy of the company on the basis of stakeholders' needs and expectations.

Other works did not consider the contextualization. Indeed, X. Wang et al. (2014) and Sansa et al. (2017) have used predefined scenarios as inputs to their frameworks based on technical criteria and technological choices related only to the product, Romli et al. (2015) have proposed alternatives for redesign on the basis of prior knowledge of the product including only customers' requirements. Also, Bereketli & Genevois (2013) and Younesi & Roghanian (2015) have deployed the first phase of the QFD method to generate scenarios. In addition, it is important to note that the expectations of stakeholders did not simultaneously address all aspects of sustainable development. Most of these requirements were technical, related to costs and quality and in some works, environmental requirements were considered. To this end, the first research question that we will address in this thesis is:

***Q1: How to identify internal and external issues and stakeholders' requirements that can generate strategic scenarios at an advanced design stage?***

2. **Tactical level:** At this level, previous works have suggested tactics based on non contextualized generic criteria. In most works, the number of design criteria was limited which has affected the diversity and the number of possible scenarios. Most of proposed frameworks have been deployed within the product's life cycle phases. In most cases, only the environmental profile was considered. In addition, we note that decision criteria were not deployed by life cycle phase in the works of Bereketli & Genevois (2013) and Herva et al. (2012). In fact, Bereketli & Genevois (2013) have proposed three criteria (i.e. Cost, Quality and environmental concerns) and they have derived a set of alternatives from these criteria that covered all life cycle phases but generically without any specific deployment with regard to these phases. Herva et al. (2012) have collected data relative to raw materials only as input variables to compare two systems. As output variables, they have computed Energy, air and water emissions, and solid waste.

Other works have considered the economic aspect by computing costs relative to the product's design and development (Bereketli & Genevois, 2013; Fagnoli et al., 2014; Younesi & Roghanian, 2015). However, most of them have ignored the social aspects (Song & Sakao, 2017; Frizziero et al., 2018; Badurdeen et al., 2018; Gonzalez-Garay & Guillen-Gosalbez, 2018). For instance, Song & Sakao (2017) have addressed the requirements related to technical, environmental and cost issues, they have also focused on safety of operations issues.

Moreover, Younesi & Roghanian (2015) have treated the quality of the product from the user perspective to measure the social aspect. In addition, Badurdeen et al. (2018) have integrated criteria related to the end-of-life treatment of the product adopting the 6R tool (Reduce, recycle, redesign, recover and remanufacture). Chapman & Shigetomi (2018) have considered the social aspect by proposing criteria based on the nation's life style to assess sustainable development. Also, B. He et al. (2019) have proposed five criteria to sustainable life cycle assessment (i.e. environmental, technical, energy, resources, economic). Sansa et al. (2017) have deployed criteria based on life cycle assessment indicators. we can mention in particular the human health and climate change, the economic prosperity and resilience and the well-being of stakeholders. Gonzalez-Garay & Guillen-Gosalbez (2018) have proposed sustainability criteria on the basis on environmental and economic indicators. The environmental indicators were derived from environmental life cycle assessment methods whereas the economic indicators were derived from the computation of costs and the estimation of the economic potential. Thus, the second research question is as follows: **Q2: How to develop tactical design criteria that are coherent with**

***strategic scenarios per life cycle phase and how to generate diversified and significant operational scenarios?***

3. **Operational level:** At this level, the optimal operational design scenario is selected on the basis of multi-criteria tools. Researchers have dealt with various problems related to multi-criteria decision support for the choice of an optimal design solution. Different methods have been used such as fuzzy logic techniques combined with the risk approach to address uncertainty issues (Herva et al., 2012). The goal was to compute a single score in order to select the best option among two raw material types. Other works have proposed the use of the fuzzy ANP (X. Wang et al., 2014; Younesi & Roghanian, 2015; Sansa et al., 2017). In fact, X. Wang et al. (2014) and Sansa et al. (2017) have used the fuzzy ANP to deal with dependencies among life cycle phases within the selection process. In the other hand, Younesi & Roghanian (2015) have used this tool to address inner dependencies between the customer attributes. Bereketli & Genevois (2013) and C. Ng & Chuah (2016) have implemented the fuzzy AHP to address uncertainties in judgments of experts. Moreover, Song & Sakao (2017) and Badurdeen et al. (2018) have used multi-objective tools on the basis of genetic algorithms to select the adequate solution. Certainly, the proposed methods have addressed aspects of uncertainty and dependencies. However, their implementation becomes complicated if the number of solutions is high. In fact, scenarios depend on several diverse parameters related simultaneously to the strategy, the environmental, economic and social aspects. These parameters are derived from different phases of the product's life cycle and it is highly recommended to address these parameters and indicators per life cycle phase for more accurate results and in order to improve the performance of the life cycle of a given product since its design phase. To this end, most of the proposed frameworks for sustainable design improvements are based on life cycle assessment tools. In this context, many studies have highlighted the complexity of LCA methods and have used either preferences (Bereketli & Genevois, 2013; X. Wang et al., 2014; Fagnoli et al., 2014; Romli et al., 2015; Younesi & Roghanian, 2015; C. Ng & Chuah, 2016) or indicators (Herva et al., 2012; B. He et al., 2019) to assess environmental and cost impacts. Hence, we propose the following research question: ***Q3: How to enable optimal design scenario selection at an early stage of design process from an environmental, economic and social perspectives?***

## 2.3.2 Proposed model for sustainable design scenario selection

In this subsection, on the basis of the guidelines (see subsection 2.3.1) and the literature review of previous related works, we propose a generic model that answers the research questions raised in the previous subsection. The proposed model deals with sustainable design issues and principles. The model, as shown in Figure 2.4, is based on the strategic, tactical and operational levels.

The model consists of five main steps.

### 2.3.2.1 Contextualization and design strategy

The first step aims to form product design scenarios contextualized to the organization's objectives. First, the internal and external issues are identified and analyzed. Second, the needs and expectations of the company's stakeholders are identified and classified within categories. These inputs are then combined to identify design strategies. Subsequently, confrontation matrices are deployed to determine strategic scenarios  $SS$  at an advanced stage of design. These scenarios are composed of a conjunction between the internal and external issues, and the requirements of the company's stakeholders. The first step forms the strategic level of the proposed model.

### 2.3.2.2 Identification of tactical criteria and alternatives per life cycle phase

The second step identifies different tactical design criteria  $C_{ij}$  per life cycle phase  $LCP_i$  where  $i$  is the number of the phase and  $j$  is the number of the criterion in phase  $i$ . At this point, operational design alternatives  $A_{ijk}$  where  $k$  is number of alternatives, are identified for each criterion  $C_{ij}$  per phase.

### 2.3.2.3 Identification of operational scenarios

The third step combines  $A_{ijk}$  to form many operational scenarios  $OS_l$  for a given product where  $l$  is the number of operational scenarios. The operational design scenarios are generated by forming all sets of possible combinations between the  $A_{ijk}$ . Thus, if the number of design alternatives is significantly high, the number of possible combinations between the  $A_{ijk}$  is more and more important and significant. Step 2 and 3 form the tactical level of the proposed model

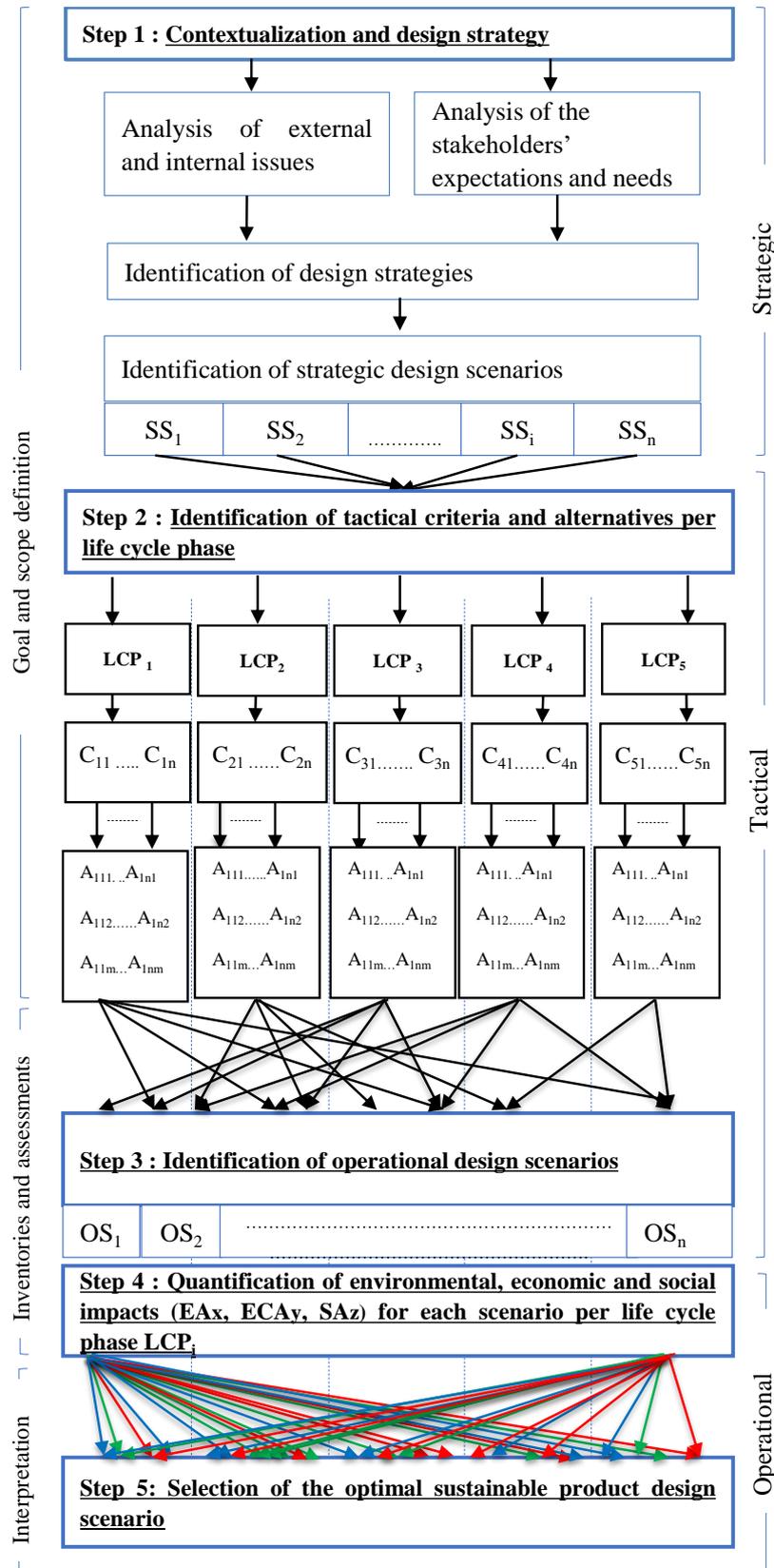


Figure 2.4: The proposed model for optimal design scenario selection (Sansa et al., 2019)

#### **2.3.2.4 Quantification of environmental, economic and social impacts**

The fourth step is dedicated to assessing potential environmental, economic and social impacts for each operational scenario using life cycle assessment tools. Based on this assessment indicators are computed for each  $OS_l$  per life cycle phase in order to facilitate the comparison process between the  $OS_l$  with more objective judgments.

#### **2.3.2.5 Selection of the optimal sustainable product design scenario**

The last step is the selection of the optimal solution on the basis of indicators computed in the fifth step. First, all the scenarios are ranked in order to reduce their number and keep only relevant ones. Next, a multi-criteria decision system is implemented to compute a global single score for each scenario to select the one having the highest score. Step 4 and 5 form the operational level of the proposed model.

Our reasoning follows the LCA methodology's steps (ISO, 2006a,b). Indeed, the strategic and tactical parts of the model form the first step of the LCA which is the goal and scope definition. The operational part ensures the assessment of the impacts in the different life cycle phases. This assessment is based on a prior inventory dedicated to each  $OS_l$ . The interpretation step is embodied in the multi-criteria decision support step.

## **2.4 Conclusion**

In this chapter, we have identified challenges facing the achievement of sustainable design and design principles. Also, we have performed a literature review of recent related works published between 2012 and 2019 and we have analyzed them with regard to the identified design issues and principles. On the basis of this review, three research questions were raised that will be answered in the next chapters. Hence, we have proposed a three-leveled model for design scenarios selection to answer these research questions. In the next chapter, we will detail the first three steps of the proposed model that cover the strategic and tactical level.

Chapter **3**

**Contextualization and design strategies**

## **3.1 Introduction**

In this chapter, we will focus on the strategic and tactical levels which concern the identification of contextualized design strategies and the generation of design scenarios. First, we will present and detail the different issues, the needs and expectations of the stakeholders. Second, we will present our contribution in identifying these elements at the design stage and tools that we have used within our proposed model.

## **3.2 Identification of internal and external issues**

The first level of the proposed model handles the strategic layer. In fact, the design and development of a product cannot be limited to technological options, the chosen scenario must be adapted to the context of the company. The objective is to reduce the probability of selecting an incoherent scenario. For instance, if financial constraints are not considered. The company might face challenges when implementing the chosen solution. On the basis of recommendations of the different international standards, we have decided to include the context of the organization into the strategic layer of the proposed model.

The definition of this context means the identification of internal and external factors that impact the company directly or indirectly. These factors affect its ability to provide the best products and services for its customers. In one hand, internal factors are issues that arise from the company's structure, governance, culture...etc. They might have a positive or a negative effect on the company's performance to satisfy its customers. On the other hand, external factors include the whole environment surrounding the organization such as social, political, economic, legal environments. For instance, the current state of instability of the country post the 2011 revolution affects the company from an economic and political perspectives.

Various tools are used to identify these internal and external factors. In Table 3.1, we have selected the most relevant ones in order to highlight their advantages and drawbacks. A detailed description of these tools can be found in Downey (2005).

Table 3.1: Advantages and drawbacks of strategic tools

Strategic tools	Advantages	Drawbacks
SWOT (Strengths, Weaknesses, Opportunities, Threats) (Brad & Brad, 2015)	<ul style="list-style-type: none"> <li>• It is a simple tool that is widely used which can be applied to all sectors and it is adapted to all types of organizations or individuals.</li> <li>• It guides the users to classify the issues of the company into four categories: Strengths, weaknesses, opportunities, threats. This classification provides a clearer vision to define the strategy.</li> <li>• It is based on both quantitative and qualitative data integrated which enhances the decision making.</li> <li>• From a cost perspective, conducting a SWOT analysis does not require specific technical skills nor financial resources</li> </ul>	<ul style="list-style-type: none"> <li>• There is no weighting process. In fact, the SWOT provides only a list of issues. However, there is no mechanism to rank the significance of an issue with regard to the other. The identification of the issues' significance is purely subjective.</li> <li>• Some ambiguity can be detected in the identification of issues. An opportunity might be simultaneously a threat. For instance, the opportunity to access a foreign market through export might lead to significant costs that can impact significantly the generated profits.</li> </ul>
PESTEL (Political, Economic, Social, Technological, environmental and legal) (Kauskale & Geipele, 2017)	<ul style="list-style-type: none"> <li>• It is a simple framework that categorizes the analysis of issues.</li> <li>• It is low-cost since this tool only requires time to collect the necessary data.</li> <li>• It provides an in-depth understanding of external issues.</li> </ul>	<ul style="list-style-type: none"> <li>• It only handles the external factors.</li> <li>• The factors of the PESTEL analysis are continuously evolving and changing with regard to the current situation. To this end, it must be constantly updated to provide an accurate and valid identification of issues.</li> <li>• The data is not always available especially for external issues and data collection is very time-consuming.</li> </ul>

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Table 3.1 – continued from previous page

Strategic tools	Advantages	Drawbacks
Porter's five forces (Supplier power, Buyer power, Competitive rivalry, Threat of substitution, Threat of new entry) (Porter, 2008)	<ul style="list-style-type: none"> <li>• This framework guides the company to position itself with regard to the competitive market.</li> <li>• It deals with customers and suppliers on the basis of the competition aspect.</li> </ul>	<ul style="list-style-type: none"> <li>• This framework focuses only on the strengths and competitive factors.</li> <li>• This approach cannot be applied to all industries since in some companies, there are more important factors than what this tool offers such as legal and environmental factors.</li> </ul>
Value chain analysis	<ul style="list-style-type: none"> <li>• This framework aims at boosting the profit.</li> <li>• It can be adapted to any industry.</li> <li>• It enables a comparison between the company business model and its competitors.</li> </ul>	<ul style="list-style-type: none"> <li>• This tool involves only the economic factors.</li> <li>• In terms of application, few experts master the use of this method and it is not popular among all organizations.</li> </ul>
7S analysis (i.e. Systems, Strategy, Structure, Share values, Staff, Style, Skills) (Ravamfar, 2015)	<ul style="list-style-type: none"> <li>• This framework considers seven important factors including soft and hard elements.</li> <li>• It guides the company to locate its strengths and weaknesses among internal factors.</li> </ul>	<ul style="list-style-type: none"> <li>• This tool involves only internal factors.</li> <li>• Similar to the SWOT and PESTEL analysis, there is no weighting process to rank the significance of the identified internal factors.</li> </ul>
Early warning systems (Reinhardt, 1984)	<ul style="list-style-type: none"> <li>• This system detects or predicts significant events with regard to competitors.</li> </ul>	<ul style="list-style-type: none"> <li>• The application of this tool is mainly based on assumptions and predictions. There is a risk of obtaining ineffective analysis.</li> </ul>

On the basis of the advantages and disadvantages of each strategic tool highlighted in Table 3.1, we can deduce that the SWOT analysis is more adapted to the first step of our approach since it gives a clear identification of the issues by classifying them into strengths, weaknesses, opportunities and threats. In addition, among these methods, the 7S and PESTEL address a variety of important and significant factors that cover the internal and external environment of the company. Hence, in our model, we propose to integrate the 7S and PESTEL within the SWOT analysis in order to target and analyze more in depth the internal and external issues. First, the identification of the internal and external factors is done using the SWOT analysis. Then, to facilitate and guide this deployment, the internal factors (resp. external factors) will be classified using the 7S technique (resp. PESTEL analysis). The aim of this classification is to give a clearer vision of the company's strategy and to guide the stakeholders to better understand the strengths, the opportunities and exploit them to overcome its weaknesses and threats. In the following subsections, we will present and detail each tool and demonstrate their applicability when combined.

### **3.2.1 The SWOT analysis**

SWOT analysis is the acronym of Strengths, weaknesses, opportunities and threats. It is considered as the most used tool by stakeholders to define their strategy in order to achieve their goals. It is a very well-known technique that helps stakeholders understand their internal and external issues by classifying them into 4 main categories as shown in Figure 3.1. According to a survey performed three years ago by a south African enterprise, the SWOT analysis is the most used business tool having 87% of votes (Du Toit, 2016). The SWOT analysis has its origins through the work of business policy academics at Harvard University and other American business schools since the sixties (Hill & Westbrook, 1997). These works state that a successful strategy is based on ensuring the perfect fit between the company's internal advantages and throwbacks (Strengths and weaknesses) and its external situation (Threats and opportunities) (K. R. Andrews et al., 1971; K. Andrews, 1980).

Following these interpretations, this tool is considered powerful because it uncovers the possible opportunities that the company can exploit through the understanding of its strengths. Also, by analyzing the weaknesses that prevent the company from moving forward and developing its resources, the stakeholders will be able to overcome the threats that might prevent the stakeholders from achieving their objectives. The matrix of the SWOT analysis is presented in Figure 3.1.

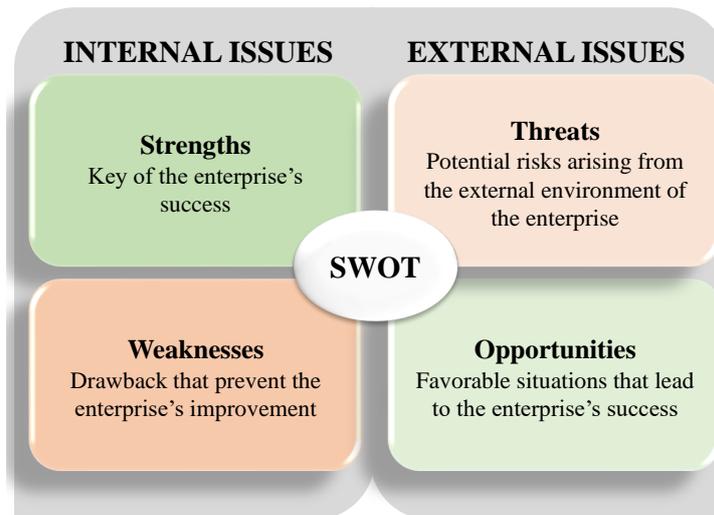


Figure 3.1: The SWOT analysis matrix

### 3.2.1.1 Strengths

The strengths are the internal positive issues that lead to a successful management of the enterprise. It includes all human and material resources that promote the image of the company and generate profits. For instance, highly qualified and motivated staff are the key to the company's success. In fact, in addition to delivering a product that satisfies the requirements of customers, the quality of provided services (handling of customers' claims, continuous improvement of product's characteristics) are more important elements that enable the enterprise to promote its image and stand within its competitors. Also, sustainability consciousness drives the stakeholders to invest in sustainability actions to minimize its impacts and leads to improvements and innovation paths. The identification of strengths is done through answering the following questions:

- What are the advantages that the company have ?
- What makes the company different from the other competitors?
- What are the assets that the staff has?
- What are the processes that are successful?

### 3.2.1.2 Weaknesses

The weaknesses are the critical constraints that prevent the enterprise from achieving its goals. To this end, the stakeholders must include these factors into their strategy and develop the

adequate action plans to convert these weaknesses into strengths and overcome the constraints. Similar to strengths, weaknesses are internal factors that include the resources of the company. We can mention in particular a high rate of the staff's absence, high import costs, and the limited space in the warehouse. These weaknesses lead to the risk of decrease in the productivity rate and delays in delivery to the customers. The identification of weaknesses is performed by answering the following questions:

- Is the company lacking equipment or staff?
- What are the gaps that limit the company's performance in the perspective of achieving the desired objectives?
- What are the processes that need improvements?
- What are the critical financial constraints that face the enterprise?

### **3.2.1.3 Threats**

The threats are the potential risks that might prevent the enterprise from improving its performance. These external factors are a significant threat to the company since they affect its resources. These factors are the legal, political and socio-cultural constraints. For example, the implementation of new strict regulations and new taxes threaten the economic state of the enterprise (i.e. unexpected fines and penalties). In addition, the actual political situation is critical and threaten the stability of workers and increase strikes' rate, natural disasters might also destroy goods and generate potential environmental impacts (i.e. chemical spills caused by floods). To this end, stakeholders must anticipate these threats and take them into consideration in the definition of their strategy. The identification of threats is done by answering the following questions:

- Is there any potential competitors that may enter the market?
- Are suppliers able to deliver adequate quantities of raw material with respect to deadlines and provide the best quality of services and products?
- Is it possible that future technological advances and innovations might affect the business performance?
- Does customers' behaviour negatively affect the profits of the company?

#### 3.2.1.4 Opportunities

The opportunities are the favourable situations which promote improvement actions and the development of the company. They are related to the external environment and have a positive impact that contributes to the business's success. For instance, the set of new laws encourages sustainability projects and provide grants to implement such projects. Moreover, the increase of the exchange rate positively affects incomes from export activities. It is important to note that such opportunity can be a threat if the company imports raw material. Thus, the list of internal and external factors is not exclusive and it is dynamic according to the enterprise's situation. Hence, most of stakeholders usually conduct this analysis annually to track changes and to update the company's strategy. The identification of opportunities is done by answering the following questions:

- Are there upcoming events that are beneficial to the enterprise such as seminars in the same field of activity?
- Is the political state of the country positively affecting the economic situation?
- Is the location of the company strategic for its activity?
- Are the new regulations positively impacting the progress of the enterprise's activity?

When answering all questions, the stakeholders are able to define a list of the enterprise's strengths, weaknesses, opportunities and threats to develop into a strategy of improvement. Since the context analysis has become a requirement of international standards, most competitive industries are investing into their context analysis.

#### 3.2.2 The PESTEL analysis

The PESTEL analysis is also an analytic tool to analyse the macro-environmental factors that have a significant impact on the performance of the enterprise. It is an acronym for Political, Economic, Social, Technological, environmental and legal factors (See Figure 3.2).

It is often used to classify external factors (i.e. Opportunities and threats) to better illustrate the situation of the company. In the following, we will define each factor of the PESTEL analysis.

- **Political factors:** Each activity related to the government and has a certain impact on the industry is classified as a political issue such as the government policy, the political state

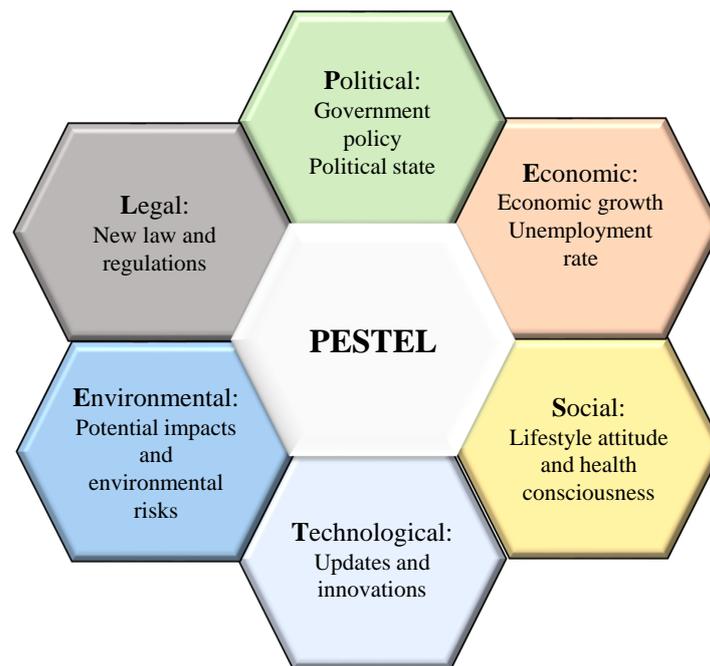


Figure 3.2: The PESTEL analysis framework

whether stable or unstable, new tax policy, new laws related to labor or the environment, trade restrictions..etc. This classification is applicable to threats and opportunities as external issues. Organizations must be adapted to the current political state and must anticipate potential future legislation in order to adjust their strategy accordingly.

- **Economic factors:** The economic situation of the country affects the performance of the organization. These factors include exchange rates, economic growth, interest rates, unemployment rates and consumers' income. These factors affect the enterprise on the long term since they influence consumers' behaviour and may decrease their purchasing rate. Consequently, the price of the product or the service might be affected.
- **Social factors:** The social factors include all issues related to the population. They represent the demographic characteristics, values of the population within which the company operates. We can mention in particular the growth rate of the population, safety emphasis, lifestyle attitude and health consciousness, and cultural barriers. These factors may also include the workforce and its devotion and willingness to work under specific conditions.
- **Technological factors:** These issues are related to technological updates and innovations that may impact the operations of the industry such as technological change, research and development activities, innovations and technological awareness. These factors have

an influence on decisions to launch new products or invest in new equipment. Taking into account the technological development, stakeholders will be able to limit the costs of implementing a new technology that risks to become obsolete due to innovative technological changes worldwide.

- **Environmental factors:** Over recent years, environmental issues have become the most important ones among other factors due to the increase of environmental impacts and significant risks facing mankind caused by the increase in the pollution rate and the decrease in the availability of natural resources. An article published in the website of Diesel service & supply (service & supply, n.d.) stated that 320 billion kilowatt-hours of energy are consumed every day which most of this quantity is obtained by burning fossil fuels, a nonrenewable sources of energy. This massive consumption is leading to the depletion of these resources. To this end, environmental consciousness and policy must be initiated on the personal and industrial level. For example, climate change impact significantly industries in fields such as agriculture, tourism and farming. Moreover, considering the potential impacts that might be generated from the company's activities leads this latter to get involved in sustainability practices.
- **Legal factors:** These factors align with the political ones. However, they are more specific to laws and legislation that cover all interested parties. For example, these laws can be related to employment, protection of the customer, workers' health and safety and copyrights. Companies must ensure their absolute conformity to the available laws in order to run their activities successfully and ethically. It is important to note that if the company is operating on the international level, stakeholders must also include the rules and laws of each country involved in the business as each country has its own set of laws and regulations. In addition, stakeholders must perform a regulatory watch periodically to be aware of any potential change in the applicable laws or the publication of new ones.

### 3.2.3 The 7S analysis

The 7S analysis or called the Mckinsey framework is a successful tool useful for the company for better understanding of its own internal factors and to plan the adequate actions to overcome these factors. It was designed by an American consulting firm and was then applied in various organizations worldwide. The 7S refers to seven elements that share the same first letter "S" as illustrated in Figure 3.3.

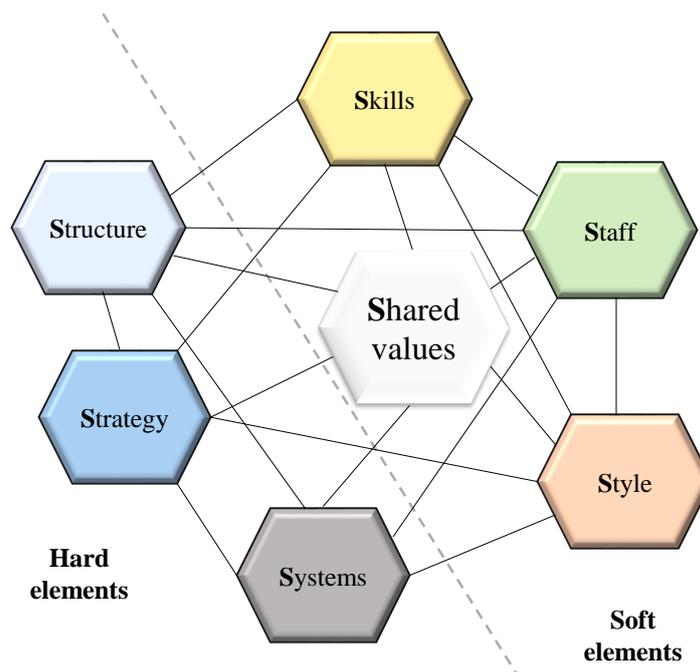


Figure 3.3: The 7S analysis framework

These elements guide the company in understanding its internal issues and classify them according to these elements. The 7S are classified into two categories; hard and soft elements. In fact, the difference between both categories is that the soft elements (i.e. Style, shared values, skills and staff) are included in the organization's culture whereas hard elements (i.e. Strategy, structure and systems) are factors over which the organization has a direct influence.

### 1. Soft elements

- *Style*: It includes leadership values and management styles of a successful business.
- *Shared values*: It includes ethics and standard values which the enterprise vision is based on.
- *Skills*: Not only employees' skills are concerned but also those related to the enterprise.
- *Staff*: It concerns the skills of the employees and their roles and responsibilities within the company.

### 2. Hard elements

- *Strategy*: The strategy is the vision and mission of the organization in order to achieve its desired objectives.

- *Structure*: The structure of the organization covers all the hierarchy and the flowchart of its different departments. Stakeholders must clearly define the hierarchy and distribute roles and authorities accordingly.
- *Systems*: The systems are all methods and tools related to processes' operations, procedures, and communication at the operational level.
- *Staff*: It concerns the skills of the employees and their roles and responsibilities within the company.

### 3.2.4 Integration of the SWOT, 7S and PESTEL

The arguments for our methodological choices are justified as follows; Indeed, (Tamayo-Orbegozo et al., 2017) have used the SWOT method and highlighted that the diagnosis of external and internal factors aligned with the organization's philosophy and culture helps to define the strategic axes of eco-innovation. For the classification of external issues, they have considered critical environmental, regulatory and technological factors. The internal issues addressed concern knowledge, resources and skills. The contextualization of the design targeted the regional factor. Based on this work, we recommend improving the deployment of SWOT with a better classification of issues within a contextualized design framework for sustainability. In fact, (Ravanfar, 2015) have shown that the 7S method makes it possible to evaluate the effectiveness of organizations according the seven success criteria. They reported that it is advantageous to facilitate organizational changes, help implement new strategies, and to identify areas for development. This is how we adopt it for the classification of internal strengths  $ST_i$  and weaknesses  $WE_i$ . Based on the work of Kauškale & Geipele (2017), we have adopted the PESTEL method to classify the external threats  $Th_i$  and opportunities  $OP_i$ .

## 3.3 Identification of the needs and expectations of the stakeholders

The previous section detailed the identification of the internal of external issues of the enterprise and the used tools in order to clarify the strategy vision. However, for a complete identification and to be compliant with the requirements of the latest version of the international standards. The needs and expectations of the stakeholders must be included for a complete analysis. In what follows, we will identify stakeholders and detail the set of their requirements.

Stakeholders are individuals who are involved directly or indirectly in the company's activity and performance. They are classified into two categories as shown in Figure 3.4.

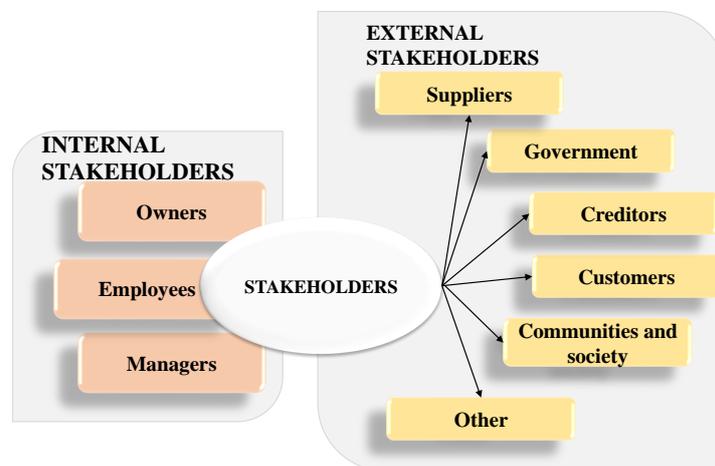


Figure 3.4: Examples of the organization's stakeholders

### 3.3.1 Internal stakeholders

Internal stakeholders or interested parties as denoted in the international standards are groups of individuals that are involved in the performance of management and operational processes. They have mutual interactions with the company, they can influence strategic decisions and they might be influenced by a certain activity of the enterprise. Usually, internal stakeholders have a financial stake in the company. They include employees, partners, owners, and managers.

- **Owners:** The owners are the highest level of the company's hierarchy structure. They hold important shares of the enterprise. They have a very significant role in the strategy since they are the final decision makers regarding all the issues that might affect the sales revenue and the achievement of goals.
- **Managers:** The managers are the second level of the hierarchy. They have a substantial role in the strategy and they participate in operational decisions. They pilot all the processes of the company and implement improvement actions' plans.
- **Employees:** The employees represent the last level of the hierarchy but the most important ones since all the processes of the company rely on their skills and devotion to maintain a successful enterprise. Employees are often the key element to the progress of

the objectives and the well run of the company. They also have significant time and financial investments. Successful organizations consider employees' needs and expectations when defining their vision, strategy and mission.

### 3.3.2 External stakeholders

In addition to internal stakeholders, the organization is exposed to external ones due to the integration of business into society. They have a significant role in the accomplishment of understanding the external environment and the positive and negative impacts. External stakeholders include but are not limited to customers, suppliers, communities, government, creditors, and society.

- **Customers:** These are the most important stakeholders for every organization since the increase of the sales' revenue and the survival of the company relies on its customers' behaviour. The primary activity of the organization is to deliver the best quality products and services to satisfy its customers. They are considered as an important part of the business's strategy. Nowadays, big data are applied to determine the needs of users. These databases guide organizations to anticipate future customers' needs and refine the business strategy.
- **Suppliers:** These stakeholders are the second key element of the organization's success. The development of a certain product and the insurance of its quality depend on raw materials delivered by suppliers. Every organization must satisfy its suppliers' requirements by respecting payment deadlines and planning orders according to its manufacturing program.
- **Communities:** Local community is usually impacted indirectly by the organization. For example, the manufacturing process of products generates pollution, the distribution process may increase the traffic rate if the location is near an urban zone. Moreover, noises or waste generated from the factory may affect the population's health and safety. As a conclusion, organizations must also include these stakeholders' needs into their strategy.
- **Government:** The state is considered as a primary stakeholder, the government offers regulatory oversight, legal matters and guides the enterprise through legal procedures and ethical practices to avoid amends.

In the literature, many studies have used the concept of Stakeholders for the development of organization's strategies. Few studies have focused on the impacts of integrating stakeholders

into the sustainable design process (Tyl et al., 2015). In addition, O'Hare et al. (2014) have published a book where they give instructions about the use of eco-innovation tools. They addressed the life cycle stakeholders. This tool guides managers to identify their key stakeholders by classifying them into four categories:

- Supply chain stakeholders which include the parties that provide services and goods to the company such as the suppliers.
- Customers stakeholders which are all companies or physical buyers that benefit from the company's goods and services.
- Professional interest stakeholders whose activities may have an impact on the company.
- Personal interest stakeholders where the activities of the company have an impact on them.

Thus, our idea consists in taking into account the needs and expectations of stakeholders  $REQ_i$  who can influence the organization or whom the organization have an impact. Then, we propose to deploy these requirements with regard to the product's life cycle phases from an environmental, economic and social perspectives. This deployment is done for each stakeholders' category. The different categories of stakeholders depend on the activity of the company.

### **3.4 Generation of strategic scenarios**

In the previous sections, we have identified and classified the internal and external issues by integrating the SWOT, 7S and PESTEL analysis. Then, we have identified the requirements of stakeholders and classified them by life cycle phase since stakeholders are involved through all the product life cycle from the extraction of raw materials until the end of life treatment. On the basis of these inputs, strategic scenarios can be generated. To this end, we propose to adopt a confrontation matrix in order to generate four types of strategic scenarios as illustrated in Figure 3.5.

All subsequent analyzes are guided by environmental, social and economic thinking. Thus, in order to answer the first research question Q1, three articulated systems are combined in synergy with the design process. The central system is the life cycle of the product. The remaining two are the stakeholders and the organization's context. Hence, two types are formed on the basis of the identified opportunities whereas the last ones are generated on the basis of the identified threats:

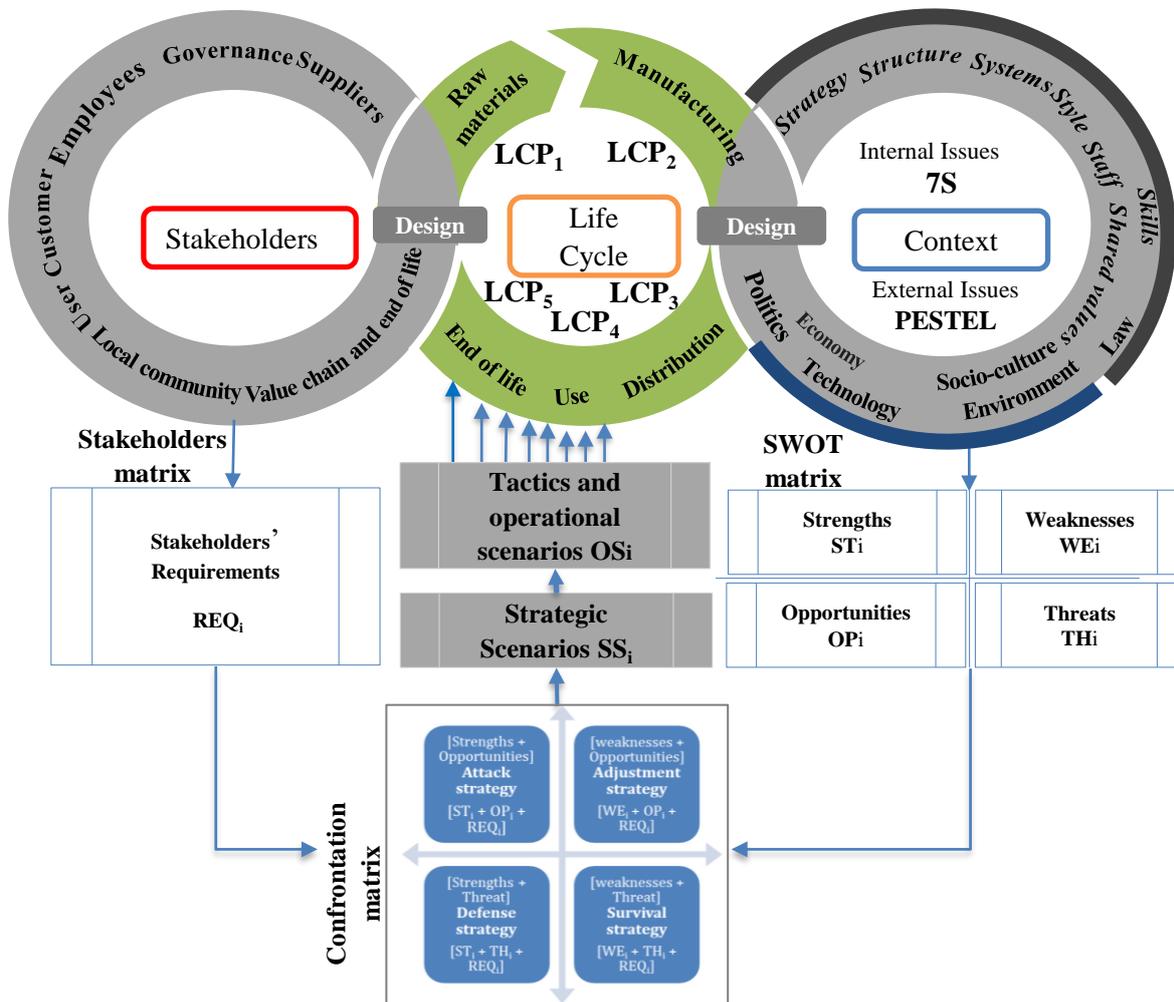


Figure 3.5: Confrontation matrix to generate strategic scenarios (Sansa et al., 2019)

1. Attack Strategic Scenarios (ASS): The attack strategy is the conjunction between strengths and opportunities of the organization.
2. Adjustment Strategic Scenarios (AJSS): The adjustment strategy is the combination of weaknesses and opportunities.
3. Defense Strategic Scenarios (DSS): The defense scenarios are based on a strategy that combines strengths and threats.
4. Survival Strategic Scenarios (SSS): The last type of scenarios are the conjunction between weaknesses and threats.

In addition, we propose to reinforce this methodology by introducing the relevant stake-

holders' requirements deployed per life cycle phase. In fact,  $ASS$ ,  $AJSS$ ,  $DSS$ , and  $SSS$ , are generated following the algorithm 1 below.

---

**Algorithm 1:** Generation of strategic scenarios
 

---

**Data:**  $ST, OP, WE, TH, REQ$   
**Result:**  $ASS, AJSS, DSS, SSS$

```

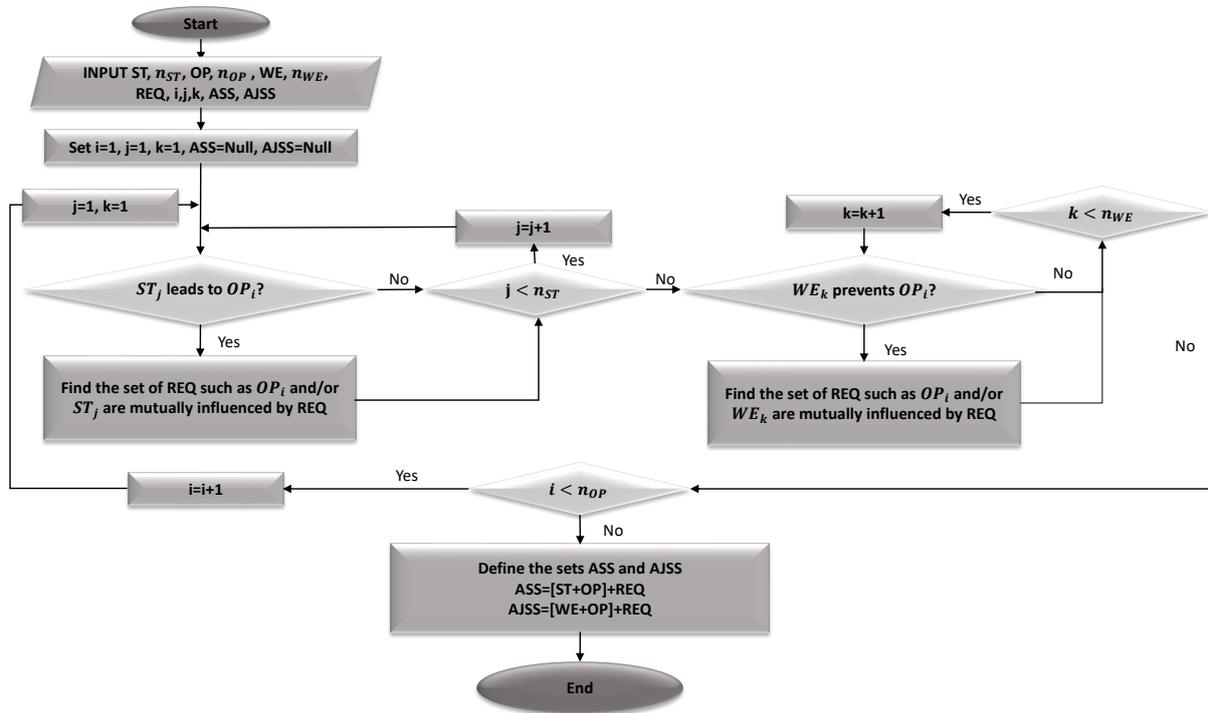
1 begin
2   foreach  $OP$  do
3     Find the  $ST$  leading to  $OP$ 
4     Find  $REQs$  such as [ $OP$  and/or  $ST$ ] are mutually influenced by  $REQ$ 
5     Define the sets  $ASS = [ST + OP] + REQ$ 
6     foreach  $OP$  do
7       Find the  $WE$  preventing  $OP$ 
8       Find  $REQs$  such as [ $OP$  and/or  $WE$ ] are mutually influenced by  $REQ$ 
9     Define the sets  $AJSS = [WE + OP] + REQ$ 
10    foreach  $TH$  do
11      Find the  $ST$  reducing  $TH$ 
12      Find  $REQs$  such as [ $TH$  and/or  $ST$ ] are mutually influenced by  $REQ$ 
13    Define the sets  $DSS = [ST + TH] + REQ$ 
14    foreach  $TH$  do
15      Find the  $WE$  increasing  $TH$ 
16      Find  $REQs$  such as [ $TH$  and/or  $WE$ ] are mutually influenced by  $REQ$ 
17    Define the sets  $SSS = [WE + TH] + REQ$ 

```

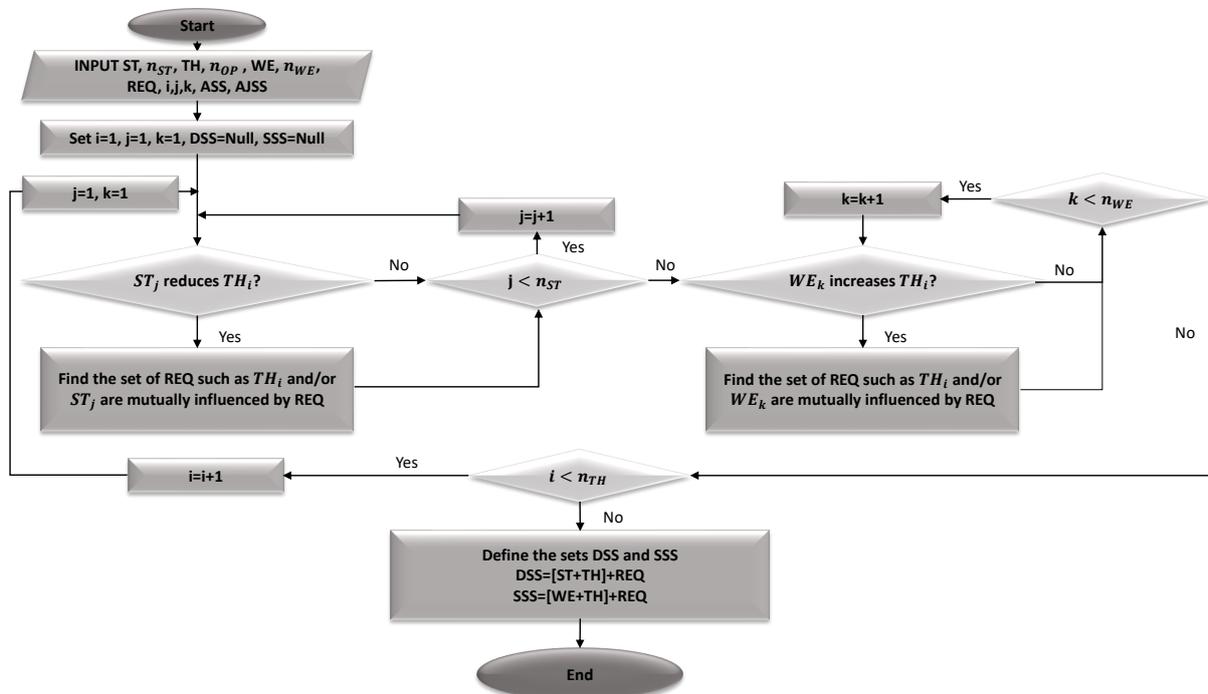
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The steps of the algorithm are illustrated in the following flowchart as shown in Figure 3.6 where  $N_{ST}$ ,  $N_{WE}$ ,  $N_{OP}$ , and  $N_{TH}$  are respectively the numbers of the identified strengths, weaknesses, opportunities, and threats.  $i, j$  and  $k$  are the counters.

Figure 3.6(a) details the steps of generation of  $ASS$  and  $AJSS$  scenarios. In fact, for each defined opportunity  $OP$ , all strengths  $ST$  are tested if they lead to this  $OP$  and all the weaknesses  $WE$  are tested if they prevent it. Then, they are combined with the set of requirements to define the  $ASS$  and the  $AJSS$ . The same procedure is conducted to generate  $DSS$  and  $SSS$  by checking for each threat  $TH$  if the  $ST$  reduces this  $TH$  and if  $WE$  increases it as detailed in Figure 3.6(b).



(a) Generation of attack and adjustment scenarios (i.e. ASS and AJSS)



(b) Generation of defense and survival scenarios (i.e. DSS and SSS)

Figure 3.6: Generation of strategic scenarios (Sansa et al., 2019)

## 3.5 Deployment of tactics and generation of operational scenarios

A tactical layer has been implemented as a link between the strategic scenarios ( $ASS$ ,  $AJSS$ ,  $DSS$ ,  $SSS$ ) and the operational scenarios  $OS_l$  in order to answer the research question Q2. This section highlights the possibility of generating a multitude of alternatives for sustainable design choices.

### 3.5.1 Tactics for sustainable design

The tactics lie in the identification and characterization of design criteria  $C_{ij}$  oriented towards sustainability and classified by life cycle phase. These criteria must be coherent with the different types of  $SS_i$ . They fit into the entire value chain of the product's life cycle. These criteria also relate to both product and/or organization and may be technological, methodological, geographic, logistical, financial or combinations of them. Many studies rely on criteria of the eco-design strategy wheel (Prahalad & Hamel, 1994; Luga, 2016; Wahab et al., 2017; Tomovska & Radivojević, 2017; Tettey et al., 2017). These criteria concern: (1) The choice of materials (2) Clean production techniques, (3) New concepts, (4) Reduction of mass, (5) Extension of lifespan, (6) Optimization of distribution and end of life (7) Environmental impact limitations. X. Wang et al. (2014) have identified twenty design criteria deployed per life cycle phase. For instance, to select the material, the authors have set three criteria (i.e. Plastics, Electronic component, Metal). Sansa et al. (2017) have used environmental, economic and social indicators as criteria.

In our proposed model, design criteria are enriched by including social and economic aspects such as design criteria related to optimization of costs and the well-being of workers. In fact, in the identification of tactics, we can consider low investment costs and preferences for local materials, the respect of the human rights and the safety of workers. Hence, design criteria  $C_{ij}$  are identified for each  $SS$ .

### 3.5.2 Generation of operational scenarios

Operational alternatives  $A_{ijk}$  are identified for each criterion  $C_{ij}$ . These alternatives can be local or foreign modes of supply, locations' possibilities for manufacturing or distribution, hiring alternatives in certain social categories, schemes and working methods, manufacturing tech-

nologies, materials, economic sources of finance. By combining the alternatives, numerous opportunities characterizing the operational scenarios are generated. These scenarios incorporate implicitly contextualized strategies and tactics into all life cycle phases  $LCP_i$ . The process of the identification of relevant alternatives is detailed in algorithm 2 and illustrated in the flowchart 3.7.

---

**Algorithm 2:** Generation of relevant alternatives
 

---

**Data:**  $SS, LCP_i$   
**Result:**  $OS$

```

1 begin
2   foreach  $SS$  do
3     | Define adapted tactics taking into account the type of  $SS$  (i.e.  $ASS, AJSS, DSS, SSS$ )
4   foreach  $Tactic$  do
5     | Identify design criteria  $C_{ij}$ 
6     | Assign  $C_{ij}$  to a  $LCP_i$ 
7   foreach  $C_{ij}$  do
8     | Identify the operational alternatives  $A_{ijk}$ 
9   foreach  $A_{ijk}$  do
10    | Relevance test:
11    | if ( $Influence\ or\ control(high/Average)$ ) then
12    | | Keep  $A_{ijk}$ ;

```

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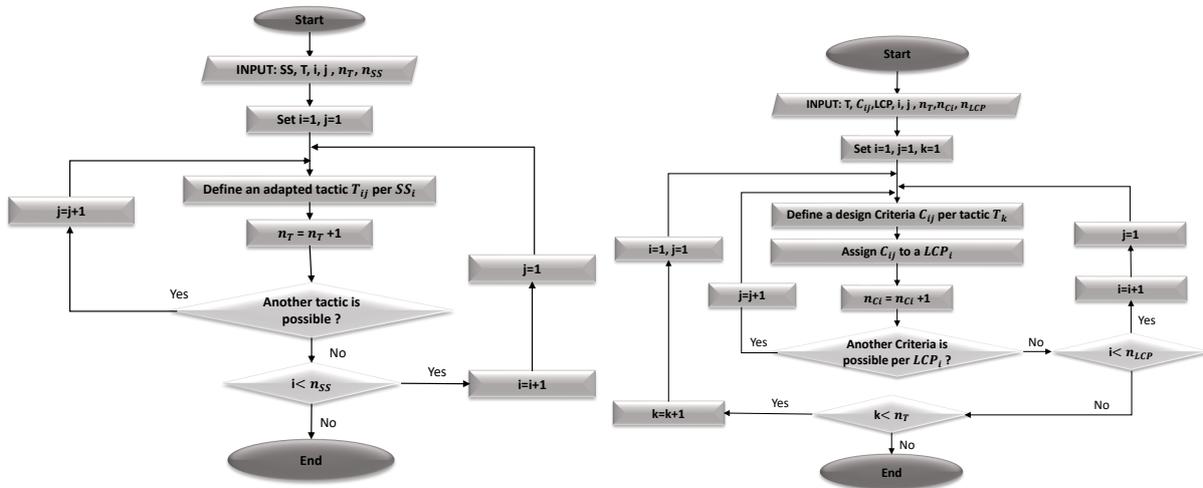
Once all relevant alternatives  $A_{ijk}$  are filtered and selected, it is possible to compute the number of all possible operational design scenarios using equation 3.1.

$$N_{OS} = \sum_{i=1}^{n_A} C_i^{n_A} \quad (3.1)$$

where  $N_{OS}$  is the number of the scenarios' combinations, and  $C_i^{n_A}$  is the combinations of alternatives.

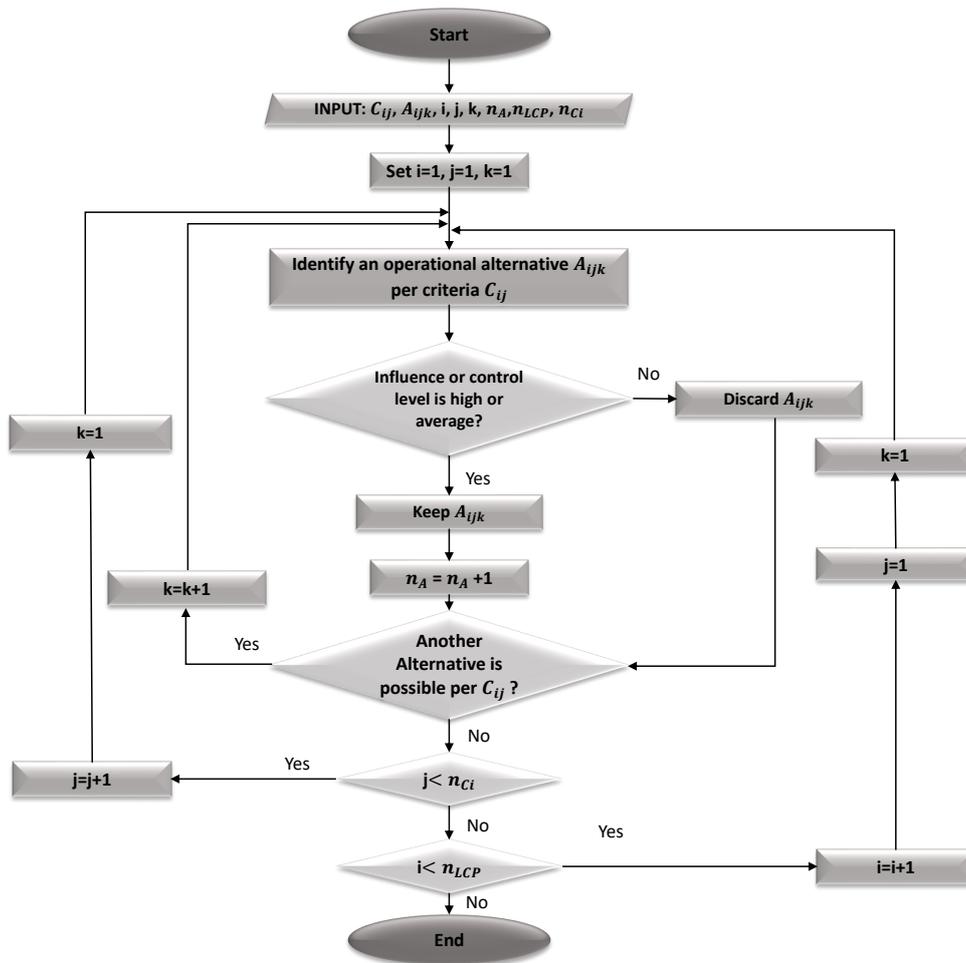
## 3.6 Conclusion

In this Chapter, we have detailed the first three steps of our proposed model. The internal and external issues have been identified by integrated the SWOT, 7S and PESTEL analysis. The requirements of the stakeholders have been identified and classified per life cycle phase and then combined with the company issues using a confrontation matrix to generate sustainable strategic scenarios. The second step is the identification of tactics in order to define design



(a) Identification of tactics for each strategic scenario

(b) Identification of design criteria for each tactic



(c) Identification of operational alternatives for each design criteria

Figure 3.7: Generation of relevant alternatives (Sansa et al., 2019)

criteria and derive relevant alternatives per life cycle phase. The last step is the generation of relevant operational scenarios by combining these alternatives. In the next chapter, we will detail the last two steps of the proposed model which form the operational level.

Chapter **4**

**Optimization and selection of a  
sustainable design scenario**

## 4.1 Introduction

The objective of this chapter is to select an optimal operational scenario that potentially generates the minimum environmental, economic and social impacts and answers the third research question Q3. This choice is made through three stages: (1) An impact assessment through indicators by category. (2) A reduction in the number of operational scenarios through the selection of those that are most relevant from a sustainability perspective. (3) The selection of the optimal operational scenario from those selected in (2), by comparing them against environmental, economic and social attributes by life cycle phase. In the following subsections, we will detail each step and the methodology considered in the selection process.

## 4.2 Identification of challenges faced at the operational level

As detailed in subsection 2.3.2 of chapter 2, the operational part of the proposed model covers step 4 and 5 which are respectively the computation of environmental, economic and social indicators for each generated operational scenario and the selection of the optimal one. In fact, at this level, three challenges are detected. The first one is the mutual interaction between the impacts. In this context, the attempt to minimize the significance of an impact can affect in a positive or a negative way the contribution to another impact in the same phase of the product's life cycle or in another phase. This challenge is very common to most of LCA assessment studies and it is considered as one of the limits of LCA method. For instance, the aim of each company is to reduce the costs related to the manufacturing of its products. To this end, managers will select the closest country to minimize the freight costs as the main goal which leads also to the minimization of the GHG emissions related to freight from an environmental perspective. This interaction is positive. In another context, the promoting of green and sustainable products requires significant investments and resources to meet sustainability requirements. These extra charges and costs affect directly the market price of final products which affect the purchasing ability from the consumer perspective.

The second challenge is the dependence between life cycle phases during the comparison phase between operational scenarios to select the best one. In fact, X. Wang et al. (2014) have addressed this issue in its proposed framework. Indeed, the manufacturing process steps in  $LCP_2$  and the waste treatment mode selection in  $LCP_5$  depend on the chosen raw materials in  $LCP_1$ . Hence, not all combination between design alternatives are accurate and coherent. Thus, decision makers must consider these dependencies when computing scores for each operational

scenario for more coherent results and in order to reduce the probability of selecting an incoherent scenario.

The last issue is the uncertainty matter. At the operational level, the first root cause of the uncertainty of results is the principle of aggregation adopted in most impact assessment tools. In fact, the computation of indicators related to the impacts is done by aggregating the data inventory results with predefined characterization factors. These factors express the contribution of a single unit to the different impacts categories. The calculation process of such factors goes through several modelling which increases uncertainty in the obtained results. In this context, Roy et al. (2014) have addressed the uncertainty of characterization factors CF related to aquatic acidification. Thus, the computed indicators are uncertain due to the CF and the collected data. In fact, at the design stage, the collected data are imprecise and not fully available, most of them are based on assumptions and estimations according to the context. The second cause is decision makers' judgments during the comparison between operational scenarios. Indeed, most of multi-criteria decision mechanisms are based on judgments in order to weight scenarios and obtain a single score for each one. Although these judgments are based on in-depth analysis, there is a high probability of subjectivity in the preferences leading to the final decision. Hence, in order to address these challenges and to answer the research question Q3, we propose a multi-criteria decision system at the operational level of our model. First, we have pointed out in Table 4.1 the advantages and drawbacks of most common Multi-Criteria Decision-Making (MCDM) methods on the basis of a review carried out by Velasquez & Hester (2013) in order to select the most suitable tools for our decision making mechanism.

Table 4.1: Advantages and drawbacks of strategic tools

MCDM methods	Advantages	Drawbacks
Multi-Attribute Utility Theory (MAUT) (Keeney & Raiffa, 1976)	<ul style="list-style-type: none"> <li>• This method addresses the uncertainty and takes into account decision makers' initial preferences.</li> <li>• It addresses interactions between attributes.</li> </ul>	<ul style="list-style-type: none"> <li>• It requires several inputs and a precise knowledge of preferences.</li> </ul>
AHP (T. Saaty, 1980) and ANP(T. Saaty, 1980)	<ul style="list-style-type: none"> <li>• The AHP and the ANP decompose the multi-criteria problem into a hierarchical and a network structure respectively which can be adapted to all multi-criteria decision problems.</li> <li>• The ANP addresses the dependence between criteria.</li> </ul>	<p>The judgments of decision makers are subjective and there is a risk of inconsistency. Thus, a consistency check is required in all steps of the AHP and ANP</p>
ELimination Et Choix Traduisant la REalité (ELECTRE) (Benayoun et al., 1966)	<ul style="list-style-type: none"> <li>• This tool deals with uncertainty issues.</li> </ul>	<ul style="list-style-type: none"> <li>• This method doesn't consider the dependency between criteria.</li> </ul>
Fuzzy set theory (Zadeh, 1965)	<ul style="list-style-type: none"> <li>• The fuzzy set theory is the most used method to deal with uncertain and imprecise inputs.</li> <li>• It provides more robust and realistic results.</li> </ul>	<ul style="list-style-type: none"> <li>• This tool doesn't provide a weighting process to select the best alternative.</li> <li>• It ignores interactions and dependence between criteria.</li> </ul>
Simple Multi-Attribute Rating Technique (SMART) (Edwards & Barron, 1994)	<ul style="list-style-type: none"> <li>• This method provides a weighting process to guide decision makers through the selection of the best option.</li> <li>• It is simple to use in multi-criteria decision problems.</li> </ul>	<ul style="list-style-type: none"> <li>• Although it is simple to use, its framework is still complicated (Konidari &amp; Mavrakis, 2007).</li> <li>• It requires utility and preferential independence.</li> </ul>

Continued on next page

Table 4.1 – continued from previous page

MCDM methods	Advantages	Drawbacks
Goal programming (Reinhardt, 1984)	<ul style="list-style-type: none"> <li>This tool handles a large number of alternatives.</li> </ul>	<ul style="list-style-type: none"> <li>This method doesn't provide a weighting process.</li> <li>It ignores the uncertainty and the dependency issues.</li> </ul>
Preference Ranking Organisation Method for Enrichment Evaluations (PROMETHEE) (Brans & Vincke, 1985)	<ul style="list-style-type: none"> <li>This tool handles a large number of alternatives.</li> </ul>	<ul style="list-style-type: none"> <li>This method doesn't provide a clear methodology to weight the alternatives.</li> <li>It ignores uncertainty and dependency issues.</li> </ul>
Simple Additive Weighting (SAW) (Brans & Vincke, 1985)	<ul style="list-style-type: none"> <li>This tool handles a large number of alternatives.</li> </ul>	<ul style="list-style-type: none"> <li>The calculation is based on estimations and no consistency check is required which might lead to illogical results (Podvezko, 2011).</li> </ul>
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Tzeng & Huang, 2011)	<ul style="list-style-type: none"> <li>This tool is widely applied in design and innovation.</li> <li>The framework is simple and easy to use.</li> <li>The simulation remains the same regardless the number of criteria and alternatives.</li> </ul>	<ul style="list-style-type: none"> <li>It is characterized by a high subjectivity (Kochkina et al., 2017).</li> <li>The weighting of alternatives is difficult.</li> <li>It ignores uncertainty and dependency issues.</li> <li>No consistency check is required.</li> </ul>

As detailed in Table 4.1, these MCDM methods handle decision problems and most of them are based on decision makers' judgments and preferences. However, the choice of suitable MCDM methods depends on their ability to address uncertainty issues, dependency and interactions between criteria, attributes, and alternatives. In order to satisfy these constraints, we propose to combine some of these methods to build a complete decision making mechanism adapted to the requirements of our model.

Referring to Table 4.1, the ANP method is the most appropriate tool to address the dependency between criteria. In addition, it is possible to integrate the fuzzy set theory within the steps of the ANP to handle imprecise and uncertain decision makers' judgments. Moreover, we propose to use the MAUT method by applying the Choquet Integral to address interactions between attributes.

Therefore, the operational level of the proposed model is composed of three steps as follows:

- An assessment of operational scenarios' impacts through the computation of the environmental, economic, and social indicators using a simplified LCA.
- A first selection of the most relevant scenarios from a sustainability perspective in order to reduce their number using the Choquet integral to address the interaction issue between environmental, economic and social attributes.
- A final selection of the optimal scenario among the relevant ones by comparing them with respect to environmental, economic and social attributes per life cycle phase using the fuzzy ANP in order to address uncertainties of indicators' results and dependencies between the life cycle phases

In the following sections, the implementation of each step will be detailed as well as the tools and methods integrated in the multi-criteria decision system of the proposed model.

### 4.3 Assessment of operational scenarios

At this stage, operational design scenarios are generated from the combination of different design alternatives  $A_{ijk}$ . For each one, we propose to evaluate potential impacts that may occur later on during the product's life cycle. Since the proposed model is applicable in an advanced stage of design, the full LCA framework cannot be used due to the high amount of data required to obtain desired results. Thus, we propose to use a simplified LCA originally proposed by C. Y. Ng & Chuah (2014). The simplified framework excludes the interpretation step of the

full LCA and it is limited to available collected data. The data has many sources, it can be theoretical, usually derived from the literature on life cycle assessments performed on a similar type of products. We can mention in particular the works of Yung et al. (2011); Andrae & Andersen (2010); Hong et al. (2015); Duan et al. (2009); Liu et al. (2015) that proposed detailed life cycle assessments for electronic products. The second type of Data is the theoretical technical data retrieved from available data-sheets of similar products' components. The last type is the data collected from the company's activities in order to gather specific information relative to the organization's strategy and to target essentially design alternatives that composed the operational scenarios.

First, in order to conduct the assessment, the Functional Unit FU must be defined and set by quantifying the different characteristics of the product's functions (ISO, 2006b). Second, the systems boundaries must be set to define processes included in the LCA. Third, the life cycle inventory is elaborated. In this context, for each generated operational scenario, data have been collected in order to build environmental and social life cycle inventories. The inputs and outputs are identified by life cycle phase  $LCP_i$  and calculated with regard to the FU and the reference flows for each operational scenario  $OS_j$  where  $i = [1..5]$  and  $j = [1..n_{OS}]$ . The ecoinvent 3.3 database (Wernet et al., 2016) and the SHDB are used to assess collected data and convert them into impacts categories in order to compute the related indicators. For the economic assessment, the costs per phase are computed for each scenario on the basis of the organization's available budgets and estimated costs per phase.

The last step is to compute environmental social and economic impacts ( $EA_x, ECA_y, SA_z$ ) using impact assessment methods. These methods are differentiated according to their impacts' categories, geographical and temporal criteria as well as specificities with respect to spatial variability. As part of our model, decision makers will choose the appropriate impact assessment method based on the objectives, tactics and the design criteria identified to generate operational scenarios. The impact assessments for each scenario are carried out using an LCA software. The outputs of the analysis are quantified environmental, economic, and social indicators per life cycle phase. These computed indicators will be used as references for decision makers' judgments and initial preferences in order to rank the operational scenarios. In the following section, we will detail the selection process of relevant operational scenarios and the methods used within this process.

## 4.4 Selection of relevant operational scenarios

The selection of relevant operational scenarios is done by eliminating the ones having the lowest scores with regard to sustainability and on the basis of the computed indicators. Since we are facing a multi-criteria decision problem, the more adopted tools and known tools are the AHP and AHP methods. Yet, both methods do not address interactions issues between indicators (Hereinafter referred to as attributes). Hence, we propose to integrate the Choquet integral (Grabisch & Roubens, 2000) within our proposed decision-making mechanism. This tool is popular and widely used in solving multi-criteria decision problem due to its capability to model interactions between attributes by computing the capacity relative to the attributes. In the sequel, we will give a brief recall on the Choquet integral method.

### 4.4.1 The Choquet integral in multi-criteria decision making

The Choquet integral is considered as a basic and common tool to model decisions under uncertainty. It is an aggregation operator characterized by a non-additive set function. The Choquet integral has been applied in several researches (Garg et al., 2017; Sirbiladze & Badagadze, 2017; Ferreira et al., 2018; Demirel et al., 2018). For instance, Ferreira et al. (2018) have proposed the use of the Choquet integral in order to enhance the decision-making virtuous cycle of ethical practices in the banking sector. This was achieved by comparing the ethical performance of four banks and ranking them from the best to worst performers. Also, Demirel et al. (2018) have suggested to combine the Choquet integral with hesitant fuzzy sets to prevent the erosion of soil in Turkey. Their approach has guided decision makers to select the optimal alternative to prevent soil erosion which is reforestation.

The Choquet integral is a non-additive integral and an aggregation operator relative to the MAUT (Keeney & Raiffa, 1976). The MAUT is defined by a set of objects  $X \subseteq X_1, \dots, X_n$  where  $n \geq 2$ . This set is relative to a set of attributes  $N = 1, \dots, n$ . The main objective of the utility theory is to model numerically the preferences of the decision maker. These preferences are modelled as a binary relation on  $X$  using a utility function as described below.

$$x \geq y \Leftrightarrow U(x) \geq U(y), \forall x, y \in X$$

where  $U$  is a function that expresses the preferences of the decision maker over a subset of selected objects. Hence, the resulting global utility function provides the preference relation on  $X$ . In the context of decision making, the global utility function is able to convert an attribute

value to a satisfaction degree called partial score. Once the utility function is determined, the next step is to identify a capacity as follows:

**Definition 4.4.1.** A fuzzy measure  $\mu$  on  $X$  also denoted by the Choquet capacity is a set of function  $\mu : \mathcal{P}(N) \rightarrow [0, 1]$  satisfying the following conditions:

1.  $\mu(\phi) = 0, \mu(N) = 1$ .
2. For any  $S, T \subseteq N, S \subseteq T \Rightarrow \mu(S) \leq \mu(T)$ .

where  $N := \{1, \dots, n\}$  is a set of criteria and  $\mathcal{P}(N)$  is the power set of  $N$

The capacity  $\mu(S)$  is the generalization of weighting vectors that are deployed in computing weighted sums. It is used to model the importance of the set of criteria. The capacity  $\mu$  on  $N$  has two types namely:

- Additive capacity if  $\mu(S \cup T) = \mu(S) + \mu(T)$  for all subsets  $S, T \subseteq N$ .
- Cardinality based if  $\mu(T)$  depends on the cardinality of  $T$  for any  $T \subseteq N$ .

It is important to note that there is a particular case when the capacity can be both additive and cardinality based. Thus, it is called “Uniform capacity” and it is defined by  $\mu^*(T) = \frac{t}{n}$  for all  $T \subseteq N$  where  $t$  is the cardinality of  $T$ .

**Definition 4.4.2.** The Choquet integral of a function  $X : N \rightarrow \mathbb{R}$  represented by a vector  $(x_1, \dots, x_n)$  with respect to a capacity  $\mu$  on  $N$  is defined by (Grabisch et al., 2008) as follows:

$$C_\mu(x) = \sum_{i=1}^n x_{\sigma(i)} [\mu(A_{\sigma(i)}) - \mu(A_{\sigma(i+1)})] \quad (4.1)$$

Where  $\sigma$  is a permutation on  $N$  satisfying  $x_{\sigma(1)} \leq \dots \leq x_{\sigma(n)}$  and  $A_{\sigma(i)} = \{\sigma(i), \dots, \sigma(n)\}$  for  $i \in [1, \dots, n]$  and  $A_{\sigma(n+1)} = \phi$

In order to better understand the modelling of the interaction phenomena by the capacity, several indices can be calculated. In the context of multi-criteria decision making problems, the importance and the interaction indices are frequently used.

#### 4.4.1.1 The importance index

The importance index is the measure of the importance of a criterion  $i \in N$ . It can be measured through its Shapley value (Marichal, 2004). This value is defined as follows:

$$\phi(i) = \sum_{T \subseteq N \setminus i} \frac{(n-t-1)!t!}{n!} [\mu(T \cup i) - \mu(T)] \quad (4.2)$$

In fact, for each subset of criteria  $S \subseteq N$ ,  $\mu(S)$  is considered as an importance of  $S$  in the decision problem.

The Shapley value of a criterion  $i$  can be interpreted as an average value of the marginal contribution  $\mu(T \cup i) - \mu(T)$  of  $i$  to a subset  $T$  not containing it. The important and most known property is that  $\phi_\mu(1), \dots, \phi_\mu(n)$  constitutes a probability distribution over  $N$ .

#### 4.4.1.2 The interaction index

The interaction index models the concept of interaction between two criteria  $i$  and  $j$ . This modelling is based on the capacity  $\mu$  of both criteria as described below.

1. If  $\mu(ij) \geq \mu(i) + \mu(j)$ , the modelled interaction is positive. In other terms, this latter is characterized by a complementary effect between  $i$  and  $j$ .
2. If  $\mu(ij) \leq \mu(i) + \mu(j)$ , the modelled interaction is negative. The criteria  $i$  and  $j$  have a redundant interaction between them.
3. If  $\mu(ij) = \mu(i) + \mu(j)$ , no interaction is modelled between  $i$  and  $j$ . Both criteria have independent roles in the decision problem.

On the basis of the above description and in order to measure the interaction between  $i$  and  $j$ , the coefficient should depend on the difference  $\mu(ij) - [\mu(i) + \mu(j)]$ . As detailed in Grabisch & Roubens (1999), comparing  $\mu(ij)$  and  $\mu(i) + \mu(j)$  does not address all interaction possibilities. In fact, the decision maker must also consider the case when  $i, j$  and  $ij$  join other subsets. Thus, the interaction index, between  $i$  and  $j$  must consider all possible coefficients (i.e.  $\mu(T \cup i), \mu(T \cup j), \mu(T \cup ij)$  for  $T \subseteq N \setminus ij$ ).

To this end, Murofushi & Soneda (1993) proposed the measuring of the interaction index as follows:

$$I_\mu(ij) = \sum_{T \subseteq N \setminus ij} \frac{(n-t-2)!t!}{(n-1)!} [\mu(T \cup ij) - \mu(T \cup i) - \mu(T \cup j) + \mu(T)] \quad (4.3)$$

where  $[\mu(T \cup ij) - \mu(T \cup i)]$  and  $[\mu(T \cup ij) - \mu(T \cup j)]$  are the marginal contributions. The difference between these contributions is called the marginal interaction between  $i$  and  $j$  in the presence of  $T$ .

Hence, we can model the interactions as described below.

1. If  $[\mu(T \cup ij) - \mu(T \cup i)] > \mu(T \cup j) - \mu(T)$ , there is a positive interaction between  $i$  and  $j$ .
2. If  $[\mu(T \cup ij) - \mu(T \cup i)] < \mu(T \cup j) - \mu(T)$ , there is a negative interaction between  $i$  and  $j$ .
3. If  $[\mu(T \cup ij) - \mu(T \cup i)] = \mu(T \cup j) - \mu(T)$ , there is no interaction between  $i$  and  $j$ .

$I_\mu(ij)$  is considered as the measure of the average marginal interaction between  $i$  and  $j$  where  $I_\mu(ij) \in ]-1, 1[$  for  $ij \subseteq N$ . Several methods are available to identify capacities. one of the most popular tools is the least square based approaches (Mori & Murofushi, 1989; Grabisch, 1995). This method requires the prior knowledge of the desired overall evaluations of the available attributes that should be given by the decision maker. In the next subsection, we will integrate the Choquet integral within the implementation of our proposed model in order to reduce the number of generated operational scenarios.

#### 4.4.2 Elimination of non-relevant scenarios

In order to reduce the number of scenarios, the first step is to rank them from environmental, economic, and social perspectives. To this end, the decision maker uses the computed environmental, economic and social attributes for each operational scenario (see Section 4.3) as reference for their judgments to provide their initial preferences. It is important to note that the selection of the most relevant scenarios is not only based on the global scores, but also on the ability of the company to implement the optimal scenario from financial and resources perspectives.

Hence, on the basis of the principles of the Choquet integral detailed in the previous subsection, the first step is to calculate partial scores denoted  $PS_{ij}$  where  $i = \{1, \dots, n_{atr}\}$  represents the attributes and  $j = \{1, \dots, n_{OS}\}$  represents the operational scenarios. The decision makers define judgments' intervals (From Low to High) for each attribute. These interval present the utility function in an interval of  $[0..1]$  whose partial scores are computed using equation 4.4.

$$PS_i = \begin{cases} 0 & \text{if } x_i \geq V_{High} \\ 1 & \text{if } x_i \leq V_{Low} \\ \frac{V_{High} - x_i}{V_{High} - V_{Low}} & \text{if } x_i \in ]V_{Low}, V_{High}[ \end{cases} \quad (4.4)$$

Where  $V_{High}$  and  $V_{Low}$  are the bounds of the judgment interval defined by the user and  $x_i$  is the indicator value of the attribute  $i$ . The second step consists in calculating the Shapley indices  $\phi$  representing the weights of the attributes ( $EA_x, ECA_y, SA_z$ ) under the following condition:

$\sum_{i=1}^n \phi_i = 1$  where  $n$  is the number of attributes.

As detailed in subsection 4.4.1, each  $\phi_i$  is determined through mutual interaction coefficients  $I_\mu(ij)$  between  $i$  and  $j$  where:  $\phi_i - (\frac{1}{2} \sum_{j=1}^n |I_{ij}|) \geq 0, \forall i \in [1, n]$  and  $j \neq i$ .

Three types of mutual interactions can be observed as follows:

1. If  $I_\mu(ij) < 0$ , there is a synergy between attributes  $i$  and  $j$ .
2. If  $I_\mu(ij) > 0$ , there is a contradiction between the attributes  $i$  and  $j$ .
3. If  $I_\mu(ij) = 0$ , there is no interaction between the attributes  $i$  and  $j$ .

Therefore, the Choquet integral for each scenario is computed using equation 4.5.

$$Ch_{OS}(\mu(Atr_1, \dots, Atr_n)) = \sum_{i=1}^n \phi_i \times PS_i - \frac{1}{2} \sum_{j=1}^n I_\mu(PS_i - PS_j) \quad (4.5)$$

Where  $\{PS_1, \dots, PS_n\}$  are the set of partial scores of attributes of the scenario  $OS$ . The number of selected scenarios depends on the potential capacity of the organization to deploy these scenarios.

By using the Choquet integral, we have been able to rank and reduce the generated operational scenarios taking into account the interaction phenomena between environmental, economic, and social attributes. In the next section, we will detail the selection of the optimal sustainable operational scenario.

## 4.5 Selection of the optimal sustainable operational Scenario

The last phase of step 5 is the selection of an optimal sustainable scenario among the relevant scenarios identified in the previous section using the Choquet Integral. The aim is to calculate a score for each operational scenario and choose the one with the highest score. Thus, we propose the implementation of the fuzzy ANP (Satty, 1996) given its ability to deal with the challenges related to dependency and uncertainty identified in section 4.2. In this context, the fuzzy ANP has been implemented in several works that are dedicated to solve multi-criteria decision making problems. We can mention in particular the works of Tavana et al. (2013); X. Wang et al. (2014); Q. He et al. (2015); Nilashi et al. (2016). In the following subsections, we will recall the principles of the Analytic Network process and the implementation of the fuzzy ANP within the proposed model

### 4.5.1 The Analytic Network Process

The ANP method developed by (Satty, 1996). It is an extension of the AHP (T. Saaty, 1980). In fact, the AHP decomposes the multi-criteria problem into a hierarchical structure. The highest level is the definition of the main goal of the selection process. The intermediate levels are dedicated to criteria and their relative sub-criteria. The last level of the hierarchy is dedicated to the different alternatives and choices. Although AHP method has been used in many researches to deal with the multi-criteria problems, it doesn't address the dependency issue. Thus, Satty proposed to replace the hierarchy structure by a network structure using clusters and nodes instead of elements. The network structure has made it possible to deal with two types of dependence between the inputs of the ANP; Dependence within a set of elements of the same cluster denoted inner dependence, and a dependence among different sets of elements from different clusters denoted outer dependence (T. L. Saaty, 1999). The difference between both structures is illustrated in Figure 4.1.

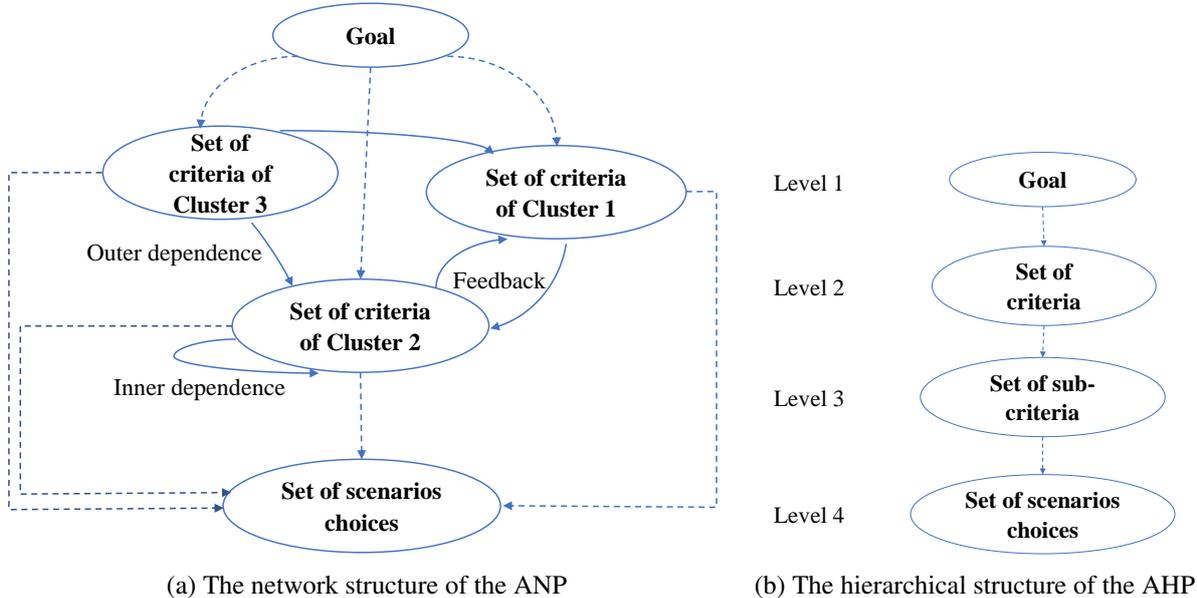


Figure 4.1: Difference between the network and the hierarchical structure

After the formulation of the problem into a network, the following step is the pairwise comparison between the different nodes of each cluster through comparison matrices having

the following form.

$$M = \begin{pmatrix} 1 & E_{12} & \cdots & E_{1n} \\ \frac{1}{E_{12}} & 1 & \cdots & E_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{E_{1n}} & \frac{1}{E_{2n}} & \cdots & 1 \end{pmatrix} \quad (4.6)$$

where the elements  $E_{ij}$  and  $E_{ji} = \frac{1}{E_{ij}}$  are the preference measurements which compare an element  $i$  with an element  $j$ . The judgments are based on Saaty's fundamental scale as presented in Table 4.2.

Table 4.2: Saaty's fundamental scale (T. Saaty, 1980)

1	Equal importance
3	Moderate importance of one over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values to refine the judgments

The fundamental scale is composed of nine intensities, the first is the equal importance of two elements with respect to a higher level element, the last is the extreme importance of an element with regard to another element. Four types of pairwise comparison matrices can be formed at this level through:

- Comparison between the criteria with respect to the main goal.
- Comparison between the criteria with respect to other criteria (Modelling the dependence)
- Comparison between the alternatives with respect to each criterion
- Comparison between criteria with respect of each alternative.

The number of the resulting matrices depends on the number of the criteria and sub-criteria. Once all matrices are formed, local priorities which is the weighting for each element should be computed in order to form the unweighted supermatrix. The local weights  $W_k$  are calculated using equation 4.7.

$$W_k = \frac{(\prod_{j=1}^n E_{kj})^{1/n}}{\sum_{i=1}^n (\prod_{j=1}^n E_{ij}^{1/n})} \quad (4.7)$$

All comparison matrices must be coherent. Indeed, a consistency check is performed for each matrix on the basis of a consistency ratio  $CR$  proposed by T. Saaty (1980) and calculated using equation 4.8.

$$CR = \frac{CI}{RI} \text{ where } CI = \frac{\lambda_{max} - n}{n - 1} \quad (4.8)$$

where  $\lambda_{max}$  is the maximum eigenvalue of the comparison matrix,  $n$  is the size of the matrix and  $RI$  is the Random Index preset by T. Saaty (1980) as presented in Table 4.3.

Table 4.3: Random Index values by matrix size (T. Saaty, 1980)

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

If the  $CR$  value is greater than 0.1, the pairwise comparison matrix is incoherent and the decision maker must review his initial judgments until all matrices are consistent.

At this step, we proceed the comparison at the cluster level in order to take into account the dependencies between the elements of these clusters. In fact, we will convert the unweighted supermatrix into a weighted supermatrix that is composed of dependent weights computed by comparing the elements of the clusters with respect to each others.

Finally, the final priority scores are obtained by multiplying the dependent weights with the local weights in order to rank the alternatives and to select the one having the highest score.

The ANP tool is applied in several multi-criteria decision problems in all sectors and fields since it is a friendly user tool. Moreover, a software dedicated to the application of the ANP has been developed “Superdecisions” (T. Saaty & William, 2004). This software covers all the step of the ANP implementation and handles all the mathematical operations to form the comparison matrices and the supermatrix through simple commands to optimize the time of the selection process.

To fall within the scope of our proposed model, the ANP method is the appropriate tool to select one optimal design scenario and it is possible to apply this method at the design stage. However, the inputs data of the ANP structure of our model and which all decision makers judgments are based on, are the impact assessment results and as we mentioned in section 4.3, the collected data are based on assumptions and estimated values. Thus, we have a second constraint which is the consideration of the uncertainty among the impact assessment results. To deal with this problem, we propose the use of the fuzzy ANP (Mikhailov & Singh, 2003) that integrates triangular fuzzy numbers into the steps of the conventional ANP.

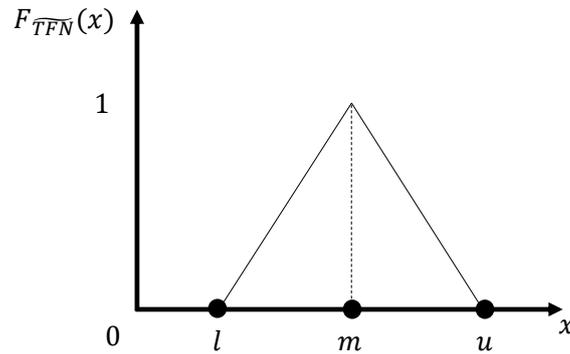


Figure 4.2: The membership function of a TFN

### 4.5.2 Triangular fuzzy numbers

The concept of fuzzy theory and fuzzy sets were initially introduced in 1965 by Zadeh (1965). Later on, fuzzy numbers were defined and introduced in many researches especially practical cases. Indeed, fuzzy numbers had developed more than fuzzy sets from application perspective especially in decision-making problems. More accurate results were obtained by implementing fuzzy numbers. In fact, these numbers are the generalization of a real number (Anand & Bharatraj, 2017). In other words, it represents a set of possible values. Each one is characterized by a weight.

Hence, each real number has an interval of possible weights that will be used in the judgments of the decision maker. In the context of our proposed model, we propose to use the TFN.

**Definition 4.5.1.** *The TFN is a fuzzy number  $T\tilde{F}N = (l, m, u)$  where its membership function  $F_{T\tilde{F}N}$  is illustrated in Figure 4.2 and defined by:*

$$F_{T\tilde{F}N} = \begin{cases} 0 & \text{if } x \leq l \\ \frac{x-l}{m-l} & \text{if } l < x < m \\ 1 & \text{if } x = m \\ \frac{u-x}{u-m} & \text{if } m < x < u \\ 0 & \text{if } x \geq u \end{cases} \quad (4.9)$$

where  $l$  is considered as the minimal possible value,  $m$  is the average value, also referred to as the most promising value since it represents the values of the original fundamental scale, and  $u$  is the maximal possible value.

In the following subsection, we will integrate the concept of TFNs within the ANP in order

to compute global scores for each operational scenario.

### 4.5.3 Selection of the optimal choice using the fuzzy ANP

In this step, the decision maker compares the selected relevant scenarios with respect to attributes per life cycle phase. We have chosen to implement the fuzzy ANP in order to deal with the dependency and uncertainty issues. It is an extension of the conventional ANP proposed by Mikhailov & Singh (2003) using fuzzy preferences and judgments by converting the preferences' scale to TFNs as presented in Table 4.4. The dependencies are modelled as a network of clusters. Uncertainties are processed through fuzzy comparisons on the basis of these triangular fuzzy numbers.

Table 4.4: Fuzzy preferences' scale

Triangular fuzzy scale (l,m,u)	Linguistic values
(1,1,1)	Equal importance
(1,1,3)	Low importance
(1,3,5)	Moderate importance of one over another
(3,5,7)	Strong importance
(5,7,9)	Very strong importance
(7,7,9)	Extreme importance

This scale offers three possible value instead of one as an interval to deal with uncertain judgments for more robust results.

The model's ANP structure has six clusters containing several nodes as shown in Figure 4.3. Namely:

- (i) A cluster to define the objective which is the selection of the optimal sustainable operational scenario.
- (ii) A cluster containing five nodes that represent the five life cycle phases.
- (iii) Three clusters for environmental, economic, and social attributes. Each one contains the impacts' indicators respectively.
- (iiii) A cluster for operational scenarios which the number is already determined by the Choquet integral.

The fuzzy ANP algorithm is structured as follows: The first step is a pairwise comparison of the attributes' nodes for each life cycle phase and the operational scenarios' nodes per each

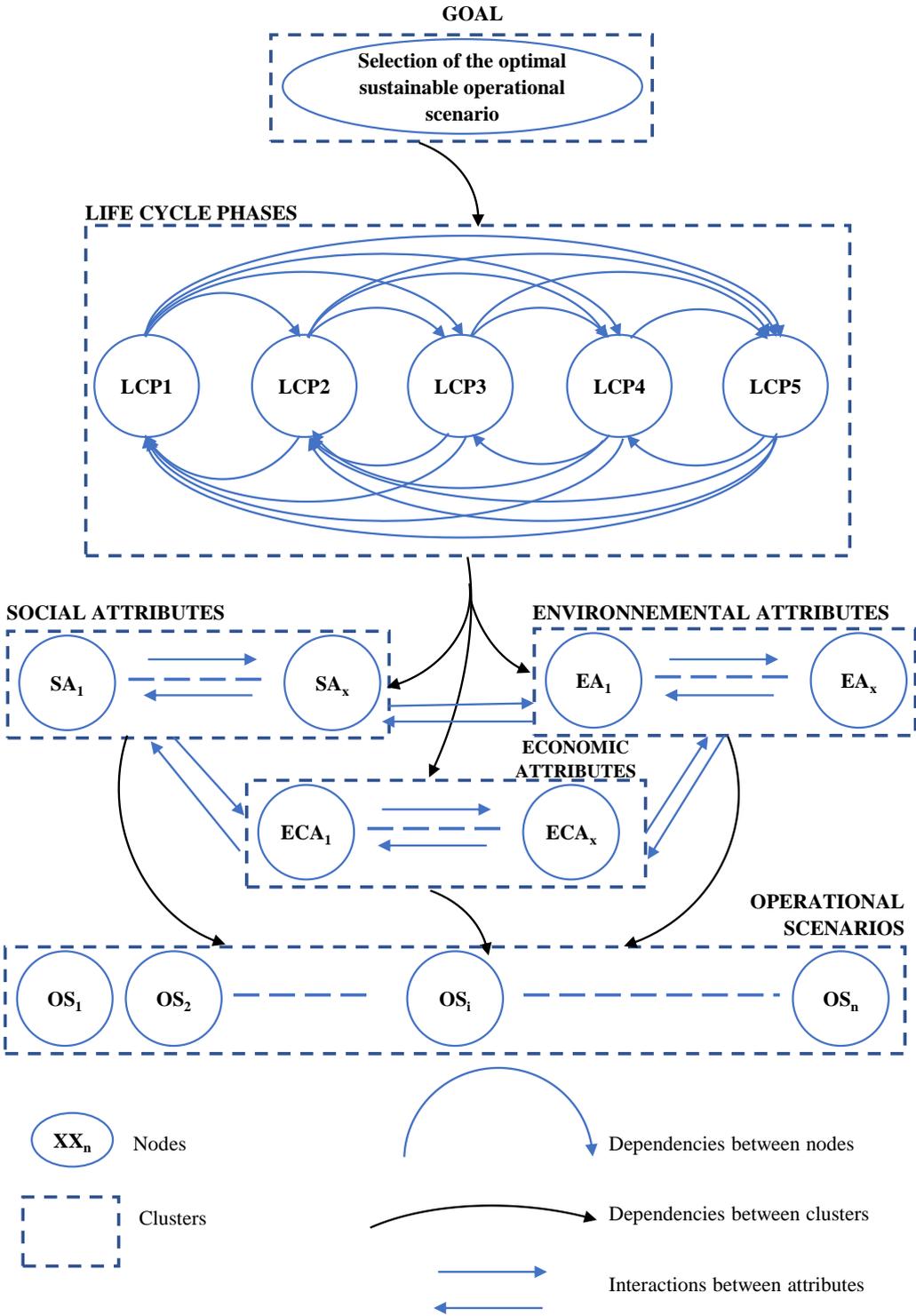


Figure 4.3: The ANP structure of the proposed model (Sansa et al., 2019)

attribute per phase. The resulting comparison matrices  $\tilde{M}$  are defined following the form of 4.6.

$$\tilde{M} = \begin{pmatrix} (1, 1, 1) & (E_{12}^l, E_{12}^m, E_{12}^u) & \cdots & (E_{1n}^l, E_{1n}^m, E_{1n}^u) \\ (\frac{1}{E_{12}^u}, \frac{1}{E_{12}^m}, \frac{1}{E_{12}^l}) & (1, 1, 1) & \cdots & (E_{2n}^l, E_{2n}^m, E_{2n}^u) \\ \vdots & \vdots & \ddots & \vdots \\ (\frac{1}{E_{1n}^u}, \frac{1}{E_{1n}^m}, \frac{1}{E_{1n}^l}) & (\frac{1}{E_{2n}^u}, \frac{1}{E_{2n}^m}, \frac{1}{E_{2n}^l}) & \cdots & (1, 1, 1) \end{pmatrix} \quad (4.10)$$

where the elements  $E_{ij}^{l,m,u} = (E_{ij}^l, E_{ij}^m, E_{ij}^u)$  and  $E_{ji}^{l,m,u} = (\frac{1}{E_{ij}^u}, \frac{1}{E_{ij}^m}, \frac{1}{E_{ij}^l})$  are the fuzzy preference which compare the attribute  $i$  (resp. Scenario  $i$ ) with the attribute  $j$  (resp. Scenario  $j$ ). On the basis of these matrices, the local weights of attributes (resp. scenarios) are computed using equation 4.11.

$$W_k^{l,m,u} = \frac{(\prod_{j=1}^n E_{kj}^{l,m,u})^{1/n}}{\sum_{i=1}^n (\prod_{j=1}^n E_{ij}^{l,m,u})^{1/n}} \quad (4.11)$$

The second step is to carry out a consistency check for all the matrices in order to check the consistency of the experts' judgments (Parkouhi & Ghadikolaei, 2017). In the case of a fuzzy comparison, the consistency is checked by building two matrices  $A_m$  and  $A_g$  from  $\tilde{M}$  where  $A_m$ 's elements are the  $E_{ij}^m$  and  $A_g$ 's elements are calculated as follows:

$$E_{ij}^g = \sqrt{E_{ij}^l \times E_{ij}^u} \quad (4.12)$$

Based on the Saaty's procedure, we calculate the two coherence ratios  $CR_m$  and  $CR_g$  using equation 4.8. If they are greater than 0.1, the expert must review his judgments.

The third step is dedicated to the quantification of the dependencies between the life cycle phases. First, a comparison matrix of the cluster life cycle phases with respect to the goal node is constructed using the matrix form 4.10 and the relative local weights are calculated using equation 4.11. Then, to quantify the dependencies, five comparison matrices are identified for each of the life cycle phases. These matrices compare the life cycle phases with respect to each others. Following the same procedure, new local dependent weights are calculated for each matrix using equation 4.11. These weights are grouped in a supermatrix. Dependency weights can thus be calculated through the supermatrix using equation 4.11.

The last step is to compute the priority weights  $W_p$  for each operational scenario using equation 4.13 in order to select the one with the highest  $W_p$ .

$$W_p = \sum_{i=1}^5 W_{lcp} \times \left( \sum_{i=1}^{n_{atr}} \sum_{i=1}^{n_{os}} W_{atr_i} \times W_{OS_{ij}} \right) \quad (4.13)$$

Where  $W_{lcp}$  are the dependency weights of the life cycle phases,  $W_{atr_i}$  are the attributes' weights,  $W_{OS_{ij}}$  are the weights of the  $OS_j$  scenarios with respect to the attribute  $i$ ,  $n_{atr}$  is the number of attributes and  $n_{OS}$  is the number of operational scenarios. Hence, our proposed multi-criteria decision making system was able to deal with three design issues (i.e. Uncertainties of judgments, interactions of the sustainability impacts and the dependencies between the life cycle phases).

## 4.6 Conclusion

The operational part dealt with the choice of the optimal scenario among a series of relevant operational ones. The implementation of this part has depended on a set of simulations based on databases and dedicated software. For the reduction of the number of scenarios, we used Choquet's integral which gave us the opportunity to overcome problems of interaction between environmental, social and economic attributes. We also implemented the Fuzzy ANP method to address dependencies between life cycle phases and uncertainties about expert preferences and values of impact attributes or indicators. In the next chapter, we will implement the proposed model in a Tunisian company that manufactures Lead Acid batteries for motorcycles.

Chapter **5**

**Sustainable design of VRLA batteries in  
Tunisia**

## **5.1 Introduction**

In this chapter, we will demonstrate the applicability of our proposed model through its implementation within a Tunisian company. In fact, in Tunisia, many short-term problems such as the increase in the rate of internal migration, waste, wealth gaps between regions, etc., have caused an imbalance in the country's resources and development patterns. This has made consideration of the sustainability's pillars a necessity in order to address these issues and ensure long-term sustainability.

Following these events, TUNISTAR Battery, a Tunisian company designing and developing batteries for motorcycles has decided to integrate the concept of sustainable development in its batteries' design. Thus, the company has decided to implement our approach. In the following sections, we will detail the contextualized analysis performed for TUNISTAR Battery, the generation of the relevant strategic and operational scenarios and the selection of the optimal one.

## **5.2 TUNISTAR Battery: Presentation and activities**

### **5.2.1 Brief recall on the current situation in Tunisian industry**

During the last twenty years, environmental, economic and social short-term problems in Tunisia have made the concept of sustainable development a strategic necessity. We can mention in particular:

- An average of 86.1 thousand internal migrants in 2014 which affected the population's distribution (Tunisia, 2016).
- A constant increase of waste with an annual quantity of 150 thousand tons of hazardous industrial waste (SDG, 2017).
- The exhaustion of water resources in numerous watersheds that lead to a situation of water stress with more than 41% of the population deprived from sanitation services (SDG, 2017).
- An energy deficit caused by a large gap between energy needs and the available resources leading to a dependency on imported expensive fossil fuels.

As a result, plans and programs were carried out to implement national sustainability actions in all sectors. In this context, a Tunisian company has decided to integrate sustainable development practices into the design of its products in the batteries and accumulators business sector. The designers of TUNISTAR Battery have decided to minimize the impact of their product through the generation of new operational scenarios for motorcycle battery design.

According to the 2014 statistics of the Tunisian Industry Portal (TIP, 2014), the batteries and accumulators sector comprises ten companies, including three offshore factories. It employs more than 1116 employees. In 2012, total exports revenues were estimated to 2 Million Tunisian Dinars. This number is very significant compared to the export revenues of other fields of the electrical sector. The main export countries are Morocco, Algeria, Iraq and countries in sub-Saharan Africa. Due to the Tunisian revolution in 2011, companies experienced a significant decline in their exports, some organizations were shut down because of social movements and the employment rate has declined. In this context, the state established a new legal investment framework through the laws (TIP, 2016, 2017) and the decree (center of organic agriculture, 2017). This framework aimed to encourage the sustainable development of products and services at national and international scales.

With this in mind, TUNISTAR Battery has decided to implement its own strategies for the sustainable design of new batteries.

### **5.2.2 Impact study of TUNISTAR Battery**

This company is located in an area developed in Bouarada characterized by a homogeneous climate. This region contains approximately twenty-five thousand inhabitants. The location of the plant site has contributed positively to the socio-economic environment of the region by creating thirty direct jobs and thereby reducing the unemployment rate in the region. TUNISTAR battery has carried out an environmental impact study. This study defined the different types of waste and releases generated by the company during battery production and the measures taken to reduce them such as summarized in Table 5.1.

However, these measures and actions are limited to manufacturing units and are organization-oriented. As a result, TUNISTAR Battery wanted to integrate the product approach into its sustainability strategy to improve the life cycle's performance of its battery. This strategy is characterized by organizational and technical systems capable of ensuring a controlled value chain in which the company can influence. The company's vision was to develop its national and international market and position itself in the African market with eco-designed products that respect corporate rights and generate profits. The design team decided to implement our

Table 5.1: Summary of the environmental impacts generated by TUNISTAR Battery and the measures to be undertaken

Impacts on the environment	Nature	Quantity	Measures
Water Discharges	Industrial wastewater	$0.4m^3/j$	The industrial wastewater will be collected in a waterproof tarpaulin and periodically discharged through an approved company to ONAS's grading station in Ben Arous.
	Sanitary wastewater	$1.5m^3/j$	The sanitary wastewater will be discharged directly into the sewerage system.
	Storm-water	According to the rainy season	Evacuated into the storm-water network.
Solid waste	Household waste	$5Kg/j$	Collected and transported to the controlled landfill.
Air pollution	The emanation of the soldering post of lead terminals		Installation of a bag filter

three-level model (See Figure 5.1) in order to generate operational design scenarios and select an optimal sustainable design solution.

It is important to mention that motorcycle battery technology has not been developed in Tunisia by the dominant accumulators on the local market (Mainly Assad and Nour), and therefore, no life cycle analysis studies have been carried out for this type of battery on a national scale.

### 5.3 Contextualized strategic analysis of TUNISTAR Battery

The designers of TUNISTAR Battery have decided to minimize the impact of their battery through the generation of new operational scenarios for motorcycle battery design. On the basis of the National Sustainable Development Strategy 2014-2020 (Ministry of equipment & sustainable development, 2014) and the 2016-2020 Development Plan (Tunisie, 2017), we have identified data related to employment targets, improvement of living conditions, health, public investment, infrastructure development in isolated areas, etc.

In addition, a brainstorming was performed in collaboration with the company's team to identify internal and external issues by combining the SWOT, 7S and PESTEL methods. The conjunction between 7S and SWOT has identified 24 internal issues classified into 12 strengths and 12 weaknesses (see Table 5.2). The conjunction between PESTEL and SWOT has identified 21 external issues classified into 11 opportunities and 10 threats (see Table 5.3).

Once identified, it is necessary to include the needs and the expectations of a range of TUNISTAR Battery stakeholders. In order to identify these needs, the designers must consider the different phases of the life cycle of the battery composed of five main life cycle phases

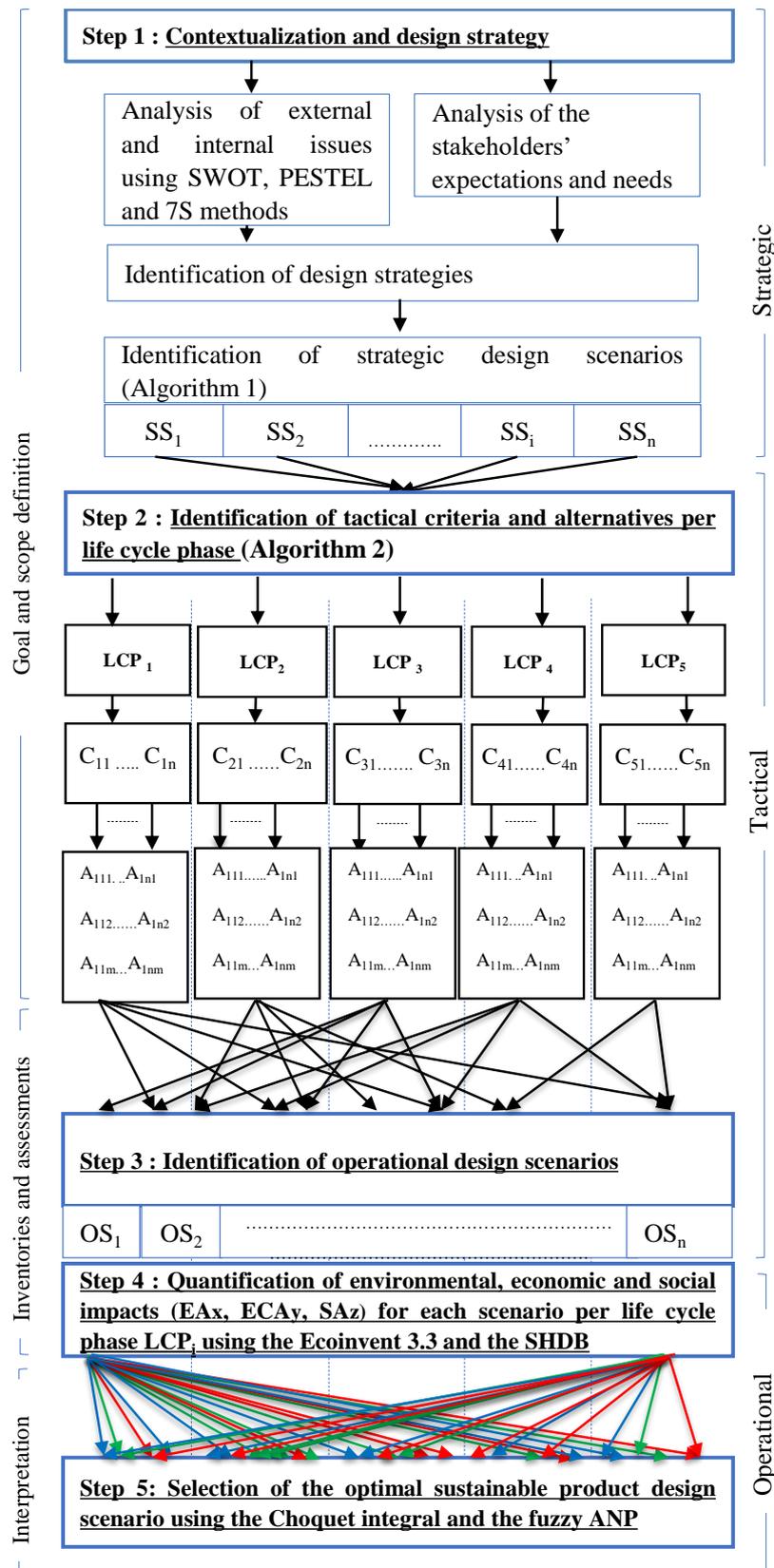


Figure 5.1: Framework of the proposed model with the selected tools

Table 5.2: Internal issues of TUNISTAR Battery

7S	Strengths $ST_i$	Weaknesses $WE_i$
Skills	$ST_1$ : Skills in industrialization and manufacturing of batteries	$WE_1$ : A language barrier in communication and negotiation of raw material purchase prices
	$ST_2$ : Good knowledge of the LCA method	
Systems	$ST_3$ : A large capacity for storing raw materials which optimizes the supply and transport of materials	$WE_2$ : A small capacity in storing final products (volume must be limited)
	$ST_4$ : Good knowledge of the LCA method	$WE_3$ : Unstable Management of distribution network
	$ST_5$ : Good storing conditions of chemical materials	$WE_4$ : Unstable management of logistics (Suppliers, delivery modes)
Staff	$ST_6$ : High efficiency of assembly operators	$WE_5$ : Low salary for manufacturing operators
	$ST_7$ : Young staff and available manpower	$WE_6$ : Occupational diseases due to constant exposure to chemical materials
		$WE_7$ : Instability in staff employment
Style	$ST_8$ : Positive collaboration of the management team in the development of new products	$WE_8$ : Insufficient understanding of environmental and social issues by the shareholders
Shared values	$ST_9$ : Delivery of local designed batteries	$WE_9$ : Lack of responsibility towards the company
	$ST_{10}$ : Environmental and social consciousness	$WE_{10}$ : Insufficient share of organization's objectives
Strategy	$ST_{11}$ : Availability of investments for new technologies	$WE_{11}$ : Uncertainties in environmental and economic aspects and impacts
Structure	$ST_{12}$ : Research and development unit	$WE_{12}$ : Insufficient communication between distribution services, R&D, manufacturing and supply

illustrated in Figure 5.2, namely:

- Production of raw materials,  $LCP_1$ : The different components of the battery (i.e. positive and negative plates, electrolyte, separator, container and covers, packaging film, labels) are manufactured from natural resources and transported to the factory.
- Manufacturing,  $LCP_2$ : A manufacturing process is required to assemble the components into a battery. The first step consists in regrouping the set of plates within the separator. Then, connections between the plates are molded to create terminals and placed into the container. At this stage, the battery is sealed, and all the connections are welded, the battery is filled with electrolyte and charged. The last step is the labelling and packaging.
- Distribution,  $LCP_3$ : This phase mainly consists in the transportation of the battery to the retailer or the final user.
- Use,  $LCP_4$ : The battery is used to start the vehicle's engine, as a main function, and it is also responsible for providing energy to the vehicle's electronic devices.
- End of life,  $LCP_5$ : During this phase the battery is disassembled, and the components are disposed of through several waste management schemes such as recycling, landfill disposal, reuse or incineration.

Table 5.3: External issues of TUNISTAR Battery

PESTEL	Opportunities $OP_i$	Threats $TH_i$
Political	$OP_1$ : Establishment of a national sustainable development strategy 2016-2020	$TH_1$ : Government instability $TH_2$ : Environmental police in the region
Economic	$OP_2$ : Possibility of raw material extraction directly from recycling units $OP_3$ : Opportunity to extract packaging material from a close factory. $OP_4$ : Increasing demand of similar products from African countries	$TH_3$ : 25% increase in lead cost $TH_4$ : competitive price of imported batteries $TH_5$ : New environmental tax
Social	$OP_5$ : Availability of qualified engineers with adequate salaries	$TH_6$ : Emergence of new regional environmental associations
Environmental	$OP_6$ : Availability of free health centers $OP_7$ : Availability of wind power located near to the manufacturing site $OP_8$ : Availability of waste management and recovery centers	$TH_7$ : Exodus in operational labor power in coastal area $TH_8$ : Geographical location near agricultural lands
Technological	$OP_9$ : Availability of local plastic injection molding (possibility of local subcontracts) $OP_{10}$ : Availability of data for battery design and manufacture	$TH_9$ : Unavailability of scientific data for low-cost new batteries with a significant capacity to store energy
Legal	$OP_{11}$ : Availability of laws that inflict prison sentences against parallel battery markets	$TH_{10}$ : National and international legal constraints related to the transportation and management of chemical products

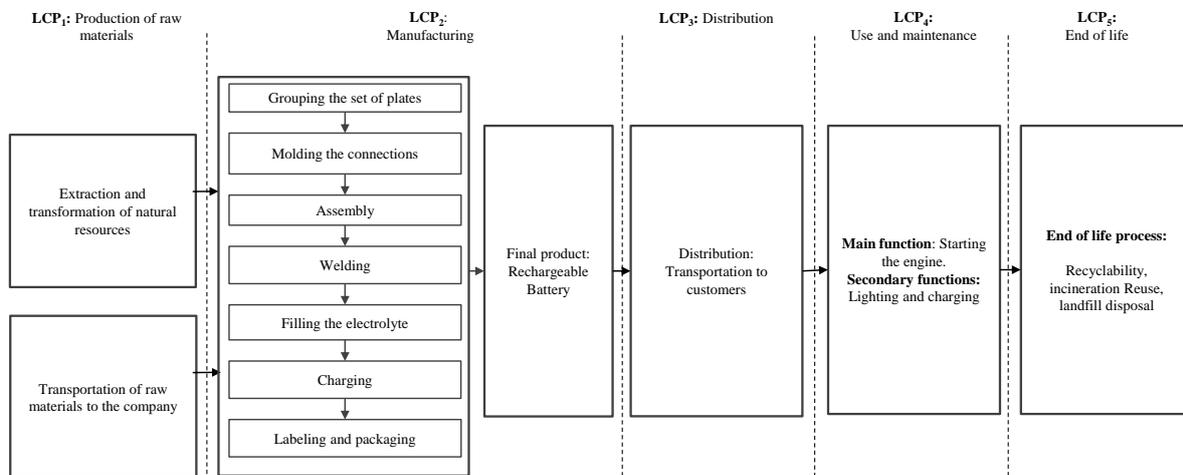


Figure 5.2: The life cycle of a battery

Hence, 24 needs and expectations were identified and classified by life cycle phase (see Table 5.4). Most of them are economic and technical requirements and a few are environmental requirements.

Table 5.4: Identification of the needs and expectations of the stakeholders

Stakeholders' category	$LCP_i$	$REQ_i$	Design requirements
Shareholder	$LCP_2$	$REQ_1$	Low investments costs
	$LCP_1$	$REQ_2$	Preference for local materials
	$LCP_2$	$REQ_3$	Stability of operators
	$LCP_2$	$REQ_4$	Investments in cleaner production's new technologies
Staff	$LCP_2$	$REQ_5$	Workers' Health and safety
	$LCP_2$	$REQ_6$	Promising Wage
The state	$LCP_1$	$REQ_7$	Encouragement of local industry
	$LCP_5$	$REQ_8$	Respect of waste management laws
	$LCP_3$	$REQ_9$	Promotion of export
Society	$LCP_5$	$REQ_{10}$	Recycling of the battery
	$LCP_2$	$REQ_{11}$	Employment of young graduates
	$LCP_2$	$REQ_{12}$	Workers' Health and safety
	$LCP_2$	$REQ_{13}$	Respect of human rights
User/Consumer	$LCP_4$	$REQ_{14}$	Technical characteristics (voltage, Power, Number of cycles)
	$LCP_4$	$REQ_{15}$	Light battery weight
	$LCP_4$	$REQ_{16}$	Easy unpacking
	$LCP_4$	$REQ_{17}$	Availability of sales' point
	$LCP_4$	$REQ_{18}$	Optimized costs
	$LCP_4$	$REQ_{19}$	Sustainability of the batteries
Distributor	$LCP_3$	$REQ_{20}$	Light battery weight)
	$LCP_3$	$REQ_{21}$	Minimal bulk during the transportation process
	$LCP_4$	$REQ_{22}$	Optimized sales' costs
Suppliers/subcontractors	$LCP_1$	$REQ_{23}$	Financial profits)
	$LCP_1$	$REQ_{24}$	Adequate quantity of supplies

## 5.4 Identification of strategies, tactics and operational scenarios

On the basis of issues mentioned in the previous section, a confrontation matrix was developed through the conjunction of internal and external issues. Relevant strategic scenarios were generated by the TUNISTAR Battery decision makers from this matrix using Algorithm 1 (See Table 5.5). These scenarios have been divided into 3 attack scenarios (i.e.  $ASS_1$ ,  $ASS_5$ ,  $ASS_8$ ), an adjustment scenario with an attack component (i.e.  $AJSS_7$ ), 2 defense scenarios (i.e.  $DS_3$ ,  $SS_6$ ) and two survival scenarios (i.e.  $SSS_2$ ,  $SSS_4$ ). All these strategic scenarios included the associated sustainability trade-offs. The attack scenarios are characterized by the use of current resources (storage spaces, operator skills and performance, etc.) in order to optimize the supply modes and control of end-of-life recovery. The defense scenarios aim at organizational and technical improvements to increase the ability to control and influence the choice of suppliers and the distribution modes. Survival scenarios aim to cope with regulatory constraints and cost increase of imported materials. Adjustment scenarios aim to deal with competition, taxes and parallel markets.

Adequate tactics were identified for each strategic scenario along with design criteria for each life cycle phase. For example, we identified tactics related to supply modes, technologies of ma-

materials, subcontracting, implementation of manufacturing sites and processes. In this context, 21 design criteria per life cycle phase were identified. These are related to dangerous materials, energy consumption, weights, supply and distribution distances, waste, costs, occupational diseases, etc. For each criterion, design alternatives were assigned. They are controllable and influencing. The most important ones are:

- The Absorbed Glass Mat (AGM) and Gel technologies (Berndt, 2006), both are VRLA batteries. AGM are lead-acid batteries that are spill-proof. In fact, the electrolyte is suspended in a fiberglass mat mounted between the positive and negative lead plates. This technology allows the battery to have a good resistance to vibration. Gel batteries are similar to AGM. However, in a gel cell, the electrolyte has the texture of a thick paste since it is suspended in a silica type gel. Both batteries have similar characteristics such as the possibility to be mounted in any position, safety of use, deep cycle and low self discharge. Gel batteries are more costly than the AGM ones but they have a longer lifespan and have better slow discharge rates. The AGM are simpler to use than the Gel batteries. These latter are very delicate and there is a high risk of malfunction due to charging errors.
- Location of the production site in Tunisia or in Tanzania. In case of a Tunisian factory site, there is a possibility of a local distribution of batteries to retailers or an export to retailers in Tanzania.
- Container and covers of the battery: Two types of plastic, Acrylonitrile Butadiene Styrene (ABS) (Bashford, 1997) or Polypropylene (PP) (Karger-Kocsis, 2012). Both types are thermoplastic polymer. Considering the same dimension of the container and covers of the battery, PP has lighter weight than ABS. However, ABS is more expensive than PP. ABS is characterized by a better resistance to temperature and has no true melting point compared to PP where the melting point is set to 160°C.

Table 5.5 synthesizes the strategic scenarios, the design criteria and their relative design alternatives. As shown, 21 criteria and 45 alternatives were identified. All possible combinations between these design alternatives form the operational design scenarios.

Table 5.5: Generation of strategic scenarios, tactics and alternatives for each life cycle phase

Issues	Requirements	Nature	Strategic description	Influence level of company	Decision criteria	$LCP_i$	Design criteria	Design alternatives
[ $ST_3$ + $ST_5$ + $ST_{10}$ + $ST_{11}$ + $OP_2$ ]	$REQ_{23}$ + $REQ_{24}$	$ASS_1$	Taking advantage of the large storage capacity of the raw materials to optimize significant quantities supplies from recovery factories	Strong	Battery technology, packaging, material transportation mode, distance, transportation mode, technology type	$LCP_1$	$C_{11}$ : Chemistry type $C_{12}$ : Material supply quantities according to the functional unit adapted to each technology	$A_{111}$ : Absorbed Glass Mat AGM, $A_{112}$ : Gel $A_{121}$ : Quantity of supplies for AGM using ABS plastic, $A_{122}$ : Quantity of supplies for AGM using PP plastic, $A_{123}$ : Quantity of supplies for Gel using ABS plastic, $A_{124}$ : Quantity of supplies for Gel using PP plastic
[ $WE_1$ + $WE_4$ + $TH_9$ + $TH_5$ ]	$REQ_2$ + $REQ_7$	$SSS_2$	Consideration of legal constraints, variation of materials' costs and improvement of negotiation skills in order to optimize the impacts' costs	Weak			$C_{13}$ : Material transportation mode $C_{14}$ : Transport distance between the country of material supply and the manufacturing site	$A_{131}$ : Terrestrial, $A_{132}$ : Shipment $A_{141}$ : China, $A_{142}$ : Turkey
$WE_{12}$ + $OP_3$	$REQ_2$	$DSS_3$	Improvement of communication about the choice of the adequate local packaging suppliers in order to optimize the environmental costs and impacts	Strong	Packaging type and quantity, Packaging Supply mode		$C_{15}$ : Packaging type $C_{16}$ : Packaging supply quantities	$A_{151}$ : PP and wood, $A_{152}$ : Cardboard and wood $A_{161}$ : Quantity of packaging supply for AGM, $A_{162}$ : Quantity of packaging supply for Gel
							$C_{17}$ : Packaging transportation mode $C_{18}$ : Packaging supply distance	$A_{171}$ : Terrestrial transport, $A_{172}$ : Shipment transport $A_{181}$ : China, $A_{182}$ : Tunisia, $A_{183}$ : Turkey

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Table 5.5 – continued from previous page

Issues	Requirements	Nature	Strategic description	Influence level	Decision criteria	$LCP_i$	Design criteria	Design alternatives
$[WE_6 + WE_7 + WE_8] + TH_7$	$REQ_3 + REQ_6 + REQ_{11} + REQ_{12} + REQ_{13}$	$SSS_4$	Consideration of occupational diseases, operators' stability and shareholders' technique for the choice of the battery's technology with less toxic materials	Average level	Technology type, material, level of danger	$LCP_2$	$C_{21}$ : Manufacturing site $C_{22}$ : Operators' exposure	$A_{211}$ : Tunisian site, $A_{212}$ : Tanzanian site $A_{221}$ : Average period in the case of AGM, $A_{222}$ : Average period in the case of Gel
$[ST_5 + ST_6 + ST_{11}] + OP_{10}$	$REQ_1 + REQ_4$	$ASS_5$	Exploitation of the operators' skills and the available scientific data to develop environmental, economic, and social perspectives	Strong	Technology (operations, material type, quantity of waste)		$C_{23}$ : Energy consumption during the manufacturing process $C_{24}$ : Quantity of waste	$A_{231}$ : Consumed energy in the Tunisian site for AGM and Gel (case of ABS plastic), $A_{232}$ : Consumed energy in the Tunisian site for AGM and Gel (case of PP plastic) $A_{241}$ : Quantity of waste for AGM, $A_{242}$ : Quantity of waste for Gel
$[WE_2 + WE_3 + WE_{11}] + OP_4$	$REQ_9 + REQ_{20} + REQ_{21} + REQ_{13}$	$DSS_6$	Seeking African market opportunities to optimize distribution modes	Average	Distribution mode (Distance, Transportation, Weight), Technology and packaging mode	$LCP_3$	$C_{31}$ : Quantity of batteries distributed per functional unit $C_{32}$ : Transportation mode of packed batteries $C_{33}$ : Distribution distance	$A_{311}$ : Quantity of AGM batteries, $A_{312}$ : Quantity of Gel batteries $A_{321}$ : Terrestrial, $A_{322}$ : Shipment $A_{331}$ : Local distribution in Tunisia if the alternative $A_{211}$ is selected, $A_{332}$ : Export from Tunisia to Tanzania, $A_{333}$ : Local distribution in Tanzania if the alternative $A_{212}$ is selected

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Table 5.5 – continued from previous page

Issues	Requirements	Nature	Strategic description	Influence level	Decision criteria	$LCP_i$	Design criteria	Design alternatives
[ $ST_1$ + $ST_2$ + $ST_9$ + $ST_7$ + $ST_{12}$ ] + $OP_{11}$ + [ $TH_4$ + $TH_5$ ]	$REQ_{14}$ + $REQ_{15}$ + $REQ_{16}$ + $REQ_{17}$ + $REQ_{18}$ + $REQ_{19}$ + $REQ_{22}$	$AJSS_7$	Exploitation of capacities in R&D, implementation of barriers against parallel markets, consideration of competitiveness threats and the new environmental and social taxes in order to optimize the prices and the environmental and social impacts	Average	Materials, transportation, processes	$LCP_4$	$C_{41}$ : Fuel consumption per battery mass  $C_{42}$ : Quantity of packaging waste  $C_{43}$ : Lifespan of each battery's technology	$A_{411}$ : Fuel consumption for AGM with ABS plastic, $A_{412}$ : Fuel consumption for AGM with PP plastic, $A_{413}$ : Fuel consumption for Gel with ABS plastic, $A_{414}$ : Fuel consumption for Gel with PP plastic  $A_{421}$ : Quantity of packaging waste for AGM, $A_{422}$ : Quantity of packaging waste for Gel  $A_{431}$ : Lifespan of AGM in Tunisia, $A_{432}$ : Lifespan of Gel in Tunisia, $A_{433}$ : Lifespan of AGM in Tanzania, $A_{434}$ : Lifespan of Gel in Tanzania
[ $ST_4$ + $ST_{10}$ ] + $OP_8$	$REQ_8$ + $REQ_{10}$	$ASS_8$	Exploitation of the available services in the waste treatment field in order to choose the adequate packaging, types of material, and mode of waste in order to minimize the costs, the environmental and social impacts	Strong	Technology, packaging mode, waste treatment mode  Quantity and type of packaging, Technology (quantity and type of materials), Waste treatment mode	$LCP_5$	$C_{51}$ : Waste treatment mode	$A_{511}$ : Recycling of AGM and Gel batteries in Tunisia, $A_{512}$ : Recycling of AGM and Gel batteries in Tanzania

Using equation 3.1, 3.16e59 operational scenarios can be generated. However, considering that the choice of certain alternatives eliminates automatically some combinations and on the basis of Algorithm 2, the number of generated operational scenarios can be reduced significantly. For example, the choice of the alternative  $A_{111}$ : *AGM technology* eliminates automatically all the alternatives related to  $A_{112}$ : *Gel technology*. Therefore, for a better illustration of the case study, only 14 operational scenarios were identified based on choosing alternatives with available data. The combination of these alternatives that presents each operational scenario are presented in table 5.6. The criteria  $C_{15}$ ,  $C_{16}$ ,  $C_{17}$ ,  $C_{18}$  and  $C_{42}$  define the characteristics and quantities of the packaging and its generated waste. Yet, TUNISTAR Battery has not the adequate data on the packaging and the team had made the assumption that all scenarios have the same packaging type. Thus, these criteria do not influence the choice of the optimal scenario and they have been eliminated from the combinations of the alternatives. Also, an assumption has been made that all scenarios have the same end of life treatment  $A_{511}$  and  $A_{512}$  which is recycling.

Table 5.6: The identified 14 scenarios

Scenarios OS	Design alternatives per life cycle phase				
	$LCP_1$	$LCP_2$	$LCP_3$	$LCP_4$	$LCP_5$
$OS_1$	$A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	$A_{211}, A_{221}, A_{231}, A_{241}$	$A_{311}, A_{321}, A_{331}$	$A_{411}, A_{431}$	$A_{511}$
$OS_2$	$A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	$A_{211}, A_{221}, A_{231}, A_{241}$	$A_{311}, A_{321}, A_{322}, A_{332}$	$A_{411}, A_{433}$	$A_{512}$
$OS_3$	$A_{112}, A_{123}, A_{131}, A_{132}, A_{141}$	$A_{211}, A_{222}, A_{231}, A_{242}$	$A_{312}, A_{321}, A_{331}$	$A_{413}, A_{432}$	$A_{511}$
$OS_4$	$A_{112}, A_{123}, A_{131}, A_{132}, A_{141}$	$A_{211}, A_{222}, A_{231}, A_{242}$	$A_{312}, A_{321}, A_{322}, A_{332}$	$A_{413}, A_{434}$	$A_{512}$
$OS_5$	$A_{111}, A_{121}, A_{131}, A_{132}, A_{142}$	$A_{211}, A_{221}, A_{231}, A_{241}$	$A_{311}, A_{321}, A_{331}$	$A_{411}, A_{431}$	$A_{511}$
$OS_6$	$A_{112}, A_{123}, A_{131}, A_{132}, A_{142}$	$A_{211}, A_{222}, A_{231}, A_{242}$	$A_{312}, A_{321}, A_{331}$	$A_{413}, A_{432}$	$A_{511}$
$OS_7$	$A_{111}, A_{122}, A_{131}, A_{132}, A_{141}$	$A_{211}, A_{221}, A_{232}, A_{241}$	$A_{311}, A_{321}, A_{331}$	$A_{412}, A_{431}$	$A_{511}$
$OS_8$	$A_{112}, A_{124}, A_{131}, A_{132}, A_{141}$	$A_{211}, A_{222}, A_{232}, A_{242}$	$A_{312}, A_{321}, A_{331}$	$A_{414}, A_{433}$	$A_{511}$
$OS_9$	$A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	$A_{212}, A_{221}, A_{232}, A_{241}$	$A_{311}, A_{321}, A_{333}$	$A_{411}, A_{432}$	$A_{512}$
$OS_{10}$	$A_{112}, A_{123}, A_{131}, A_{132}, A_{141}$	$A_{212}, A_{222}, A_{233}, A_{242}$	$A_{312}, A_{321}, A_{333}$	$A_{413}, A_{434}$	$A_{512}$
$OS_{11}$	$A_{111}, A_{121}, A_{131}, A_{132}, A_{142}$	$A_{212}, A_{221}, A_{232}, A_{241}$	$A_{311}, A_{321}, A_{333}$	$A_{411}, A_{432}$	$A_{512}$
$OS_{12}$	$A_{112}, A_{123}, A_{131}, A_{132}, A_{142}$	$A_{212}, A_{222}, A_{233}, A_{242}$	$A_{312}, A_{321}, A_{333}$	$A_{413}, A_{434}$	$A_{512}$
$OS_{13}$	$A_{111}, A_{122}, A_{131}, A_{132}, A_{141}$	$A_{212}, A_{221}, A_{234}, A_{241}$	$A_{311}, A_{321}, A_{333}$	$A_{412}, A_{432}$	$A_{512}$
$OS_{14}$	$A_{112}, A_{124}, A_{131}, A_{132}, A_{141}$	$A_{212}, A_{222}, A_{234}, A_{242}$	$A_{312}, A_{321}, A_{333}$	$A_{413}, A_{434}$	$A_{512}$

Once the operational scenarios were identified, a life cycle impact assessment was per-

formed for each operational scenario in order to quantify the potential impacts through environmental, economic and social indicators.

## 5.5 Life cycle impact assessments

To assess the environmental, economic and social assessment of each scenario, the decision maker sets the FU as follows: “*Allowing one use of a motorcycle by starting its engine and providing energy to its electronic devices*”. The reference flow, (i.e. the number of battery), associated with this functional unit depends on the choice of battery technology, country of use, and battery lifespan. The decision maker has chosen two battery technologies: AGM and Gel; and, two countries of use: Tunisia and Tanzania. An assumption was made that the user needs to start the engine three times per day. Table 5.7 summarizes the reference flows considered in the environmental, economic and social assessments.

The average annual temperature in Tanzania is higher than in Tunisia, which reduces the lifes-

Table 5.7: Parameters required for the impacts’ assessment

Country of use	Tunisia	Tanzania
Average annual temperature (°C)	20 <sup>1</sup>	25 <sup>2</sup>
Lifespan of an AGM Battery (Years)	8 <sup>3</sup>	6 <sup>3</sup>
Number of starts per lifespan	8760	6570
Reference flow for AGM	1.141 55e-4	1.522 07e-4
Lifespan of an Gel Battery (Years)	20 <sup>3</sup>	15 <sup>3</sup>
Number of starts per lifespan	21900	16425
Reference flow for Gel	4.566 21e-5	6.088 28e-5

<sup>1</sup> <http://www.tunis.climatemps.com/temperatures.php>

<sup>2</sup> <https://www.climatestotravel.com/climate/tanzania>

<sup>3</sup> <https://www.victronenergy.fr/upload/documents/Datasheet-GEL-and-AGM-Batteries-FR.pdf>

pan of the battery and increases the reference flows. All collected data were adjusted to the FU. The 14 operational scenarios were modelled using the openLCA 1.7 software and the ecoinvent 3.3 (Wernet et al., 2016) life cycle inventory database for the environmental assessment, and the Social Hotspot Database SHDB (Norris et al., 2013) for the social assessment. The economic assessment was done using a life cycle costing LCC approach (Woodward, 1997). The costs were computed per life cycle phase. Environmental and social life cycle inventories as well as computed net costs are provided in Annex A. In fact, the flows are computed per  $LCP_i$  for each scenario on the basis of the FU and the reference flows given in Table 5.7.

The potential environmental impacts are computed using the life cycle impact assessment method IMPACT World+ (Bulle et al., 2012) that provides three endpoint indicators:  $EA_1$ : Human Health,  $EA_2$ : Ecosystem Quality,  $EA_3$ : Ecosystem Services and Resources as shown in Figure

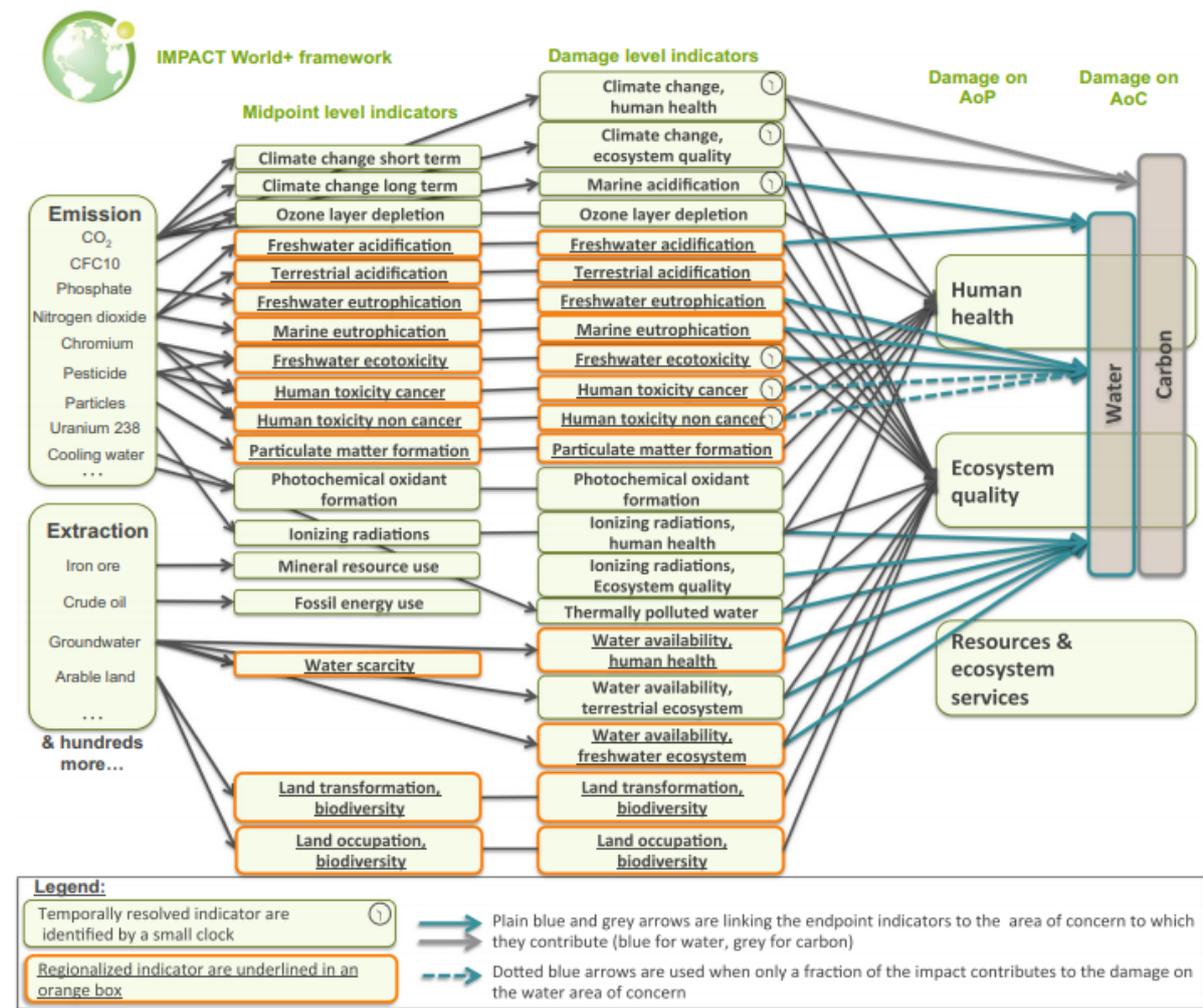


Figure 5.3: Impact World+ framework (Bulle et al., 2019)

### 5.3 .

Although the characterization model for the third indicator is still unavailable, this method was chosen since most of the midpoint impact categories have been spatially resolved and all the long-term impact categories have been temporally resolved in accordance to the ISO14040 (ISO, 2006a) and ISO14044 (ISO, 2006b) standards. Also, this method includes the most recent updates of environmental models and it is considered as the most complete impact method. The social impact method provides five categories indicators:  $SA_1$ : Labor rights and decent works,  $SA_2$ : Human rights,  $SA_3$ : Health and safety,  $SA_4$ : Governance, and  $SA_5$ : Community infrastructure (See Figure 5.4).

The economic indicator was calculated as costs required at each LCP: ECA: Net costs. It is important to note that both  $EA_1$ : Human health and  $SA_3$ : health and safety represent the impacts

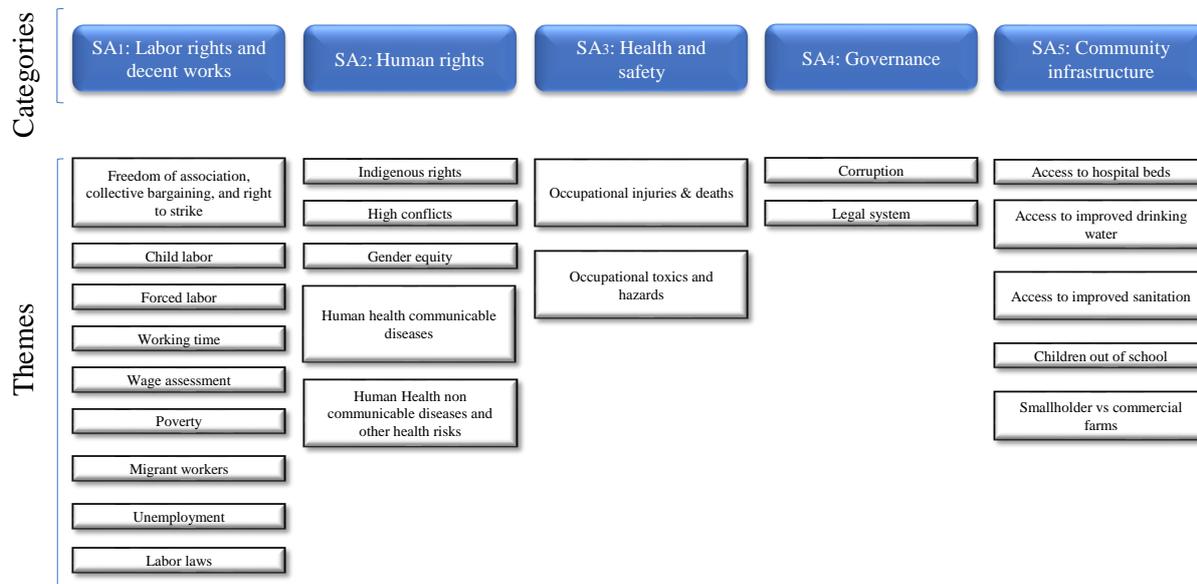


Figure 5.4: SHDB themes and categories

on human health. However, they assess two different sub-categories. In fact,  $EA_1$  considers the impacts associated to the emissions on the environment outside the company. We can mention some examples such as global warming, particulate matters, and ozone layer depletion..etc. The social category  $SA_3$  focuses only on the occupational health and safety of employees during the working hours. It is composed of two sub-categories namely: “Occupational injuries and deaths”, “Occupational toxics and hazards”.

## 5.5.1 Environmental impacts assessment

### 5.5.1.1 Human Health

Figure 5.5 presents the results for the Human Health indicator for the 14 scenarios per life cycle phase.

As shown,  $LCP_2$  is the most contributing phase, followed by  $LCP_4$ . These results essentially depend on battery technology and lifespan. Focusing on  $LCP_2$ , the amount of electricity consumed during the assembly is higher if the ABS plastic is used for the container and covers instead of the PP. Also, Tanzanian electricity contributes more to the Human health indicator than Tunisian electricity ( $4.73e-5$  DALY/kWh compared to  $8.19e-6$  DALY/kWh).

$OS_9$  and  $OS_{11}$  obtained the highest results for  $LCP_2$ , as for both scenarios, the battery is manufactured and used in Tanzania, with the AGM technology and ABS container and covers. For  $LCP_4$ , all scenarios obtained very similar results, with minor differences due to the slightly

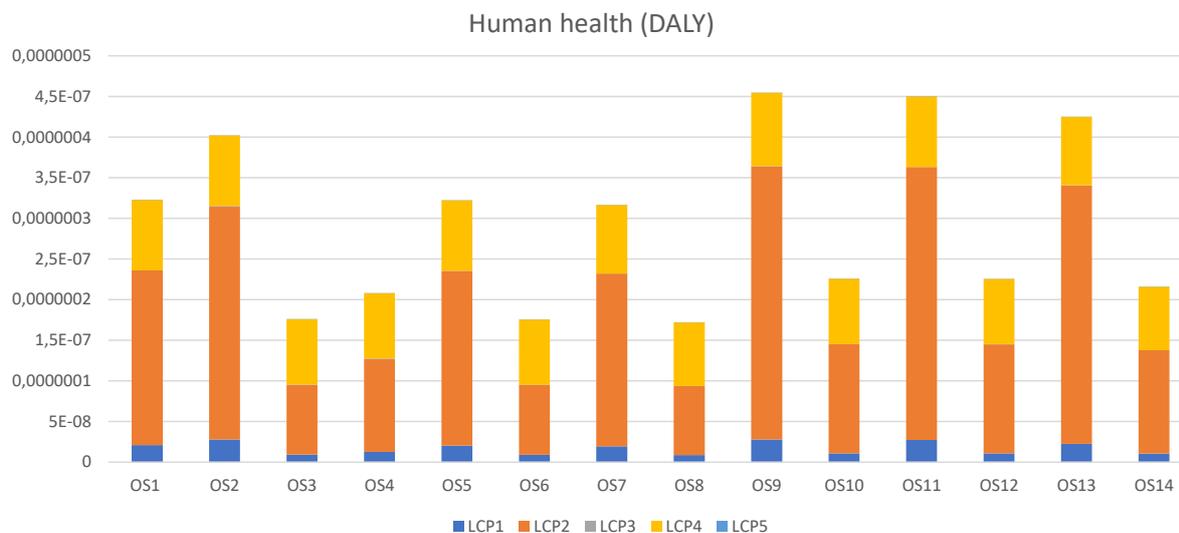


Figure 5.5: Life cycle phases contributions of the scenarios to the human health impact

heavier AGM battery with ABS container and covers. The same use transport distance (10 km) was considered for all scenarios.

From a human health perspective,  $OS_3$ ,  $OS_6$ , and  $OS_8$  are the best scenarios having the design alternative  $A_{112}$ : Gel technology which is characterized by a longer lifespan.

### 5.5.1.2 Ecosystem Quality

Figure 5.6 presents the results for the Ecosystem Quality indicator for each scenario.

As shown,  $LCP_4$  is very clearly the main contributor for all scenarios, due to fuel consumption emissions. Again, the differences between scenarios are due to the difference in battery mass, which depends on the choice of technology and type of plastic used for the container and covers. Overall,  $OS_3$ ,  $OS_4$ ,  $OS_6$ , and  $OS_8$  are the best scenarios from an ecosystem quality perspective.

### 5.5.2 Economic assessment

Figure 5.7 presents the calculated costs for each scenario per life cycle phase.

As shown, for the 6 scenarios characterized by a use in Tunisia ( $OS_1$ ,  $OS_3$ ,  $OS_5$ ,  $OS_6$ ,  $OS_7$ ,  $OS_8$ ),  $LCP_4$  has a significant contribution due to the higher cost of fuel in Tunisia, which has increased in the last two years.  $LCP_3$  is the major contributor for the  $OS_2$  and  $OS_4$  scenarios due to shipment costs from Tunisia to Tanzania. In addition, the cost difference between scenar-

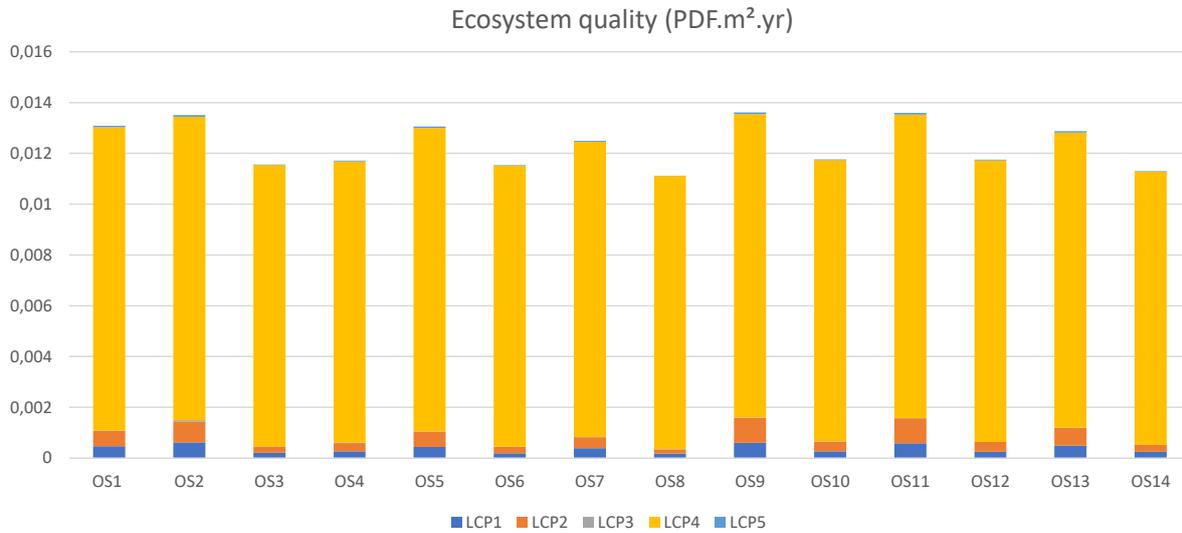


Figure 5.6: Life cycle phases contributions of the scenarios to the ecosystem impact

ios with the same distribution process is due to the battery added value computed as a cost paid by distributors. This added value depends on the technology (the Gel battery is more expensive than the AGM one, ABS plastic costs more than PP), and the production site (The price of batteries manufactured in Tanzania is higher than locally manufactured batteries). Finally, most of scenarios have significant costs during  $LCP_1$ , divided between material and transportation costs. Therefore, the global results depend on the technology, the country of manufacture, the use and the lifespan of the battery, as they affect all other parameters. Since Tanzania is geographically far from Tunisia, the transportation costs from China or Turkey are more significant if the production site is in Tanzania. In conclusion,  $OS_2$  is the most expensive scenario where  $LCP_3$  is the major contributor due to transportation costs from Tunisia to Tanzania. In addition, due to the shorter battery lifespan in Tanzania,  $LCP_1$  contributes 33% more than for  $OS_1$ . This also influences transportation costs during  $LCP_3$  in the case of  $OS_2$ .

It is important to note that all scenarios having the design alternative  $A_{112}$ : Choice of the gel technology  $OS_3$ ,  $OS_4$ ,  $OS_6$ ,  $OS_8$ ,  $OS_{10}$ ,  $OS_{12}$  and  $OS_{14}$  are the best ones from environmental perspective. The lifespan of the gel battery is the main factor that reduced the potential impacts for these scenarios. Moreover,  $OS_{10}$ ,  $OS_{12}$  and  $OS_{14}$  are the best scenarios from a cost perspective, due to low costs of manufacturing, distribution and use in Tanzania.

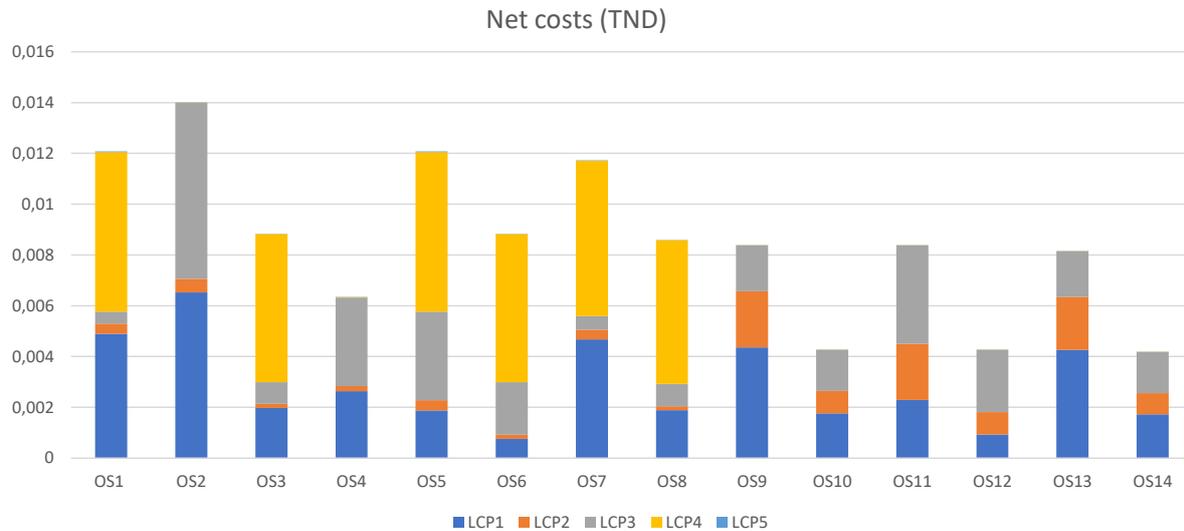


Figure 5.7: Nets costs of the scenarios computed per life cycle phases

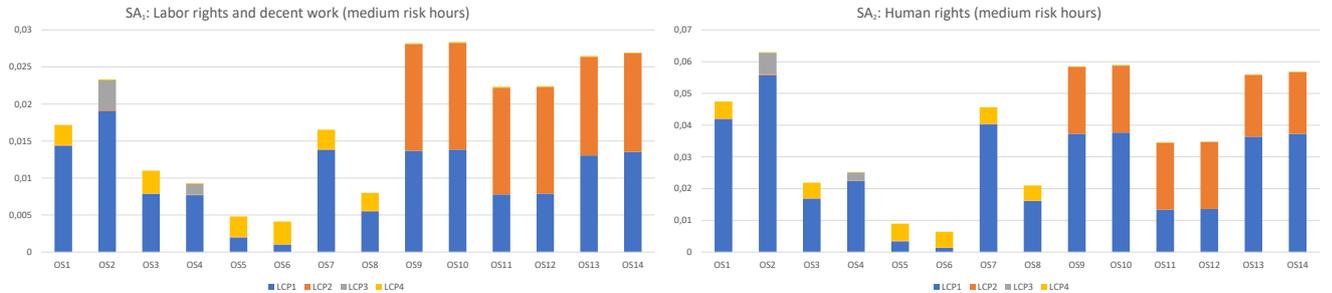
### 5.5.3 Social assessment

A total of 5 indicators, distributed across five social categories were assessed using the SHDB. By default, the database translated data associated with the indicators pertaining to the five social categories into 4 specific risk levels, ranging from very low to very high risk. The results were provided as a measure of medium risk equivalent hours of work, called work hours at risk, for each Country-Specific Sector (CSS) within the product system. Higher levels of work hours at risk in a CSS typically indicate higher level of potential social impacts in that specific location in the life cycle.

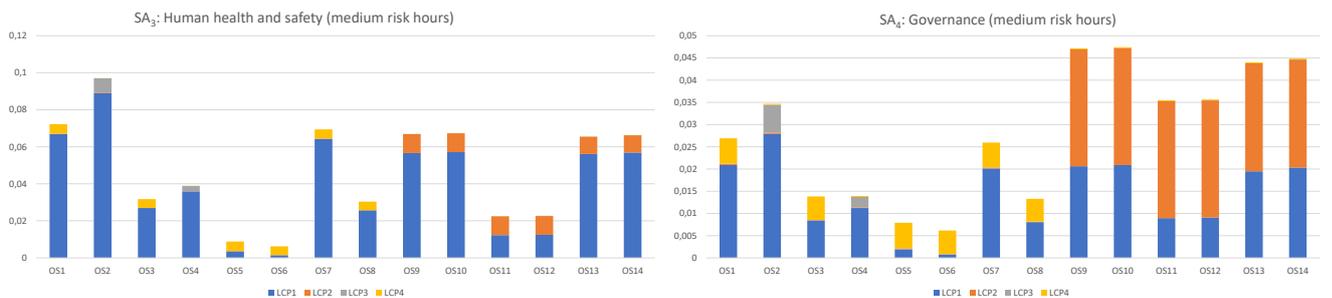
In this case study, the key life cycle phases unfold in four countries; materials' production occurs in China and Turkey, and the manufacturing phase, the distribution, the use and end of life occur in Tunisia and Tanzania (See Table 5.5 and 5.6). Figure 5.8 analyzes the contribution of each life cycle phase to the work hours at risk for the five social categories  $SA_1$ ,  $SA_2$ ,  $SA_3$ ,  $SA_4$ ,  $SA_5$  for each operational scenario.

The main takeaways from these results are:

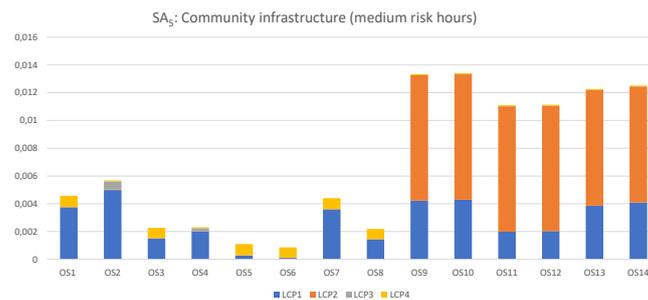
- In all five social categories,  $OS_5$  and  $OS_6$  have the lowest numbers of work hours at risk followed by  $OS_3$  and  $OS_4$ . Meanwhile,  $OS_9$  and  $OS_{10}$  have the highest numbers of work hours at risk.  $OS_{11}$  and  $OS_{12}$  have lower work hours at risk than  $OS_{10}$ . However, the contribution of these scenarios to the social impacts is still significant.



(a) Work hours at risk of each life cycle phase per operational scenario for the labor rights and decent work category (b) Work hours at risk of each life cycle phase per operational scenario for the human rights category



(c) Work hours at risk of each life cycle phase per operational scenario for the human health and safety category (d) Work hours at risk of each life cycle phase per operational scenario for the governance category



(e) Work hours at risk of each life cycle phase per operational scenario for the community category

Figure 5.8: Social impacts assessment

- For each operational scenario, all phases have approximately the same percentage of contribution to the work hours at risk for the five social categories. However, it should be noted that the absolute number of work hours at risk vary greatly from one social category to another, as illustrated by the different result scales. For example,  $SA_3$ 's (Human Health and Safety) highest work hours at risk result is 0.1, while  $SA_5$  (community infrastructure) has the lowest values of work hours at risk, the highest contribution is at 0.014.
- Overall, the extraction of raw material phase  $LCP_1$  has an important contribution to the work hours at risk for all five social categories, except in scenarios  $OS_5$  and  $OS_6$ . The main hotspot in this phase is the CSS “*Water transport/China*” and its upstream. It contributes to more than 50% of total work hours at risk. In the case of  $OS_5$  and  $OS_6$ ,  $LCP_1$  has a limited contribution to the work hours at risk. The main contributor to  $LCP_1$  in these operational scenarios is also the sector “*Water transport*” but the country is Turkey rather than China. Its contribution is around 30%. The 20% difference between both CSS (“*Water transport/China*” and “*Water transport/Turkey*”) is due to the difference in the import's distance. This translates into more hours of work for the sector in China, this ultimately affecting the total work hours at risk for the CSS. For scenarios  $OS_5$  and  $OS_6$ , the use phase  $LCP_4$  is the main contributor to the work hours at risk, where the CSS “*Petroleum, coal products/Tunisia*” contributes to approximately 60% of the work hours at risk.
- A contribution of the distribution phase  $LCP_3$  is seen in the cases of  $OS_2$  and  $OS_4$ . The main contributor is the CSS “*Water transport/Tunisia*”, with a contribution of about 20 to 30% except for the subcategory unemployment that exceeds 50% for both scenarios.
- For operational scenarios  $OS_9$ ,  $OS_{10}$ ,  $OS_{11}$ ,  $OS_{12}$ ,  $OS_{13}$ ,  $OS_{14}$ , the highest level of work hours at risk is seen in the manufacturing phase  $LCP_2$ , except for  $SA_3$  (Human health and safety) where  $LCP_1$  has the highest contribution. The subcategory “*Occupational toxics and hazards*” has a high level of work hours at risk that limited the contribution of  $LCP_2$  in this social category. For  $SA_1$  (Labor rights and decent work),  $SA_2$  (Human rights),  $SA_4$  (Governance), and  $SA_5$  (Community infrastructure), the contribution of  $LCP_2$  exceeded 50%. The CSS responsible for this significant contribution to the work hours at risk is “*Water /Tanzania*” with an average of 33.74%. This CSS comprises the collection, the purification and the distribution of water. In Tanzania, the water sector has a significant level of work hours at risk compared to the other CSS modelled in  $LCP_2$ . The CSS

behind this contribution is “*Construction/TZ*” which represents an average of 22% of the work hours at risk and the CSS “*Commerce/TZ*” with an average of 18% of the overall contribution. In the cases of  $OS_1$ ,  $OS_2$ ,  $OS_3$ ,  $OS_4$ ,  $OS_5$ ,  $OS_6$ ,  $OS_7$ , and  $OS_8$ ,  $LCP_2$  has a negligible contribution to the work hours at risk (0.7%). Hence, the main factor of the variation of the  $LCP_2$ 's contribution is the country of the manufacturing site. Changing the site from Tunisia to Tanzania increases significantly the contribution of  $LCP_2$ .

With regard to the main objective of the proposed model, which is to identify the best operational scenarios, the main conclusion derived from the social analysis is that  $OS_5$  and  $OS_6$  are the best operational scenarios from a social perspective. In comparison with other scenarios, the contribution of  $LCP_1$  in  $OS_5$  and  $OS_6$  is reduced by more than 50%. The contribution of  $LCP_2$  is negligible since the manufacturing site is in Tunisia for both scenarios. The main contributing phase is  $LCP_4$ . Within it, it is the CSS “*Water transport/Turkey*” and its upstream that contributes the most (60%) to the work hours at risk. However, it is not this CSS itself that is the main contributor, but rather the CSS “*Commerce/Turkey*” located in its upstream.

The selection of the optimal scenario at this level is not an easy task due to the diversity of impacts. It is necessary to compute a single score for each operational scenario through a multi-criteria decision support system using the Choquet integral to rank the scenarios in order to choose pertinent ones and the fuzzy ANP to select the optimal operational design scenario.

## 5.6 Selection of pertinent operational scenarios

In order to reduce the number of scenarios, the Choquet integral is used to select the most relevant ones on the basis of the impacts assessment results (see section 5.5). First, it is necessary to normalize the impact values by computing the partial scores  $PS_i$  using equation 4.4. To this end, the decision maker defined the following judgments intervals for each attribute  $[V_{low}, V_{high}]$ :  $EA_1$ : Human Health =  $[1.72e-7, 4.55e-7]$  DALY,  $EA_2$ : Ecosystem Quality =  $[1.11e-2, 1.36e-2]$  PDF.m<sup>2</sup>.yr,  $ECA$ : Net costs =  $[4.18e-3, 1.40e-2]$  TND,  $SA_1$ : Labor and decent work =  $[4.13e-3, 2.84e-2]$  medium risk hours,  $SA_2$ : Human rights =  $[6.38e-3, 6.30e-2]$  medium risk hours,  $SA_3$ : Human health and safety =  $[6.20e-3, 9.71e-2]$  medium risk hours,  $SA_4$ : Governance =  $[6.18e-3, 4.74e-2]$  medium risk hours,  $SA_5$ : Community infrastructure =  $[8.64e-4, 1.34e-2]$  medium risk hours. The  $PS_i$  are presented in Table 5.8.

The next step is to compute the Choquet integral for each scenario using the kappalab package (Grabisch et al., 2008). In fact, the Kappalab package, also called laboratory for capacities, is a toolbox for capacity simulation used as a package for the R software (i.e. Free software

Table 5.8: Partial scores computed for each scenario

OS	Environmental attributes (EA)		Economic attributes (ECA)	Social attributes (SA)				
	Human health	Ecosystem quality	Net costs	Labor rights and decent Work	Human rights	Health and safety	Governance	Community infrastructure
OS <sub>1</sub>	0.4662	0.2097	0.1962	0.4614	0.2748	0.2743	0.4973	0.7036
OS <sub>2</sub>	0.1854	0.0365	0.0000	0.2086	0.0000	0.0000	0.3092	0.6153
OS <sub>3</sub>	0.9860	0.8255	0.5268	0.7170	0.7262	0.7193	0.8144	0.8880
OS <sub>4</sub>	0.8727	0.7591	0.7807	0.7858	0.6669	0.6402	0.8135	0.8847
OS <sub>5</sub>	0.4685	0.2264	0.1962	0.9718	0.9543	0.9710	0.9580	0.9814
OS <sub>6</sub>	0.9870	0.8297	0.5268	1.0000	1.0000	1.0000	1.0000	1.0000
OS <sub>7</sub>	0.4887	0.4453	0.2315	0.4882	0.3059	0.3045	0.5207	0.7169
OS <sub>8</sub>	1.0000	1.0000	0.5514	0.4408	0.7423	0.7343	0.8275	0.8954
OS <sub>9</sub>	0.0000	0.0000	0.5720	0.0064	0.0781	0.3325	0.0061	0.0049
OS <sub>10</sub>	0.8097	0.7372	0.9907	0.0000	0.0716	0.3272	0.0000	0.0000
OS <sub>11</sub>	0.0159	0.0123	0.5720	0.2494	0.5009	0.8201	0.2892	0.1836
OS <sub>12</sub>	0.8101	0.7494	0.9907	0.2451	0.4978	0.8186	0.2857	0.1798
OS <sub>13</sub>	0.1047	0.3020	0.5953	0.0778	0.1233	0.3472	0.0823	0.0900
OS <sub>14</sub>	0.8445	0.9325	1.0000	0.0582	0.1080	0.3387	0.0621	0.0706

environment for statistical computing). Kappalab is widely used in decision making and frequently used to compute the Choquet integral of alternatives. This toolbox is composed of four main routines to identify capacities based on initial preferences of decision makers. In this context, the decision maker decided to rank the scenarios in a preference order based on the number of  $PS_i$  above 0.5. Thus, the operational scenarios have been classified as follows: ( $OS_6 > OS_8 > OS_3 > OS_4 > OS_5 > OS_{12} > OS_{10} > OS_{11} > OS_{14} > OS_7 > OS_{13} > OS_9 > OS_1 > OS_2$ ) where the attributed desired scores are respectively: Overall = [0.95, 0.9, 0.85, 0.8, 0.75, 0.7, 0.65, 0.6, 0.55, 0.5, 0.45, 0.4, 0.35, 0.3].

The next step is to create 14 R vectors representing the operational scenarios.

```

> OS1 <- c(0.4662, 0.2097, 0.1962, 0.4614, 0.2748, 0.2743, 0.4973, 0.7036)
> OS2 <- c(0.1854, 0.0365, 0, 0.2086, 0, 0, 0.3092, 0.6153)
> OS3 <- c(0.986, 0.8255, 0.5268, 0.717, 0.7262, 0.7193, 0.8144, 0.888)
> OS4 <- c(0.8727, 0.7591, 0.7807, 0.7858, 0.6669, 0.6402, 0.8135, 0.8847)
> OS5 <- c(0.4685, 0.2264, 0.1962, 0.9718, 0.9543, 0.971, 0.958, 0.9814)
> OS6 <- c(0.987, 0.8297, 0.5268, 1, 1, 1, 1, 1)
> OS7 <- c(0.4887, 0.4453, 0.2315, 0.4882, 0.3059, 0.3045, 0.5207, 0.7169)
> OS8 <- c(1, 1, 0.5514, 0.8408, 0.7423, 0.7343, 0.8275, 0.8954)
> OS9 <- c(0, 0, 0.572, 0.0064, 0.0781, 0.3325, 0.0061, 0.0049)
> OS10 <- c(0.8097, 0.7372, 0.9907, 0, 0.0716, 0.3272, 0, 0)
> OS11 <- c(0.0159, 0.0123, 0.572, 0.2494, 0.5009, 0.8201, 0.2892, 0.1836)
> OS12 <- c(0.8101, 0.7494, 0.9907, 0.2451, 0.4978, 0.8186, 0.2857, 0.1798)

```

```
> OS13 <- c(0.1047,0.302,0.5953,0.0778,0.1233,0.3472,0.0823,0.09)
> OS14 <- c(0.8445,0.9325,1,0.0582,0.108,0.3387,0.0621,0.0706)
```

The symbol > represents the prompt in the R shell, the symbol <- represents the operator of assignment, and c is the R function used for vector creation (Grabisch et al., 2008). Then, to apply the least squares approaches, the 14 defined vectors should be concatenated into a 14 row matrix M using the rbind which is the matrix creation function in R.

```
> M <- rbind(OS6,OS8,OS3,OS4,OS5,OS12,OS10,OS11,OS14,OS7,OS13,OS9,OS1,OS2)
```

At this stage, the decision maker should provide his initial preferences presented above as follows:

```
> Overall <-c(0.95,0.9,0.85,0.8,0.75,0.7,0.65,0.6,0.55,0.5,0.45,0.4,0.35,0.3)
```

Finally, least squares identification routine is called in order to compute capacities.

```
> ls<-least.squares.capa.ident(8,2,M,Overall)
```

The first argument defines the number of attributes, the second provides the desired order of k-additivity, the third presents the matrix M formed using the vectors. The last one presents the vector containing the desired preferences. The result is stored in an R list object, denoted ls.

The solution, a 2-additive capacity given under the form of its Möbius representation, can be obtained by typing:

```
> m <-ls$solution
```

Hence, the Choquet integral for each operational scenario and with respect to the computed capacity is obtained by typing:

```
> Choquet.integral(m,OSi)
```

For instance, the Choquet integral of  $OS_1$  is obtained by typing:

```
> Choquet.integral(m,OS1)
```

Table 5.9 presents the Choquet integral for the 14 operational scenarios.

Table 5.9: Choquet integral of the 14 operational scenario

Operational scenarios	$OS_1$	$OS_2$	$OS_3$	$OS_4$	$OS_5$	$OS_6$	$OS_7$	$OS_8$	$OS_9$	$OS_{10}$	$OS_{11}$	$OS_{12}$	$OS_{13}$	$OS_{14}$
Choquet integral	0.422	0.252	0.819	0.811	0.740	0.946	0.510	0.882	0.375	0.592	0.582	0.748	0.412	0.617

On the basis of these scores and the available financial and human resources, the decision maker selected the first 10 scenarios with the highest scores (i.e.  $OS_3, OS_4, OS_5, OS_6, OS_7, OS_8, OS_{10}, OS_{11}, OS_{12}, OS_{14}$ ). It is important to note that the 4 scenarios with the lowest scores have the same alternative  $A_{111}$ : *AGM technology*. Indeed, the lifespan of this battery is very low compared to Gel technology which favors this alternative in the choice of the optimal scenario. In addition to the technological criterion,  $OS_2$  had a low score due to the export of the battery to Tanzania for use which significantly increased the contribution of  $LCP_3$  to all impacts. Hence, 60% of the chosen scenarios have the alternative  $A_{311}$ : *Local distribution in Tunisia*. Moreover, the choice of the design alternative  $A_{212}$ : *Tanzanian site* increased the contribution of  $LCP_1$  to the impacts, considering the increase in the transport distance of the materials. Finally, among the scenarios having the design alternative  $A_{212}$ ,  $OS_9$  and  $OS_{13}$  had low scores due to the significant difference in battery lifespan between both technologies (see Table 5.7).

## 5.7 Choice of the optimal scenario

To choose the optimal scenario among the 10 relevant ones, the first step is to define the ANP structure of our decision support system using the software Super decisions (T. Saaty & William, 2004) that can model the clusters and their related nodes as shown in Figure 5.9. The first cluster represents the goal that contains the node “Optimal scenario selection”. The second cluster contains 5 nodes, representing each phase of the battery’s life cycle. The redundant arrow represents the dependency between the 5 phases. The 3 clusters in blue shades are the sustainability attributes, 2 nodes for the environmental attributes  $EA_1$  and  $EA_2$ , one node for the

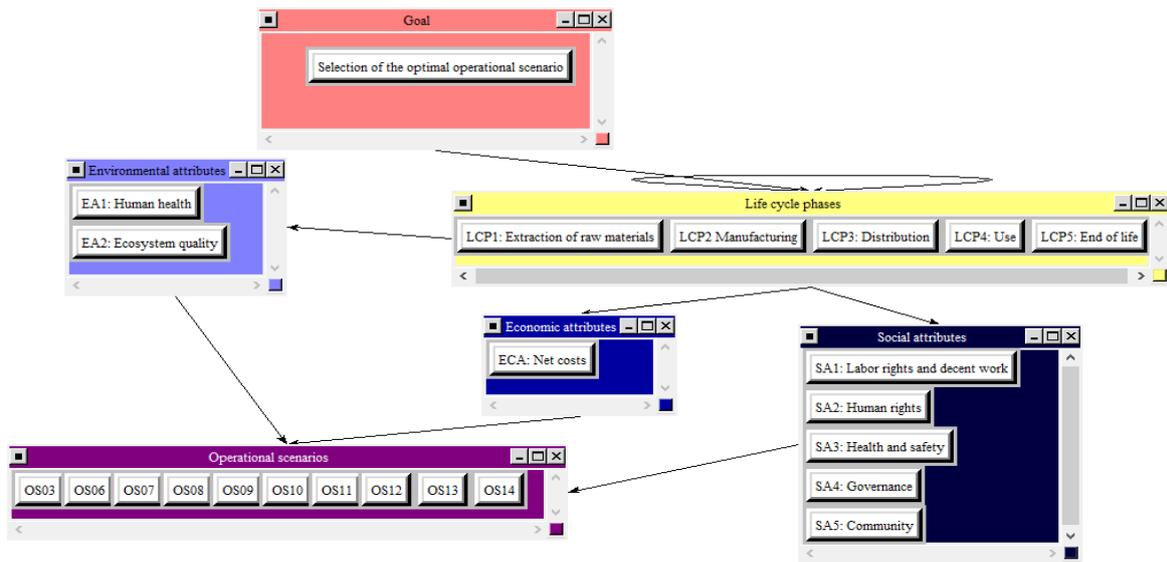


Figure 5.9: The ANP structure of the model

Table 5.10: Weights of the sustainability attributes per life cycle phase

Attributes/Life cycle phases	$LCP_1$	$LCP_2$	$LCP_3$	$LCP_4$	$LCP_5$
$EA_1$	0.097118	0.054218	0.058305	0.095143	0.610568
$EA_2$	0.095833	0.124295	0.20779	0.207853	0.270108
$ECA$	0.141575	0.033597	0.171994	0.047252	0.119324
$SA_1$	0.036424	0.14168	0.092887	0.048809	
$SA_2$	0.026284	0.123356	0.084651	0.183078	
$SA_3$	0.066155	0.376335	0.306391	0.327722	
$SA_4$	0.344791	0.110991	0.046647	0.059478	
$SA_5$	0.191821	0.035527	0.031336	0.030664	

economic attribute  $ECA$ , and 5 nodes for the social attributes  $SA_1$ ,  $SA_2$ ,  $SA_3$ ,  $SA_4$ , and  $SA_5$ . The last cluster contains 10 nodes representing the 10 relevant scenarios.

The next step is to perform a pairwise comparison between the attributes with respect to each life cycle phase. The comparison matrices were constructed on the basis of the TFNs' scale presented in Table 4.4 (Safaei et al., 2013) using the matrix form 4.10. The weights relative to each attribute are computed using equation 4.11 and presented in Table 5.10.

It is important to note that due to the unavailability of data, the end of life phase  $LCP_5$  was not modelled with the SHDB. As shown in Table 5.10, each attribute has different weights for each life cycle phase. In fact, the decision-maker's judgments were derived from the conjunction of the external and internal issues of TUNISTAR Battery and the requirements of the stakeholders as detailed in Table 5.5. Indeed, for  $LCP_1$ , the attack strategy was the minimization of supply in terms of costs derived from the combination of  $[ST_3 + ST_5 + ST_{10} + ST_{11}] + OP_2$  and  $REQ_{23} + REQ_{24}$ . The survival strategy was the consideration of regulatory constraints gen-

erated from the combination of  $[WE_1 + WE_4] + [TH_9 + TH_3]$  and  $REQ_2 + REQ_7$ . Hence, the  $EA_1, EA_2, ECA, SA_4$  and  $SA_5$ , are the most important compared to the remaining attributes.

For  $LCP_2$ , the company had two main strategies. The survival strategy was to ensure the safety, stability and health of workers by protecting them from toxic materials which is deduced from the combination of  $[WE_6 + WE_7 + WE_8] + TH_7$  and  $REQ_3 + REQ_5 + REQ_6 + REQ_{12} + REQ_{13} + REQ_{11}$ . The attack strategy was the minimization of waste from the manufacturing process that can affect the quality of ecosystems generated from the combination of  $[ST_5 + ST_6 + ST_{11}] + OP_{10}$  and  $REQ_1 + REQ_4$ . In this case, the indicators  $SA_1, SA_2$ , and  $SA_3$ , are the most important ones followed by  $EA_2$ .

During  $LCP_3$ , the defense strategy was to optimize the distribution modes in terms of costs and the impact on the ecosystem quality combining  $[WE_2 + WE_3 + WE_{11}] + OP_4$  and  $REQ_9 + REQ_{20} + REQ_{21}$ . The decision maker assigned a significant importance to  $EA_2$  and  $ECA$ . Also, it is necessary that the company ensures the safety of the carrier which justifies the important weight granted to  $SA_3$ .

During the  $LCP_4$  phase, the company took into consideration the threats of parallel battery market competitors issued from the attack and adjustment strategy deduced from  $[ST_1 + ST_2 + ST_9 + ST_7 + ST_{12}] + [OP_{11} + [TH_5 + TH_4]]$  and  $REQ_{14} + REQ_{15} + REQ_{16} + REQ_{17} + REQ_{18} + REQ_{19} + REQ_{22}$ . To this end, TUNISTAR Battery must ensure the quality of the battery for a longer lifespan and must offer competitive selling prices. It must also take into consideration the protection of the user during the use of the battery. Thus, indicators  $SA_2, SA_3, EA_1$  and  $EA_2$  were the most important ones.

Finally, given the lack of data for  $LCP_5$ , the company's attack strategy of the combination  $[ST_{10} + ST_4] + OP_8$  and  $REQ_{10} + REQ_8$  was to choose recyclable materials and packaging which justifies the significant weights attributed to  $EA_1$  and  $EA_2$ . The following step is to compare the 10 scenarios with respect to each attribute per life cycle phase. The comparison was mainly based on the impact assessment results (See section 5.5). Hence, 35 comparison matrices were constructed and the related weights were computed using equation 4.11. Table 5.11 presents the weights relative to the scenarios per life cycle phase.

Each life cycle phase has an optimal scenario. For example,  $OS_6$  is the optimal scenario for  $LCP_1$  followed by  $OS_5$ . Indeed, these two scenarios have the same alternative  $A_{142}$ : *Import Turkey* compared to other scenarios having the alternative  $A_{141}$ : *China Import*. The significant difference in the supply distance affected the values of the impact indicators. Also, the factor increasing the score of  $OS_6$  compared to  $OS_5$  is the choice of the Gel technology (see table 5.7).  $OS_8$  is the optimal scenario for  $LCP_2$ , this scenario is distinguished by the choice of the type

Table 5.11: Weights of scenarios per life cycle phase

$OS_j/LCP_i$	$LCP_1$	$LCP_2$	$LCP_3$	$LCP_4$	$LCP_5$
$OS_3$	0.0925	0.1928	0.1151	0.0492	0.1155
$OS_4$	0.0502	0.1255	0.0179	0.2141	0.0812
$OS_5$	0.1589	0.0817	0.0339	0.0291	0.0305
$OS_6$	0.2837	0.1838	0.0808	0.0492	0.1111
$OS_7$	0.0298	0.0944	0.0695	0.0373	0.0573
$OS_8$	0.1253	0.2154	0.1226	0.0677	0.3162
$OS_{10}$	0.0430	0.0273	0.1541	0.1379	0.0716
$OS_{11}$	0.0732	0.0185	0.1154	0.0994	0.0233
$OS_{12}$	0.0964	0.0272	0.1479	0.1314	0.0734
$OS_{14}$	0.0469	0.0335	0.1428	0.1847	0.1199

of PP plastic whose electricity consumption during the manufacturing process is low compared to ABS.  $OS_{10}$  is the optimal scenario for  $LCP_3$ . The weight of the battery and the distribution costs influenced the score. The gel battery is lighter than the AGM battery and the distribution costs in Tanzania are lower than those in Tunisia, which distinguishes the scenarios with the alternative  $A_{333}$ : *Distribution in Tanzania* (see table 5.10).

During the use phase  $LCP_4$ ,  $OS_4$  has the best score followed by scenarios having the alternative  $A_{434}$ : *lifespan of Gel in Tanzania*. Finally,  $OS_8$  is the best scenario for  $LCP_5$ . Due to the unavailability of data, the variation of the results is limited to the quantity of the waste which favors  $OS_8$  and  $OS_{14}$  having the minimum quantity of waste. The minimal difference between the two scores is due to the preference of the decision maker to choose the production and distribution in Tunisia rather than Tanzania.

To compute the final score, the weights of each operational scenario (see table 5.11) must be multiplied by the weights of the life cycle phases. However, it is necessary to highlight the dependencies between the phases of life cycles. First, a comparison matrix of the life cycle phases with respect to the goal was constructed using the matrix form (equation 4.10).

$$\tilde{M} = \begin{pmatrix} (1, 1, 1) & (\frac{1}{5}, \frac{1}{3}, 1) & (3, 5, 7) & (\frac{1}{9}, \frac{1}{7}, \frac{1}{5}) & (1, 3, 5) & 0.1176 \\ (1, 3, 5) & (1, 1, 1) & (5, 7, 9) & (\frac{1}{7}, \frac{1}{5}, \frac{1}{3}) & (3, 5, 7) & 0.2211 \\ (\frac{1}{7}, \frac{1}{5}, \frac{1}{3}) & (\frac{1}{9}, \frac{1}{7}, \frac{1}{5}) & (1, 1, 1) & (\frac{1}{9}, \frac{1}{9}, \frac{1}{7}) & (\frac{1}{5}, \frac{1}{3}, 1) & 0.0344 \\ (5, 7, 9) & (3, 5, 7) & (7, 9, 9) & (1, 1, 1) & (5, 7, 9) & 0.5637 \\ (\frac{1}{5}, \frac{1}{3}, 1) & (\frac{1}{7}, \frac{1}{5}, \frac{1}{3}) & (1, 3, 5) & (\frac{1}{9}, \frac{1}{7}, \frac{1}{5}) & (1, 1, 1) & 0.0633 \end{pmatrix}$$

The judgments of the decision maker were based on the life cycle assessment results. In fact,  $LCP_4$  contributes more than 90% to the impact on the Ecosystem Quality. Also, it contributes

approximately 25% to the impact on the Human Health for all scenarios. Thus,  $LCP_4$  was considered as the most important phase. In addition,  $LCP_2$  has a significant contribution of 65% to the impact on the Human Health and on the social categories in the case of scenarios where the manufacturing is in Tanzania (i.e.  $OS_{10}$ ,  $OS_{11}$ ,  $OS_{12}$ ,  $OS_{14}$ ). This phase was considered also important in the judgments. Moreover,  $LCP_1$  has a very significant contribution from a social perspective for all scenarios. Hence, this phase was taken into account in the judgments.

Second, to model the dependencies, 5 matrices were constructed to compare the 5 phases with respect to each other's on the basis of the context of TUNISTAR Battery. Each matrix compares 4 life cycle phases with respect to the fifth one. For instance,  $LCP_2$  is slightly more important than  $LCP_3$  with respect to  $LCP_1$ , means that the dependency between  $LCP_2$  and  $LCP_1$  is slightly more important than the dependency between  $LCP_1$  and  $LCP_3$ . In fact, the choice of the material affects the manufacturing process and the energy consumption while in the case of  $LCP_3$ , the parameter that influences the impacts' results is the battery mass. This latter depends only on the choice of the technology and the plastic type. This variation is almost negligible. Once identified, the 5 matrices generate the supermatrix as follows:

$$SM = \begin{pmatrix} (0, 0, 0) & (0.118, 0.161, 0.180) & (0.088, 0.099, 0.121) & (0.251, 0.263, 0.293) & (0.174, 0.204, 0.225) \\ (0.158, 0.199, 0.210) & (0, 0, 0) & (0.184, 0.212, 0.224) & (0.562, 0.563, 0.508) & (0.083, 0.095, 0.122) \\ (0.066, 0.061, 0.082) & (0.053, 0.051, 0.074) & (0, 0, 0) & (0.067, 0.055, 0.061) & (0.051, 0.046, 0.057) \\ (0.668, 0.625, 0.566) & (0.748, 0.694, 0.625) & (0.672, 0.638, 0.592) & (0, 0, 0) & (0.691, 0.655, 0.595) \\ (0.106, 0.115, 0.141) & (0.079, 0.093, 0.120) & (0.054, 0.050, 0.061) & (0.117, 0.118, 0.137) & (0, 0, 0) \end{pmatrix}$$

The elements of the supermatrix are the weights computed from the 5 matrices for each life cycle phase. The dependent weights are computed using equation 4.11 and presented in Table 5.12.

It is noted that the use phase  $LCP_4$  have the highest weight if the dependency is not considered

Table 5.12: Dependent weights of each life cycle phase

$LCP_i$	$LCP_1$	$LCP_2$	$LCP_3$	$LCP_4$	$LCP_5$
$W_{LCP}$	0.202007	0.344257	0.059522	0.286423	0.107791

in the judgments whereas, considering the dependencies,  $LCP_2$  has become more important due to the significant dependence between  $LCP_4$ ,  $LCP_1$  and  $LCP_2$ . In fact,  $LCP_4$  depends on the lifespan and the mass of the battery. These choices subsequently influence the assembly process and the amount of the consumed energy.

A consistency check is done for all matrices formed through this process using equation 4.12. The last step is to compute the overall score GS for each operational scenario using equation 4.13 as presented in table 5.13.

According to these results,  $OS_8$  is selected as the optimal operational scenario.

Table 5.13: Computed scores for each scenario

$OS_j$	$OS_3$	$OS_4$	$OS_5$	$OS_6$	$OS_7$	$OS_8$	$OS_{10}$	$OS_{11}$	$OS_{12}$	$OS_{14}$
$GS$	0.1185	0.1245	0.0738	0.1514	0.0591	0.1599	0.0746	0.0591	0.0833	0.0955

## 5.8 Evaluation of the optimal scenario

$OS_8$  is considered the optimal operational design scenario. It proposes the design alternatives listed in table 5.6. By choosing  $OS_8$ , the costs of the battery's materials were optimized offering cheaper type of plastic. The energy consumption was minimized during the manufacturing process from 7.704 to 5.393 kwh per battery. This scenario encourages the local market and offers job opportunities in Tunisia. However, if we distinguish the different scores for each life cycle phase separately,  $OS_8$  has low scores in the raw material phase  $LCP_1$ , the distribution phase  $LCP_3$  and the use phase  $LCP_4$ . In fact, as mentioned in the previous sections, the impacts indicators' values depend on the mass of the battery which is adapted to the Functional Unit FU. These parameters allow  $OS_{10}$  to have the best score thanks to the low costs of fuel in Tanzania compared to those in Tunisia. In addition, this scenario is better than  $OS_8$  socially, the work hours are higher in Tunisia than in Tanzania (an average contribution of  $LCP_3$  of 0.5% compared to 0.005% respectively) due to the variation of the number of work hours at risk required to transport the battery. Similarly,  $OS_4$  is the best scenario for  $LCP_4$ . Since the lifespan is the same in both  $OS_4$  and  $OS_8$ , the choice of the country is responsible for the contribution rate. Also, the cost computed in  $LCP_4$  are low in case of  $OS_4$  compared to  $OS_8$  ( $1.1808e-5$  TND compared to  $5.6585e-3$  TND).

From this analysis, we can deduce that the choice of the optimal scenario varies according to the life cycle phases. The implementation of the proposed model was validated and its effectiveness was proved through the ability to select one optimal scenario. The second advantage of the selection model is the possibility to detect and identify the hot spots in each life cycle phase in order to optimize the potential impacts of  $OS_8$ . Thus, it is possible to define an optimal combination of design alternatives which leads to an ideal design operational scenario. For example, it is possible to optimize the contribution of  $OS_8$  to the impacts in  $LCP_1$  by changing the alternative  $A_{141}$ : *China import* to  $A_{142}$ : *Turkey import*. For  $LCP_3$  and  $LCP_4$ , the choice of Tanzania as the country for distribution and use reduce the impacts in both phases. To this end, it is possible to change  $A_{211}$ : *Tunisian site* by  $A_{212}$ : *Tanzanian site*. However, this modification will increase the contribution of  $LCP_1$  to the impacts significantly due to the distance of the material's transport. In addition, if the decision maker only changes the distribution mode from

Table 5.14: The rate of decline of the contribution of  $LCP_1$  to sustainability impacts

The attributes	$EA_1$	$EA_2$	$ECA$	$SA_1$	$SA_2$	$SA_3$	$SA_4$	$SA_5$
$LCP_1$	2.99%	8.15%	62.33%	86.46%	92.02%	94.82%	91.05%	92.92%

local to export to Tanzania, the contribution of  $LCP_3$  will become significant. As a result, the decision maker decided to act only on the combination of alternatives for  $LCP_1$  to prevent the mentioned risks that will affect the rate of contribution of  $LCP_1$  and  $LCP_3$ . Table 5.14 shows the rate of decline of the  $LCP_1$ 's contribution in case of adopting the alternative  $A_{142}$ .

The contribution of  $LCP_1$  to the social categories has decreased by an average of 91.45%. Indeed, the risks associated to the CSS “Chemical, rubber, plastic products / Turkey” are low compared to the same CSS in China. The risks are evaluated at 0.02045 work hours at risk for the CSS in Turkey compared to 0.1881 work hours at risk for the one in China. Also,  $LCP_1$ 's contribution to costs has been minimized by 62.33%. In fact, optimizing the distance between the country of materials' import and Tunisia has resulted a significant reduction in the costs. This reduction offers an opportunity to increase the profit of the company from the sale of the battery since the selling price will not be modified. Hence, choosing the design alternative  $A_{142}$  has positively affected  $OS_8$  socially and economically. However, it has negligible influence on  $LCP_1$ 's contribution to environmental impacts.

## 5.9 Contributions and applicability of the proposed model

With regard to the investigations deployed and simulations undertaken in the study, we summarize in the following the contributions by considering the strategic, tactical and operational levels. Based on the results of the case study detailed through subsections 5.3 to 5.8, we confirm the strategic contribution of contextualizing sustainable design. In fact, by combining three strategic tools (i.e. SWOT, 7S, PESTEL), we were able to generate design scenarios based on the conjunction of strengths, weaknesses, opportunities and threats of the company. This contribution has led to:

- Preventing the risk of selecting incoherent, impractical, and unrealistic scenario. The selected option is mainly based on design alternatives that are already derived from the requirements, the internal and external issues of the company. In addition, these alternatives are sorted as relevant using control and influence criteria.
- Extending the types of alternatives to the external environment of the company. Indeed,

if the post-revolution situation, new regulations, social movements and investment opportunities of the 2016-2020 sustainable development plan had not been taken into consideration, TUNISTAR would have been limited to select a technological optimal scenario among the identified ones. In addition, we point out that the various possibilities identified for export, subcontracting, implementation in Tanzania, hiring and many other alternatives, have made it possible to develop sustainable design tactics by combining these strategies with the battery's life cycle phases and a multitude of alternatives.

Through this reasoning, TUNISTAR has managed to channel its tactics by adopting the principles of influence and control in the different phases of the battery life cycle. This contribution is clearly appreciated in terms of reducing the number of scenarios to 14 relevant ones. At the operational level, the contribution is focused on multi-criteria decision support. Simulations have shown that risks change significantly according to environmental, economic, and social aspects. For example, scenarios  $OS_3$ ,  $OS_6$ ,  $OS_8$  had similar results from an environmental perspective. Considering the social aspect,  $OS_6$  becomes a better choice with minimum potential impacts. Economically,  $OS_{10}$ ,  $OS_{12}$ ,  $OS_{14}$  are the best scenarios since in Tanzania, costs of manufacturing, distribution and use are very low compared to local manufacturing, distribution and use. This quantitative approach that computes 8 combined impact indicators was beneficial for the popularization of the results of each scenario, which facilitated the decision-making support process for the experts. In this operational layer, we have tested the model's ability to handle dependencies between life cycle phases as well as uncertainties related to expert judgments. For instance, we have repeated the simulations taking into consideration the following conditions:

- The dependency is considered in the simulations, the uncertainty issue is not taken into account.
- The dependency is not considered, the uncertainty issue is considered in the simulations.
- Both dependency and uncertainty issue are not considered in the decision process.

The results of these simulations are given in Table 5.15.

In the first case,  $OS_6$  has the highest score which is a logical result given that uncertainties of experts judgments are not taken into account. In fact, this scenario combines the best design alternatives such as the gel technology which has a better lifespan, an import from Turkey instead of China, and a local distribution. These design alternatives generate potentially less

Table 5.15: Comparison between the operational scenarios scores

$OS_j$	$OS_3$	$OS_4$	$OS_5$	$OS_6$	$OS_7$	$OS_8$	$OS_{10}$	$OS_{11}$	$OS_{12}$	$OS_{14}$
$GS$ (dependence/uncertainty)	0.1185	0.1245	0.0738	0.1514	0.0591	0.1599	0.0746	0.0591	0.0833	0.0955
$GS$ (dependence/No uncertainty)	0.1232	0.1275	0.0741	0.1625	0.0567	0.1588	0.0709	0.0583	0.0777	0.0903
$GS$ (No dependence/uncertainty)	0.0927	0.1613	0.0569	0.1123	0.0517	0.125	0.098	0.0741	0.0995	0.1287
$GS$ (No dependence/No uncertainty)	0.094	0.1663	0.0551	0.1162	0.0504	0.1201	0.0983	0.0744	0.0987	0.1264

environmental, economic and social impacts when combined.

In the second and third case,  $OS_4$  has the highest score. The main differences between  $OS_4$  and  $OS_6$  are:  $OS_4$  offers a distribution in Tanzania and an import from China whereas  $OS_6$  offers a local distribution and an import from Turkey. Although  $OS_6$  offers better alternatives than  $OS_4$  from a sustainability perspective, without considering the dependencies,  $LCP_4$  is the most contributory to the impacts. Therefore, this phase is considered as more important and it is the main focus of decision makers in the decision making process. To this end,  $OS_4$  is the best scenario since the use of the battery in Tanzania generates less impacts than in Tunisia especially economically and socially. Hence, the aforementioned results are considered theoretical and cannot be considered as optimal solutions. The consideration of all challenges faced at the operational level in the decision process provided results that better reflect reality taking into account that the choice of raw materials influences manufacturing processes and distribution of final products.

The aforementioned contributions that are confirmed through the case study, are also applicable for larger projects. Indeed, interesting leads and patterns can be considered in the context of sustainable development of complex product and service design. We can mention in particular the sustainable development of communities where contextualization and stakeholders are taken into account (ISO, 2016b). In this context, there are many examples, such as projects related to intelligent cities' development, the design of energy plants and the development of transport, as well as infrastructure design. It is in this perspective that strategic, tactical and operational deployment is necessary. For the proposed model, these areas of application are very significant, given the number and diversity of scenarios and the problems of their dependence with life cycle phases of products and services.

## **5.10 Conclusion**

In this chapter, we have proved the applicability and the effectiveness of the proposed model by applying it within a real case study of a local company that wishes to improve the design of its lead acid batteries from a sustainability perspective.

The context analysis had guided the decision makers into the generation of operational scenarios that are adapted to the needs and the requirements of stakeholders and company's issues. The context analysis has also facilitated the collection of the required data for the environmental, economic and social analysis.

In addition, we are able to consider all interaction between sustainability indicators, uncertainties of judgments and dependencies between the life cycle phases by applying the Choquet integral and the fuzzy ANP. Indeed, considering all these issues has prevented the decision makers of TUNISTAR from choosing an incoherent scenario which reduced the risk of additional time, investments, and more researches.

# Conclusion

In this Thesis, we have focused on the development of a generic model that aims to minimize the combined environmental, economic, and social impacts. The main interest is to contribute to the sustainable development of systems, which is nowadays an important issue on a global scale. The model combines the system approach and the product approach from a life cycle perspective. It is structured around three important levels, namely; The strategic, tactical and operational levels applied in the design of new products or services.

To achieve this objective, we have based our researches on recent international standards and relevant research works to support multi-criteria decision-making. We have been able to define the issues, research questions and guidelines for the construction of our model. With regard to the issues of sustainable design, we have chosen the complexity of the LCA, the dependencies and interactions, the maturity level of economic and social aspects, the uncertainties issues, the complexity of multi-criteria choices, and the strategic vision and contextualization of design. Based on the literature, we have also determined the principles and paradigms of sustainable design, namely, early integration, life cycle approach, multi-criteria concept, consideration of sustainability aspects and the choice of optimal design solution or scenario. Considering the literature review outlined in Chapter 2, we have detected that most of the works do not take into account all the principles mentioned above. Following this first review, we concluded that a generic model that covers all aspects of sustainability is needed.

Thus, we have pointed out and detailed guidelines for the implementation of our model. These latter have recommended the combination of the system approach and the product approach while maintaining the outline of the LCA method. The structure of the guidelines prompted us to refine our literature review to effectively identify the research questions to which it is relevant to build our model.

Thus, at the strategic level, the first question was: *Q1: How to identify internal and external*

*issues and stakeholders' requirements that can generate strategic scenarios at an advanced design stage?*

The second, which is at the tactical level, was: *Q2: How to develop tactical design criteria that are coherent with strategic scenarios per life cycle phase and how to generate diversified and significant operational scenarios?*

The last question was: *Q3: How to enable optimal design scenario selection at an early stages of design process from an environmental, economic and social perspectives?*

To answer our research questions and problems, we have articulated our model into five generic steps. The first was dedicated to the generation of strategic scenarios by considering internal and external issues as well as the expectations of relevant stakeholders of the organization that aims to design a product. In this context, we have implemented the SWOT, PESTEL and 7S methods. Then, to generate strategic design scenarios, we have established dedicated confrontation matrices.

In the second step, we have identified design tactics by identifying tactical criteria which include the functional aspects and criteria of sustainable development. They have also been defined by deploying alternatives and technological solutions by phase of the product's life cycle. The third step allows the generation of operational scenarios. They are formulated by combining design alternatives derived from contextualized strategic scenarios. In order to optimize their number, we have adopted the criteria of control and influence of organizations in the different phases of the life cycle. The fourth step was dedicated to quantifying the environmental, social and economic impacts specific to each operational scenario. This quantification was based on the LCA method using international generic databases, Ecoinvent and SHDB. This quantification was based on the choice of impact indicators whose calculation formulas are very complex and standardized by various methods available in the literature.

Given the imprecise nature of the impact indicators and the large number of design scenarios, we have dedicated the fifth and final step to the development of decision making mechanism for the optimal choice of a sustainable design operational scenario. This mechanism is based on the Choquet integral and the fuzzy ANP method combined. Both methods addressed issues of expert uncertainty, interaction between impact indicators and dependencies between phases of the product life cycle.

For the validation of our model, we have chosen to apply it for the design of a motorcycle battery for the Tunisian company TUNISTAR. Our choice for this practical case is justified first of all by the importance of the impacts related to Waste Electronic and Electrical Equipment (WEEE) and also by the significant nature of the sustainable development context in the

Tunisian socio-economic environment. Simulations and experiments were carried out within the CIRAIG in Canada, for reasons of availability and exhaustiveness of the environmental and social databases related to Tunisia and other countries included in the scenarios options. In this context, the application of our model has generated 4 types of strategic design scenarios that take into account the strengths, weaknesses, threats and opportunities as well as the expectations and needs of TUNISTAR's stakeholders. They are oriented towards the use of existing resources for supply chain optimization, appropriate technological options, distribution and use policies, taking into account parallel markets and prices.

Based on strategic scenarios, tactical criteria were identified, such as the choice of materials, the location of production sites or even the choice of suppliers and the methods of acquisition and distribution. Thus, 21 tactical criteria were proposed. Considering these criteria, the designers proposed alternatives and options for their deployment by life cycle phase. AGM and Gel technologies have been proposed, Tanzanian and Tunisian production sites, land and sea transport modes. The importing countries considered are China and Turkey. A total of 45 alternatives were identified. In summary, we were able to build a multitude of operational scenarios and reduced them to 14 scenarios considering TUNISTAR's criteria of control and influence.

For each identified scenario, an environmental and social life cycle analysis were carried out as well as cost calculations by life cycle phase. A total of 8 indicators were quantified; 2 environmental indicators, 1 economic indicator and 5 social indicators. Through these simulations, we were able to deduce that scenarios characterized by a Gel battery technology and local manufacturing, distribution and use, are the best scenarios from an environmental perspective. Indeed, the impact on human health has been reduced by more than 40% thanks when selecting these scenarios compared to the first basic one  $OS_1$  scenario which is based on the choice of the AGM technology.

On the other hand, from an economic point of view, the results showed that scenarios that are also characterized by the choice of gel technology but whose manufacturing, distribution, use and end of life are in Tanzania, are the best ones. Costs have been reduced by 65% compared to  $OS_1$ . This is due to the difference in living standards between Tunisia and Tanzania. Indeed, according to the results of cost calculations, the use phase is the most impacting, especially in Tunisia. This is due to the difference in fuel prices.

Socially, scenarios that offer an import from Turkey and a local manufacturing, distribution, use and end of life are the optimal ones. These choices have made it possible to reduce by 50% the contribution of the extraction of raw materials phase  $LCP_1$  to social impacts. This is justified by Turkey's choice of import countries, which has significantly reduced work hours at risk. Indeed,

the impact on human health and safety has been reduced by 87% and the impact on labor and decent work has been reduced by 72%.

Despite the relevance of the results, at this stage it is impossible to choose the optimal scenario from a sustainability point of view. To this end, we reduced the number of scenarios to 10 by eliminating the worst scenarios using the Choquet integral that ranked these scenarios on the basis of a computed score. The eliminated 4 scenarios are characterized by the AGM technology choice having a shorter lifetime than the Gel option, two of which have the alternative of a manufacturing site in Tanzania. For the selection of an optimal choice, we applied the fuzzy ANP. It should be noted that the use of indicator results as a basis for judgments has significantly reduced the subjectivity of these judgments. In fact, all the comparison matrices developed are 100% consistent. Finally, based on the computed scores, the  $OS_8$  with the choice of gel technology, the type of plastic PP, local manufacturing, distribution, use and end of life was chosen as the optimal sustainable scenario. Moreover, thanks to the implementation of our proposed model, not only did TUNISTAR Battery succeed in selecting an optimal choice for the development of its product, but also, improvement paths were detected by life cycle phase. For example, this scenario could be further optimized by changing the alternative choice of the import country. By choosing Turkey, the contribution of this scenario to the social impacts during the  $LCP_1$  phase of raw material extraction decreased by approximately 91%.

From the point of view of application and applicability, the implementation of the model on a real case was successful. The comparison between the actual operational scenarios did show significant differences between the sustainable impacts of each scenario. In the absence of our approach, TUNISTAR could have been resigned to technical and economic choices and the impacts could have been more significant at the social and environmental levels. Our proposal gave the designers the opportunity to have a sustainable and contextualized design scenario.

Through this practical case, we have demonstrated that the adoption of design criteria related to the operational safety aspect is no longer sufficient. Taking into account the context of the organizations has affected design choices in a wide spectrum both in geographical and temporal space. The IMPACT WORLD+ impact assessment method was very useful for this consideration. The worst scenario having the lowest score was  $OS_2$  characterized by the AGM technology and an export to Tanzania. We have concluded that the choice of export combined with the choice of AGM technology significantly increased the contribution to the impacts in the distribution phase  $LCP_3$ , which affected the total score compared to the remaining scenarios. The choice of this scenario increases the contribution of the distribution phase by 87% to the impact on human health, 83% to the impact on ecosystem quality, 93% to the net costs, and 98% to

all social impacts (i.e. Labor rights and decent work, human rights, human health and safety, governance and community infrastructure).

In terms of the duration and complexity of the implementation of the model, the majority of the time was spent on collecting data for the different operational scenarios and alternatives. As for the complexity of implementation, it has been facilitated by the use of dedicated software, namely OpenLCA and superdecisions for ANP. The actual duration for the design choice was one year. However, this criterion is not the most important one if we consider the organizational and technical knowledge base acquired by TUNISTAR.

The application of the model is also effective for more complex cases where the impacts are very significant. We mention the development of cities with transport networks, health services or even the sizing of nuclear or other power plants. The advantages of our model are its ability to create contextualized value within a sustainable development framework. In this context, it can be used as an argument for positive differentiation between marketed products. The final environmental, social and economic balance sheet of the design scenario can be used as a relevant sales argument for consumers and informed populations.

The prospects for this work remain certain. Indeed, the adaptive nature of the model still needs to be addressed in case of changes in input parameters. In fact, the context of organizations, issues and stakeholders' needs are changing. This contributes to an opportunity to improve our proposal by adding an artificial intelligence layer that allows the prediction of trends for a better anticipation of the impacts related to sustainable development. Yet, these improvements require knowledge management devices with large amount of data. Other future works are also interesting. They concern the improvement and extension of existing design methods from a product life cycle perspective and not only limited to the product/process design part. This is reflected in the Advanced Product Quality Planning (APQP) and QFD methods widely used in the automotive and aeronautical sectors. This will certainly lead us to create a new generation of Failure modes, their Effects and their Analysis (FMEA) and monitoring plans extended to the distribution, use and end-of-life phases of products and services.

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# **Environmental, economic and social assessments of the operational scenarios**

## **A.1 Introduction**

In this appendix, we will present the assessment of impacts of the fourteen operational scenarios. First reference flows are computed for each scenario per life cycle phase on the basis of the combined design alternatives as detailed in Table and Table . All the collected data have been processed and flows have been computed according to the reference flows calculated in Table. The openLCA has been used to assess these data and compute the impacts indicators using ecoinvent3.3 data base for environmental impacts and the social hotspot database for social impacts. The costs of the each scenario have also been computed in each life cycle phase. The computed costs represents the economic indicator. In the following sections, we will present the computed flows for each scenario. Then, we will detail the assessment results.

## **A.2 Environmental assessment: Computation of elementary flows**

Data are collected during four months in order to build the inventory. For each scenario, the quantities are normalized according to the reference flow derived from the FU “*Allowing one use of a motorcycle by starting its engine and providing energy to its electronic devices*” (See

Table 5.7). The following tables( From Table A.1 to A.14) represent the inventory data for each operational scenario that are generated using the OpenLCA software.

### **A.3 Economic Assessment: computation of net costs for each scenario**

In the following section, we will present the calculated costs for each operational design scenario per each life cycle phase. The computation of the net costs is based on data collected from the estimated costs required for the life cycle of the battery. Table A.15 details the nature of computed costs per each life cycle phase of the battery.

Hence, on the basis of the collected data, we have computed the net costs for the fourteen operational scenarios as shown in Table A.16.

### **A.4 Social assessment: Computation of the elementary flows**

In the following section, we will present the computed flows with regard to the social aspect, the used database is the social hotspot database SHDB. Due to lack of data the  $LCP_5$  phase has been eliminated from the social assessment.

### **A.5 Impact assessment results for each operational scenario**

Table A.31 presents the computed environmental, economic and social indicators as results of the impact assessment of each operational scenario. As mentioned in chapter 5, the impact assessment is performed using the OpenLCA 1.7 software. The impact assessment methods used are the Impact world+ and the social life cycle assessment.

### **A.6 Conclusion**

In this Appendix, we have detailed the inventory analysis for the environmental, economic and social assessments for the fourteen operational scenarios. All collected data have been normalized according to the identified FU. In the last section, we have presented the assessment results within a total of eight indicators for each operational scenario.

Table A.1: Environmental flows related to  $OS_1$ 

Operational Scenario $OS_1$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	5.86e-5
	Negative plates: Lead	0.540	6.16e-5
	Epoxy adhesive	0.00836	3.54e-7
	Separator: glass fibre	0.0344	3.927e-6
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	Container and covers	0.201	2.294e-5
	Lead	0.165	1.883e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	2.283e-6
	Demineralized water: water, decarbonised, at user	0.278	3.173e-5
	Sulfuric Acid	0.197	2.248e-5
	Labelling and warranty card: printed paper	0.0005	5.707e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.566	6.469e-5
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.116	1.332e-5
	Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.115	1.319e-5
Maritime Transport: From the China port to the Tunisian port (Rades) (13877 km)	17.995	2.054e-3	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	8.795e-4
Design alternatives: $A_{211}, A_{221}, A_{231}, A_{241}$	Waste packaging: waste polyethylene (kg)	0.00227	2.591e-7
	Waste packaging: waste paperboard (kg)	0.00234	2.671e-7
	Container and covers waste (kg)	0.0068	7.763e-7
	Tap water (kg)	7.875	8.99e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Lead emissions (kg)	0.0703	8.025e-6
	Sulfuric acid emissions (kg)	0.001	1.142e-7
	Wastewater, unpolluted (kg)	0.00875	9.989e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{311}, A_{321}, A_{331}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to retailers (220 km)	0.374	4.269e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{411}, A_{431}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.45e-4	2.45e-3
	Transport, passenger, motoscooter	0.0106	0.106
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{511}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	2.22e-5
	waste graphical paper	0.01773	2.02e-6
	Separator	0.0344	3.93e-6
	Labelling	0.0005	5.71e-8
	Epoxy adhesive	0.0836	9.54e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	1.88e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	1.72e-7	

Table A.2: Environmental flows related to  $OS_2$ 

Operational Scenario $OS_2$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	7.808e-5
	Negative plates: Lead	0.540	8.219e-5
	Epoxy adhesive	0.00836	1.272e-6
	Separator: glass fibre	0.0344	5.236e-6
	Container and covers	0.201	3.059e-5
	Lead	0.165	2.511e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	3.044e-6
	Demineralized water: water, decarbonised, at user	0.278	4.231e-5
	Sulfuric Acid	0.197	2.998e-5
	Labelling and warranty card: printed paper	0.0005	7.61e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.566	8.625e-5
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.116	1.776e-5
Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.115	1.759e-5	
Maritime Transport: From the China port to the Tunisian port (Rades) (13877 km)	17.995	2.739e-3	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
Design alternatives: $A_{211}, A_{221}, A_{231}, A_{241}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	1.117e-3
	Waste packaging: waste polyethylene (kg)	0.00227	3.455e-7
	Waste packaging: waste paperboard (kg)	0.00234	3.561e-7
	Container and covers waste (kg)	0.0068	1.035e-6
	Tap water (kg)	7.875	1.198e-3
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	1.07e-5	
Sulfuric acid emissions (kg)	0.001	1.522e-7	
Wastewater, unpolluted (kg)	0.00875	1.332e-6	
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{311}, A_{321}, A_{322}, A_{332}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to Tunisian port (Gabes) (334 km)	0.584	8.901e-5
	Maritime Transport: From Gabes port to Tanzanian port (Dar Es Salaam)(7906 km)	13.441	2.045e-3
		0.017	2.587e-6
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{411}, A_{433}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.45e-4	2.45e-3
	Transport, passenger, motoscooter	0.0106	0.106
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{512}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	2.96e-5
	waste graphical paper	0.01773	2.7e-6
	Separator	0.0344	5.24e-6
	Labelling	0.0005	7.61e-8
	Epoxy adhesive	0.0836	1.27e-6
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	2.51e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	2.29e-7	

Table A.3: Environmental flows related to  $OS_3$ 

Operational Scenario $OS_3$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
Design alternatives: $A_{112}, A_{123}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	2.342e-5
	Negative plates: Lead	0.540	2.466e-5
	Epoxy adhesive	0.00836	3.817e-7
	Silica fume (5% of acid quantity)	0.00985	4.498e-7
	Separator: glass fibre	0.0344	1.571e-6
	Container and covers	0.201	9.178e-6
	Lead	0.165	7.534e-6
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	9.132e-7
	Phosphoric Acid	0.197	8.995e-6
	Labelling and warranty card: printed paper	0.0005	2.283e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.571	2.607e-5
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.117	5.37e-6
	Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.0669	3.057e-6
Maritime Transport: From the China port to the Tunisian port (Rades) (13877 km)	18.131	8.279e-4	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
Design alternatives: $A_{211}, A_{222}, A_{231}, A_{242}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	3.518e-4
	Waste packaging: waste polyethylene (kg)	0.00227	1.037e-7
	Waste packaging: waste paperboard (kg)	0.00234	1.068e-7
	Container and covers waste (kg)	0.0068	3.105e-7
	Tap water (kg)	7.875	3.596e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	3.21e-6	
Phosphoric acid emissions (kg)	0.001	4.566e-8	
Wastewater, unpolluted (kg)	0.00875	3.995e-7	
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{312}, A_{321}, A_{331}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to retailers (220 km)	0.346	1.584e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{413}, A_{432}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.27e-4	2.27e-3
	Transport, passenger, motoscooter	0.00991	0.0991
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{511}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	8.87e-6
	waste graphical paper	0.01773	8.1e-7
	Separator	0.0344	1.57e-6
	Labelling	0.0005	2.28e-8
	Epoxy adhesive	0.0836	3.82e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	7.54e-7
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	6.88e-8	

Table A.4: Environmental flows related to  $OS_4$ 

Operational Scenario $OS_4$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
Design alternatives: $A_{112}, A_{123}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	3.123e-5
	Negative plates: Lead	0.540	3.288e-5
	Epoxy adhesive	0.00836	5.09e-7
	Silica fume (5% of acid quantity)	0.00985	5.997e-7
	Separator: glass fibre	0.0344	2.094e-6
	Container and covers	0.201	1.224e-5
	Lead	0.165	1.005e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	1.218e-6
	Phosphoric Acid	0.197	1.199e-5
	Labelling and warranty card: printed paper	0.0005	3.044e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.571	3.476e-5
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.117	7.16e-6
Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.0669	4.075e-6	
Maritime Transport: From the China port to the Tunisian port (Rades) (13877 km)	18.131	1.103e-3	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
Design alternatives: $A_{211}, A_{222}, A_{231}, A_{242}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	4.69e-4
	Waste packaging: waste polyethylene (kg)	0.00227	1.382e-7
	Waste packaging: waste paperboard (kg)	0.00234	1.424e-7
	Container and covers waste (kg)	0.0068	4.14e-7
	Tap water (kg)	7.875	4.795e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Lead emissions (kg)	0.0703	3.21e-6
Phosphoric acid emissions (kg)	0.001	4.566e-8	
Wastewater, unpolluted (kg)	0.00875	3.995e-7	
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{312}, A_{321}, A_{322}, A_{332}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to Tunisian port (Gabes) (334 km)	0.542	3.302e-5
	Maritime Transport: From Gabes port to Tanzanian port (Dar Es Salaam)(7906 km)	12.468	7.591e-4
	Land Transport: From Dar Es Salaam port to retailers (10 km)	0.0157	9.601e-7
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{413}, A_{434}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.27e-4	2.27e-3
	Transport, passenger, motoscooter	0.00991	0.0991
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{512}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	1.18e-5
	waste graphical paper	0.01773	1.08e-6
	Separator	0.0344	2.09e-6
	Labelling	0.0005	3.04e-8
	Epoxy adhesive	0.0836	5.09e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	1e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	9.18e-8	

Table A.5: Environmental flows related to  $OS_5$ 

Operational Scenario $OS_5$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	5.86e-5
	Negative plates: Lead	0.540	6.16e-5
	Epoxy adhesive	0.00836	3.54e-7
	Separator: glass fibre	0.0344	3.927e-6
Design alternatives: $A_{111}$ , $A_{121}$ , $A_{131}$ , $A_{132}$ , $A_{142}$	Container and covers	0.201	2.294e-5
	Lead	0.165	1.883e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	2.283e-6
	Demineralized water: water, decarbonised, at user	0.278	3.173e-5
	Sulfuric Acid	0.197	2.248e-5
	Labelling and warranty card: printed paper	0.0005	5.707e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from Turkish factory to Turkish port (Istanbul)(59 km)	0.0765	8.734e-6
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.116	1.332e-5
	Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.115	1.319e-5
Maritime Transport: From the Turkish port to the Tunisian port (Rades) (1929 km)	2.502	2.857e-4	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Design alternatives: $A_{211}$ , $A_{221}$ , $A_{231}$ , $A_{241}$	Electricity: low voltage (kwh)	7.704	8.795e-4
	Waste packaging: waste polyethylene (kg)	0.00227	2.591e-7
	Waste packaging: waste paperboard (kg)	0.00234	2.671e-7
	Container and covers waste (kg)	0.0068	7.763e-7
	Tap water (kg)	7.875	8.99e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	8.025e-6	
Sulfuric acid emissions (kg)	0.001	1.142e-7	
Wastewater, unpolluted (kg)	0.00875	9.989e-7	
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{311}$ , $A_{321}$ , $A_{331}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to retailers (220 km)	0.374	4.269e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{411}$ , $A_{431}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.45e-4	2.45e-3
	Transport, passenger, motoscooter	0.0106	0.106
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{511}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	2.22e-5
	waste graphical paper	0.01773	2.02e-6
	Separator	0.0344	3.93e-6
	Labelling	0.0005	5.71e-8
	Epoxy adhesive	0.0836	9.54e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	1.88e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	1.72e-7	

Table A.6: Environmental flows related to  $OS_6$ 

Operational Scenario $OS_6$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	2.342e-5
	Negative plates: Lead	0.540	2.466e-5
	Epoxy adhesive	0.00836	3.817e-7
	Silica fume (5% of acid quantity)	0.00985	4.498e-7
Design alternatives: $A_{112}$ , $A_{123}$ , $A_{131}$ , $A_{132}$ , $A_{142}$	Separator: glass fibre	0.0344	1.571e-6
	Container and covers	0.201	9.178e-6
	Lead	0.165	7.534e-6
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	9.132e-7
	Phosphoric Acid	0.197	8.995e-6
	Labelling and warranty card: printed paper	0.0005	2.283e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from Turkish factory to Turkish port (Istanbul)(59 km)	0.077	3.52e-6
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.117	5.37e-6
	Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.0669	3.057e-6
	Maritime Transport: From the Turkish port to the Tunisian port (Rades) (1929 km)	2.5214751	1.151e-4
		<i>LCP<sub>2</sub>: Manufacturing</i>	
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	3.518e-4
Design alternatives: $A_{211}$ , $A_{222}$ , $A_{231}$ , $A_{242}$	Waste packaging: waste polyethylene (kg)	0.00227	1.037e-7
	Waste packaging: waste paperboard (kg)	0.00234	1.068e-7
	Container and covers waste (kg)	0.0068	3.105e-7
	Tap water (kg)	7.875	3.596e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Lead emissions (kg)	0.0703	3.21e-6
	Phosphoric acid emissions (kg)	0.001	4.566e-8
	Wastewater, unpolluted (kg)	0.00875	3.995e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{312}$ , $A_{321}$ , $A_{331}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to retailers (220 km)	0.346	1.584e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{413}$ , $A_{432}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.27e-4	2.27e-3
	Transport, passenger, motoscooter	0.00991	0.0991
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{511}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	8.87e-6
	waste graphical paper	0.01773	8.1e-7
	Separator	0.0344	1.57e-6
	Labelling	0.0005	2.28e-8
	Epoxy adhesive	0.0836	3.82e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	7.54e-7
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	6.88e-8	

Table A.7: Environmental flows related to  $OS_7$ 

Operational Scenario $OS_7$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	5.86e-5
	Negative plates: Lead	0.540	6.16e-5
	Epoxy adhesive	0.00836	3.54e-7
	Separator: glass fibre	0.0344	3.927e-6
Design alternatives: $A_{111}$ , $A_{122}$ , $A_{131}$ , $A_{132}$ , $A_{141}$	Container and covers	0.155	1.769e-5
	Lead	0.165	1.883e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	2.283e-6
	Demineralized water: water, decarbonised, at user	0.278	3.173e-5
	Sulfuric Acid	0.197	2.248e-5
	Labelling and warranty card: printed paper	0.0005	5.707e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.546	6.24e-5
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.112	1.285e-5
	Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.115	1.319e-5
Maritime Transport: From the China port to the Tunisian port (Rades) (13877 km)	17.356	1.981e-3	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Design alternatives: $A_{211}$ , $A_{221}$ , $A_{232}$ , $A_{241}$	Electricity: low voltage (kwh)	5.392	6.156e-4
	Waste packaging: waste polyethylene (kg)	0.00227	2.591e-7
	Waste packaging: waste paperboard (kg)	0.00234	2.671e-7
	Container and covers waste (kg)	0.00524	5.982e-7
	Tap water (kg)	7.875	8.99e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	8.025e-6	
Sulfuric acid emissions (kg)	0.001	1.142e-7	
Wastewater, unpolluted (kg)	0.00875	9.989e-7	
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{311}$ , $A_{321}$ , $A_{331}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to retailers (220 km)	0.363	4.153e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{412}$ , $A_{431}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.38e-4	2.38e-3
	Transport, passenger, motoscooter	0.0103	0.103
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{511}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1497	1.71e-5
	waste graphical paper	0.01773	2.02e-6
	Separator	0.0344	3.93e-6
	Labelling	0.0005	5.71e-8
	Epoxy adhesive	0.0836	9.54e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0127	1.45e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	1.72e-7	

Table A.8: Environmental flows related to  $OS_8$ 

Operational Scenario $OS_8$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
Design alternatives: $A_{112}, A_{124}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	2.342e-5
	Negative plates: Lead	0.540	2.466e-5
	Epoxy adhesive	0.00836	3.817e-7
	Silica fume (5% of acid quantity)	0.00985	4.498e-7
	Separator: glass fibre	0.0344	1.571e-6
	Container and covers	0.155	7.078e-6
	Lead	0.165	7.534e-6
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	9.132e-7
	Phosphoric Acid	0.197	8.995e-6
	Labelling and warranty card: printed paper	0.0005	2.283e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.551	2.515e-5
	Land Transport: import from the Tunisian port (Rades) to the factory (Bouarada)(90 km)	0.113	5.18e-6
	Land Transport: local tunisian supplier to the factory (Bouarada)(175 km)	0.0669	3.057e-6
Maritime Transport: From the China port to the Tunisian port (Rades) (13877 km)	17.493	7.988e-4	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
Design alternatives: $A_{211}, A_{222}, A_{232}, A_{242}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	5.392	2.462e-4
	Waste packaging: waste polyethylene (kg)	0.00227	1.037e-7
	Waste packaging: waste paperboard (kg)	0.00234	1.068e-7
	Container and covers waste (kg)	0.00524	2.393e-7
	Tap water (kg)	7.875	3.596e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	3.21e-6	
Phosphoric acid emissions (kg)	0.001	4.566e-8	
Wastewater, unpolluted (kg)	0.00875	3.995e-7	
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{312}, A_{321}, A_{331}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tunisian factory to retailers (220 km)	0.336	1.537e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{414}, A_{433}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.2e-4	2.21e-3
	Transport, passenger, motoscooter	0.00962	0.0962
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{511}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1497	6.84e-6
	waste graphical paper	0.01773	8.1e-7
	Separator	0.0344	1.57e-6
	Labelling	0.0005	2.28e-8
	Epoxy adhesive	0.0836	3.82e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.01273	5.81e-7
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	6.88e-8	

Table A.9: Environmental flows related to  $OS_9$ 

Operational Scenario $OS_9$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	7.808e-5
	Negative plates: Lead	0.540	8.219e-5
	Epoxy adhesive	0.00836	1.272e-6
	Separator: glass fibre	0.0344	5.236e-6
	Container and covers	0.201	3.059e-5
	Lead	0.165	2.511e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	3.044e-6
	Deminerlized water: water, decarbonised, at user	0.278	4.231e-5
	Sulfuric Acid	0.197	2.998e-5
	Labelling and warranty card: printed paper	0.0005	7.61e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.478	7.288e-5
	Land Transport: import from the Tanzanian port (Dar es Salaam) to the factory (Tanzania)(12 km)	0.0132	2.018e-6
	Maritime Transport: From the China port to the Tanzanian port (Dar es Salaam) (9926 km)	10.877	1.655e-3
Land transport: From Local Tanzanian supplier to Tanzanian factory (5 km)	4.205e-3	6.4e-7	
Land transport: From Tunisian supplier to Tunisian port (Gabes) (400 km)	0.0082	1.248e-6	
Maritime transport: From Tunisian port to Dar es Salaam (7906 km)	0.162	2.467e-5	
Land transport: From Dar es Salaam port to Tanzanian factory (12 km)	2.481e-3	3.775e-8	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
Design alternatives: $A_{212}, A_{221}, A_{232}, A_{241}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	1.117e-3
	Waste packaging: waste polyethylene (kg)	0.00227	3.455e-7
	Waste packaging: waste paperboard (kg)	0.00234	3.561e-7
	Container and covers waste (kg)	0.0068	1.035e-6
	Tap water (kg)	7.875	1.198e-3
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	1.07e-5	
Sulfuric acid emissions (kg)	0.001	1.522e-7	
Wastewater, unpolluted (kg)	0.00875	1.332e-6	
Design alternatives: $A_{311}, A_{321}, A_{333}$	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tanzanian factory to retailers (220 km)	0.374	5.692e-5
Design alternatives: $A_{411}, A_{432}$	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.45e-4	2.45e-3
	Transport, passenger, motoscooter	0.0106	0.106
Design alternatives: $A_{512}$	<i>LCP<sub>5</sub>: End of life</i>		
	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	2.96e-5
	waste graphical paper	0.01773	2.7e-6
	Separator	0.0344	5.24e-6
	Labelling	0.0005	7.61e-8
	Epoxy adhesive	0.0836	1.27e-6
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	2.51e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	2.29e-7	

Table A.10: Environmental flows related to  $OS_{10}$ 

Operational Scenario $OS_{10}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	3.123e-5
	Negative plates: Lead	0.540	3.288e-5
	Epoxy adhesive	0.00836	5.09e-7
	Silica fume (5% of acid quantity)	0.00985	5.997e-7
	Separator: glass fibre	0.0344	2.094e-6
Design alternatives: $A_{112}$ , $A_{123}$ , $A_{131}$ , $A_{132}$ , $A_{141}$	Container and covers	0.201	1.224e-5
	Lead	0.165	1.005e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	1.218e-6
	Phosphoric Acid	0.197	1.199e-5
	Labelling and warranty card: printed paper	0.0005	3.044e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.483	2.942e-5
	Land Transport: import from the Tanzanian port (Dar es Salaam) to the factory (Tanzania)(12 km)	0.0133	8.145e-7
	Maritime Transport: From the China port to the Tanzanian port (Dar es Salaam) (9926 km)	10.975	6.682e-4
	Land transport: From Local Tanzanian supplier to Tanzanian factory (5 km)	2.815e-3	1.714e-7
	Land transport: From Tunisian supplier to Tunisian port (Gabes) (400 km)	0.0082	4.992e-7
	Maritime transport: From Tunisian port to Dar es Salaam (7906 km)	0.162	9.868e-6
	Land transport: From Dar es Salaam port to Tanzanian factory (12 km)	2.481e-3	1.51e-8
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Design alternatives: $A_{212}$ , $A_{222}$ , $A_{233}$ , $A_{242}$	Electricity: low voltage (kwh)	7.704	4.69e-4
	Waste packaging: waste polyethylene (kg)	0.00227	1.382e-7
	Waste packaging: waste paperboard (kg)	0.00234	1.424e-7
	Container and covers waste (kg)	0.0068	4.14e-7
	Tap water (kg)	7.875	4.795e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	4.28e-6	
Phosphoric acid emissions (kg)	0.001	6.09e-8	
Wastewater, unpolluted (kg)	0.00875	5.33e-7	
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{312}$ , $A_{321}$ , $A_{333}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tanzanian factory to retailers (220 km)	0.346	2.112e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{413}$ , $A_{434}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.27e-4	2.27e-3
	Transport, passenger, motoscooter	0.00991	0.0991
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{512}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	1.18e-5
	waste graphical paper	0.01773	1.08e-6
	Separator	0.0344	2.09e-6
	Labelling	0.0005	3.04e-8
	Epoxy adhesive	0.0836	5.09e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	1e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	9.18e-8	

Table A.11: Environmental flows related to  $OS_{11}$ 

Operational Scenario	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{142}$	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	7.808e-5
	Negative plates: Lead	0.540	8.219e-5
	Epoxy adhesive	0.00836	1.272e-6
	Separator: glass fibre	0.0344	5.236e-6
	Container and covers	0.201	3.059e-5
	Lead	0.165	2.511e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	3.044e-6
	Deminerlized water: water, decarbonised, at user	0.278	4.231e-5
	Sulfuric Acid	0.197	2.998e-5
	Labelling and warranty card: printed paper	0.0005	7.61e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from Turkish factory to Turkish port (Istanbul)(59 km)	0.0646	9.84e-6
	Land Transport: import from the Tanzanian port (Dar es Salaam) to the factory (Tanzania)(12 km)	0.0132	2.018e-6
	Maritime Transport: From the Turkish port to the Tanzanian port (Dar es Salaam) (1929.8 km)	2.114	3.219e-4
	Land transport: From Local Tanzanian supplier to Tanzanian factory (5 km)	4.205e-3	6.4e-7
Land transport: From Tunisian supplier to Tunisian port (Gabes) (400 km)	0.0082	1.248e-6	
Maritime transport: From Tunisian port to Dar es Salaam (7906 km)	0.162	2.467e-5	
Land transport: From Dar es Salaam port to Tanzanian factory (12 km)	2.481e-3	3.775e-8	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
Design alternatives: $A_{212}, A_{221}, A_{232}, A_{241}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	1.117e-3
	Waste packaging: waste polyethylene (kg)	0.00227	3.455e-7
	Waste packaging: waste paperboard (kg)	0.00234	3.561e-7
	Container and covers waste (kg)	0.0068	1.035e-6
	Tap water (kg)	7.875	1.198e-3
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Lead emissions (kg)	0.0703	1.07e-5	
Sulfuric acid emissions (kg)	0.001	1.522e-7	
Wastewater, unpolluted (kg)	0.00875	1.332e-6	
Design alternatives: $A_{311}, A_{321}, A_{333}$	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tanzanian factory to retailers (220 km)	0.374	5.692e-5
Design alternatives: $A_{411}, A_{432}$	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.45e-4	2.45e-3
	Transport, passenger, motoscooter	0.0106	0.106
Design alternatives: $A_{512}$	<i>LCP<sub>5</sub>: End of life</i>		
	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	2.96e-5
	waste graphical paper	0.01773	2.7e-6
	Separator	0.0344	5.24e-6
	Labelling	0.0005	7.61e-8
	Epoxy adhesive	0.0836	1.27e-6
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	2.51e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	2.29e-7	

Table A.12: Environmental flows related to  $OS_{12}$ 

Operational Scenario $OS_{12}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
Design alternatives: $A_{112}$ , $A_{123}$ , $A_{131}$ , $A_{132}$ , $A_{142}$	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	3.123e-5
	Negative plates: Lead	0.540	3.288e-5
	Epoxy adhesive	0.00836	5.09e-7
	Silica fume (5% of acid quantity)	0.00985	5.997e-7
	Separator: glass fibre	0.0344	2.094e-6
	Container and covers	0.201	1.224e-5
	Lead	0.165	1.005e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	1.218e-6
	Phosphoric Acid	0.197	1.199e-5
	Labelling and warranty card: printed paper	0.0005	3.044e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from Turkish factory to Turkish port (Istanbul)(59 km)	0.065	3.971e-6
	Land Transport: import from the Tanzanian port (Dar es Salaam) to the factory (Tanzania)(12 km)	0.0133	8.145e-7
Maritime Transport: From the Turkish port to the Tanzanian port (Dar es Salaam) (1929 km)	2.133	1.299e-4	
Land transport: From Local Tanzanian supplier to Tanzanian factory (5 km)	2.815e-3	1.714e-7	
Land transport: From Tunisian supplier to Tunisian port (Gabes) (400 km)	0.0082	4.992e-7	
Maritime transport: From Tunisian port to Dar es Salaam (7906 km)	0.162	9.868e-6	
Land transport: From Dar es Salaam port to Tanzanian factory (12 km)	2.481e-3	1.51e-8	
	<i>LCP<sub>2</sub>: Manufacturing</i>		
Design alternatives: $A_{212}$ , $A_{222}$ , $A_{233}$ , $A_{242}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Electricity: low voltage (kwh)	7.704	4.69e-4
	Waste packaging: waste polyethylene (kg)	0.00227	1.382e-7
	Waste packaging: waste paperboard (kg)	0.00234	1.424e-7
	Container and covers waste (kg)	0.0068	4.14e-7
	Tap water (kg)	7.875	4.795e-4
Design alternatives: $A_{312}$ , $A_{321}$ , $A_{333}$	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Lead emissions (kg)	0.0703	3.21e-6
	Phosphoric acid emissions (kg)	0.001	4.566e-8
		0.00875	3.995e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{413}$ , $A_{434}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tanzanian factory to retailers (220 km)	0.346	2.112e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{512}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.27e-4	2.27e-3
	Transport, passenger, motoscooter	0.00991	0.0991
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{512}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1942	1.18e-5
	waste graphical paper	0.01773	1.08e-6
	Separator	0.0344	2.09e-6
	Labelling	0.0005	3.04e-8
	Epoxy adhesive	0.0836	5.09e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0165	1e-6
Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	9.18e-8	

Table A.13: Environmental flows related to  $OS_{13}$ 

Operational Scenario $OS_{13}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	7.808e-5
	Negative plates: Lead	0.540	8.219e-5
	Epoxy adhesive	0.00836	1.272e-6
	Separator: glass fibre	0.0344	5.236e-6
	Container and covers	0.155	2.359e-5
Design alternatives: $A_{111}$ , $A_{122}$ , $A_{131}$ , $A_{132}$ , $A_{141}$	Lead	0.165	2.511e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	3.044e-6
	DeminerIALIZED water: water, decarbonised, at user	0.278	4.231e-5
	Sulfuric Acid	0.197	2.998e-5
	Labelling and warranty card: printed paper	0.0005	7.61e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.478	7.288e-5
	Land Transport: import from the Tanzanian port (Dar es Salaam) to the factory (Tanzania)(12 km)	0.0132	2.018e-6
	Maritime Transport: From the China port to the Tanzanian port (Dar es Salaam) (9926 km)	10.877	1.655e-3
	Land transport: From Local Tanzanian supplier to Tanzanian factory (5 km)	3.975e-3	6.05e-7
	Land transport: From Tunisian supplier to Tunisian port (Gabes) (400 km)	0.0082	1.248e-6
	Maritime transport: From Tunisian port to Dar es Salaam (7906 km)	0.162	2.467e-5
	Land transport: From Dar es Salaam port to Tanzanian factory (12 km)	2.481e-3	3.775e-8
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Design alternatives: $A_{212}$ , $A_{221}$ , $A_{234}$ , $A_{241}$	Electricity: low voltage (kwh)	5.392	8.208e-4
	Waste packaging: waste polyethylene (kg)	0.00227	3.455e-7
	Waste packaging: waste paperboard (kg)	0.00234	3.561e-7
	Container and covers waste (kg)	0.0052	7.976e-7
	Tap water (kg)	7.875	1.198e-3
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Lead emissions (kg)	0.0703	1.07e-5
	Sulfuric acid emissions (kg)	0.001	1.522e-7
	Wastewater, unpolluted (kg)	0.00875	1.332e-6
Design alternatives: $A_{311}$ , $A_{321}$ , $A_{333}$	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tanzanian factory to retailers (220 km)	0.363	5.538e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{412}$ , $A_{432}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.38e-4	2.38e-3
	Transport, passenger, motoscooter	0.0103	0.103
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{512}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.1497	2.28e-5
	waste graphical paper	0.01773	2.7e-6
	Separator	0.0344	5.24e-6
	Labelling	0.0005	7.61e-8
	Epoxy adhesive	0.0836	1.27e-6
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0149	1.94e-6
	Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	2.29e-7

Table A.14: Environmental flows related to  $OS_{14}$ 

Operational Scenario $OS_{14}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Positive plates: Lead dioxide	0.513	3.123e-5
	Negative plates: Lead	0.540	3.288e-5
	Epoxy adhesive	0.00836	5.09e-7
	Silica fume (5% of acid quantity)	0.00985	5.997e-7
	Separator: glass fibre	0.0344	2.094e-6
Design alternatives: $A_{112}$ , $A_{124}$ , $A_{131}$ , $A_{132}$ , $A_{141}$	Container and covers	0.155	6.437e-6
	Lead	0.165	1.005e-5
	Thermo retractable film (packaging): packaging film, low density polyethylene	0.02	1.218e-6
	Phosphoric Acid	0.197	1.199e-5
	Labelling and warranty card: printed paper	0.0005	3.044e-8
	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: import from China factory to China port (Zhanjiang)(437 km)	0.483	2.942e-5
	Land Transport: import from the Tanzanian port (Dar es Salaam) to the factory (Tanzania)(12 km)	0.0133	8.145e-7
	Maritime Transport: From the China port to the Tanzanian port (Dar es Salaam) (9926 km)	10.975	6.682e-4
	Land transport: From Local Tanzanian supplier to Tanzanian factory (5 km)	2.585e-3	1.574e-7
	Land transport: From Tunisian supplier to Tunisian port (Gabes) (400 km)	0.0082	4.992e-7
	Maritime transport: From Tunisian port to Dar es Salaam (7906 km)	0.162	9.868e-6
	Land transport: From Dar es Salaam port to Tanzanian factory (12 km)	2.481e-3	1.51e-8
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
Design alternatives: $A_{212}$ , $A_{222}$ , $A_{234}$ , $A_{242}$	Electricity: low voltage (kwh)	5.392	3.283e-4
	Waste packaging: waste polyethylene (kg)	0.00227	1.382e-7
	Waste packaging: waste paperboard (kg)	0.00234	1.424e-7
	Container and covers waste (kg)	0.0052	3.19e-7
	Tap water (kg)	7.875	4.795e-4
	<b>Outputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Lead emissions (kg)	0.0703	3.21e-6
	Phosphoric acid emissions (kg)	0.001	4.566e-8
	Wastewater, unpolluted (kg)	0.00875	3.995e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
Design alternatives: $A_{312}$ , $A_{321}$ , $A_{333}$	<b>Transport</b>	<b>Transport value (tkm)</b>	<b>Total value per FU</b>
	Land Transport: From the Tanzanian factory to retailers (220 km)	0.336	2.051e-5
	<i>LCP<sub>4</sub>: Use</i>		
Design alternatives: $A_{413}$ , $A_{434}$	<b>Inputs</b>	<b>Total quantity per battery</b>	<b>Total quantity per FU</b>
	Petrol, low sulfur (kg)	2.2e-4	2.205e-3
	Transport, passenger, motoscooter	0.00962	0.0962
	<i>LCP<sub>5</sub>: End of life</i>		
Design alternatives: $A_{512}$	<b>Inputs</b>	<b>Total mass per battery (kg)</b>	<b>Total quantity per FU</b>
	Waste plastic	0.149	9.12e-6
	waste graphical paper	0.01773	1.08e-6
	Separator	0.0344	2.09e-6
	Labelling	0.0005	3.04e-8
	Epoxy adhesive	0.0836	5.09e-7
	Land Transport of waste plastic to the waste treatment center (85 km)	0.0149	7.75e-7
	Land Transport of waste graphical paper to the waste treatment center (85 km)	0.0015	9.18e-8

Table A.15: Nature of the different costs estimated per life cycle phase

$LCP_1$	$LCP_2$	$LCP_3$	$LCP_4$	$LCP_5$
Costs related to raw materials and their transportation to the factory	Costs related to resources required to manufacture the battery (i.e. Electricity, Water). Costs related to the generated waste (i.e. packaging, plastic, emissions of lead, electrolyte and water), costs related to other resources such as insurance, labor cost, service charge (i.e. internet, phone..etc	Costs related to the distribution of the battery from the factory to retailers	Costs related to the consumption of fuel when starting the engine	Costs related to the treatment of the battery scrap at its end of life and their transportation to the waste treatment centers.

Table A.16: Computed net costs of the operational scenarios

	Net costs per life cycle phase					Net costs per $OS$
	$LCP_1$	$LCP_2$	$LCP_3$	$LCP_4$	$LCP_5$	
$OS_1$	0.004894	0.000397	0.000476	0.006284	$2.584e-5$	0.012076
$OS_2$	0.006525	0.000529	0.006934	1.272E-05	1.347E-06	0.014003
$OS_3$	0.001971	0.000158	0.000860	0.005828	1.033E-05	0.008829
$OS_4$	0.002628	0.000207	0.003488	1.181E-05	5.391E-07	0.006336
$OS_5$	0.001876	0.000397	0.003493	0.006283	2.584E-05	0.012076
$OS_6$	0.000755	0.000158	0.002076	0.005828	1.033E-05	0.008829
$OS_7$	0.004672	0.000386	0.000535	0.006113	2.129E-05	0.011729
$OS_8$	0.001882	0.000154	0.000883	0.005658	8.517E-06	0.008588
$OS_9$	0.004356	0.002210	0.001804	1.272E-05	1.347E-06	0.008385
$OS_{10}$	0.001759	0.000884	0.001617	1.181E-05	5.391E-07	0.004274
$OS_{11}$	0.002290	0.002210	0.003871	1.272E-05	1.347E-06	0.008385
$OS_{12}$	0.000925	0.000884	0.002451	1.181E-05	5.391E-07	0.004274
$OS_{13}$	0.004259	0.002090	0.001792	1.238E-05	1.112E-06	0.008156
$OS_{14}$	0.001721	0.000836	0.001613	1.146E-05	4.451E-07	0.004182

Table A.17: Social flows related to  $OS_1$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_1$			
<i>LCP<sub>1</sub>: Extraction of raw materials</i>			
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Metal products CN	3.963e-4	1.657e-4
	Chemical products CN	2.752e-5	1.151e-5
	Plastic products CN	1.637e-4	6.849e-5
	Metal products TN	6.851e-5	2.866e-5
	Plastic products TN	1.151e-5	4.817e-6
	Chemical products TN	1.128e-5	4.72e-6
	Paper products TN	5.458e-8	2.283e-8
	Transport nec CN	2.258e-5	3.445e-5
	Transport nec TN	3.715e-5	1.554e-5
Water transport CN	4.155e-3	1.738e-3	
<i>LCP<sub>2</sub>: Manufacturing</i>			
Design alternatives: $A_{211}, A_{221}, A_{231}, A_{241}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Electricity TN	3.4e-5	1.4e-5
	Water TN	5.5e-6	2.3e-6
	Insurance	2.8e-8	1.2e-8
	Labor cost	2.9e-4	1.2e-4
	Service charge (i.e. internet, phone..etc.)	4e-5	1.7e-5
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	2.92e-5	1.22e-5
	Sulfuric acid emissions	5.2e-8	2.18e-8
	Plastic products TN	8.703e-7	3.641e-7
Wastewater, unpolluted	6.09e-9	2.55e-9	
<i>LCP<sub>3</sub>: Distribution</i>			
Design alternatives: $A_{311}, A_{321}, A_{331}$	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Transport nec TN	6e-5	2.5e-5
<i>LCP<sub>4</sub>: Use</i>			
Design alternatives: $A_{411}, A_{431}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Petroleum, coal products TN	6.283e-3	2.628e-3

Table A.18: Social flows related to  $OS_2$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_2$			
<i>LCP<sub>1</sub>: Extraction of raw materials</i>			
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	Metal products CN	5.28e-4	2.211e-4
	Chemical products CN	3.669e-5	1.534e-5
	Plastic products CN	2.183e-4	3.132e-5
	Metal products TN	3.135e-5	3.132e-5
	Plastic products TN	1.535e-5	6.422e-6
	Chemical products TN	1.504e-5	6.293e-6
	Paper products TN	7.277e-8	3.044e-8
	Transport nec CN	3.011e-5	1.259e-5
	Transport nec TN	4.953e-5	2.072e-5
	Water transport CN	5.541e-3	2.317e-3
<i>LCP<sub>2</sub>: Manufacturing</i>			
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{211}, A_{221}, A_{231}, A_{241}$	Electricity TN	4.6e-5	1.3e-5
	Water TN	7.3e-6	3.1e-6
	Insurance	3.7e-8	1.5e-8
	Labor cost	3.8e-4	1.6e-4
	Service charge (i.e. internet, phone..etc.)	5.3e-5	2.2e-5
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	3.89e-5	1.63e-5
	Sulfuric acid emissions	6.94e-8	2.9e-8
	Plastic products TN	1.161e-6	4.854e-7
	Wastewater, unpolluted	8.12e-9	3.4e-9
<i>LCP<sub>3</sub>: Distribution</i>			
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{311}, A_{321}, A_{322}, A_{332}$	Transport nec TN	1.2e-4	5.2e-5
	Water Transport TN	6.25e-3	2.62e-3
	Transport nec TZ	7e-9	2.9e-9
<i>LCP<sub>4</sub>: Use</i>			
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{411}, A_{433}$	Petroleum, coal products TZ	1.27e-5	5.32e-6

Table A.19: Social flows related to  $OS_3$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_3$			
<i>LCP<sub>1</sub>: Extraction of raw materials</i>			
Design alternatives: $A_{112}, A_{123}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Metal products CN	1.58e-4	6.631e-5
	Chemical products CN	1.142e-5	4.778e-6
	Plastic products CN	6.55e-5	2.74e-5
	Metal products TN	2.741e-5	1.146e-5
	Plastic products TN	4.606e-6	1.927e-6
	Chemical products TN	7.922e-6	3.314e-6
	Paper products TN	2.163e-8	3.132e-9
	Transport nec CN	3.1e-6	3.807e-6
	Transport nec TN	1.181e-6	4.938e-6
Water transport CN	1.674e-3	7.1e-4	
<i>LCP<sub>2</sub>: Manufacturing</i>			
Design alternatives: $A_{211}, A_{222}, A_{231}, A_{242}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Electricity TN	1.37e-5	5.73e-6
	Water TN	2.192e-6	9.168e-7
	Insurance	1.102e-8	4.611e-9
	Labor cost	1.149e-4	4.808e-5
	Service charge (i.e. internet, phone..etc.)	1.598e-5	6.685e-6
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	1.17e-5	4.88e-5
	Phosphoric acid emissions	4.02e-8	1.68e-8
	Plastic products TN	3.481e-7	1.456e-7
Wastewater, unpolluted	2.44e-9	1.02e-9	
<i>LCP<sub>3</sub>: Distribution</i>			
Design alternatives: $A_{312}, A_{321}, A_{331}$	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Transport nec TN	2.2e-5	9.3e-6
<i>LCP<sub>4</sub>: Use</i>			
Design alternatives: $A_{413}, A_{432}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Petroleum, coal products TN	5.829e-3	2.438e-3

Table A.20: Social flows related to  $OS_4$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_4$			
<i>LCP<sub>1</sub>: Extraction of raw materials</i>			
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{112}, A_{123}, A_{131}, A_{132}, A_{141}$	Metal products CN	2.113e-4	8.842e-5
	Chemical products CN	1.523e-5	6.371e-6
	Plastic products CN	8.733e-5	3.653e-5
	Metal products TN	3.654e-5	1.528e-5
	Plastic products TN	6.141e-6	2.569e-6
	Chemical products TN	1.056e-5	4.418e-6
	Paper products TN	2.911e-8	1.218e-8
	Transport nec CN	1.213e-5	5.075e-5
	Transport nec TN	1.574e-5	6.584e-6
	Water transport CN	2.233e-3	9.341e-3
<i>LCP<sub>2</sub>: Manufacturing</i>			
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{211}, A_{222}, A_{231}, A_{242}$	Electricity TN	1.83e-5	7.64e-8
	Water TN	2.92e-6	1.22e-6
	Insurance	1.47e-8	6.15e-9
	Labor cost	1.53e-4	6.41e-5
	Service charge (i.e. internet, phone..etc.)	2.13e-5	8.91e-6
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	1.17e-5	4.88e-6
	Phosphoric acid emissions	4.02e-8	1.68e-8
	Plastic products TN (Waste)	4.641e-7	1.941e-7
	Wastewater, unpolluted	2.44e-9	1.02e-9
<i>LCP<sub>3</sub>: Distribution</i>			
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{312}, A_{321}, A_{322}, A_{332}$	Transport nec TN	4.6e-5	1.9e-5
	Water Transport TN	2.32e-3	9.7e-3
	Transport nec TZ	2.6e-9	1.1e-9
<i>LCP<sub>4</sub>: Use</i>			
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{413}, A_{434}$	Petroleum, coal products TZ	1.18e-5	4.94e-6

Table A.21: Social flows related to  $OS_5$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_5$			
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{142}$	Metal products TR	3.963e-4	1.657e-4
	Chemical products TR	2.752e-5	1.151e-5
	Plastic products TR	1.637e-4	6.849e-5
	Metal products TN	6.851e-5	2.866e-5
	Plastic products TN	1.151e-5	4.817e-6
	Chemical products TN	1.128e-5	4.72e-6
	Paper products TN	5.458e-8	2.283e-8
	Transport nec TR	1.539e-5	6.439e-6
	Transport nec TN	3.715e-5	1.554e-5
	Water transport TR	1.145e-3	4.791e-3
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{211}, A_{221}, A_{231}, A_{241}$	Electricity TN	3.4e-5	1.4e-5
	Water TN	5.5e-6	2.3e-6
	Insurance	2.8e-8	1.2e-8
	Labor cost	2.9e-4	1.2e-4
	Service charge (i.e. internet, phone..etc.)	4e-5	1.7e-5
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	2.3e-5	1.2e-5
	Sulfuric acid emissions	5.2e-8	2.2e-8
	Plastic products TN	8.703e-7	3.641e-7
	Wastewater, unpolluted	5.2e-9	2.5e-9
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{311}, A_{321}, A_{331}$	Transport nec TN	6e-5	2.5e-5
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{411}, A_{431}$	Petroleum, coal products TN	6.283e-3	2.628e-3

Table A.22: Social flows related to  $OS_6$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_6$			
<i>LCP<sub>1</sub>: Extraction of raw materials</i>			
Design alternatives: $A_{112}, A_{123}, A_{131}, A_{132}, A_{142}$	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Metal products TR	1.58e-4	6.631e-5
	Chemical products TR	1.142e-5	4.778e-6
	Plastic products TR	6.55e-5	2.74e-5
	Metal products TN	2.741e-5	1.146e-5
	Plastic products TN	4.606e-6	1.927e-6
	Chemical products TN	7.922e-6	3.314e-6
	Paper products TN	2.163e-8	3.132e-9
	Transport nec TR	6.204e-6	2.595e-6
	Transport nec TN	1.181e-6	4.938e-6
Water transport TR	4.616e-3	1.931e-4	
<i>LCP<sub>2</sub>: Manufacturing</i>			
Design alternatives: $A_{211}, A_{222}, A_{231}, A_{242}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Electricity TN	1.37e-5	5.73e-6
	Water TN	2.192e-6	9.168e-7
	Insurance	1.102e-8	4.611e-9
	Labor cost	1.149e-4	4.808e-5
	Service charge (i.e. internet, phone..etc.)	1.598e-5	6.685e-6
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	1.17e-5	4.88e-5
	Phosphoric acid emissions	4.02e-8	1.68e-8
	Plastic products TN	3.481e-7	1.456e-7
Wastewater, unpolluted	2.44e-9	1.02e-9	
<i>LCP<sub>3</sub>: Distribution</i>			
Design alternatives: $A_{312}, A_{321}, A_{331}$	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Transport nec TN	2.2e-5	9.3e-6
<i>LCP<sub>4</sub>: Use</i>			
Design alternatives: $A_{413}, A_{432}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Petroleum, coal products TN	5.829e-3	2.438e-3

Table A.23: Social flows related to  $OS_7$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_7$			
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{111}, A_{122}, A_{131}, A_{132}, A_{141}$	Metal products CN	3.963e-4	1.657e-4
	Chemical products CN	2.752e-5	1.151e-5
	Plastic products CN	9.088e-5	3.802e-5
	Metal products TN	6.851e-5	2.866e-5
	Plastic products TN	1.151e-5	4.817e-6
	Chemical products TN	1.128e-5	4.72e-6
	Paper products TN	5.458e-8	2.283e-8
	Transport nec CN	2.178e-5	9.11e-6
	Transport nec TN	3.649e-5	1.526e-5
	Water transport CN	4.008e-3	1.676e-3
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{211}, A_{221}, A_{232}, A_{241}$	Electricity TN	2.4e-5	1e-5
	Water TN	5.5e-6	2.3e-6
	Insurance	2.8e-8	1.2e-8
	Labor cost	2.9e-4	1.2e-4
	Service charge (i.e. internet, phone..etc.)	4e-5	1.7e-5
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	2.92e-5	1.22e-5
	Sulfuric acid emissions	5.2e-8	2.18e-8
	Plastic products TN	7.206e-7	3.0144e-7
	Wastewater, unpolluted	6.09e-9	2.55e-9
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{311}, A_{321}, A_{331}$	Transport nec TN	5.8e-5	2.4e-5
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{412}, A_{431}$	Petroleum, coal products TN	6.113e-3	2.557e-3

Table A.24: Social flows related to  $OS_8$ 

Operational Scenario	Life cycle phases of the lead acid battery		
$OS_8$			
<i>LCP<sub>1</sub>: Extraction of raw materials</i>			
Design alternatives: $A_{112}, A_{124}, A_{131}, A_{132}, A_{141}$	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Metal products CN	1.58e-4	6.631e-5
	Chemical products CN	1.142e-5	4.778e-6
	Plastic products CN	3.635e-5	1.521e-5
	Metal products TN	2.741e-5	1.146e-5
	Plastic products TN	4.606e-6	1.927e-6
	Chemical products TN	7.922e-6	3.314e-6
	Paper products TN	2.163e-8	3.132e-9
	Transport nec CN	8.78e-6	3.673e-6
	Transport nec TN	1.154e-5	4.827e-6
Water transport CN	1.615e-3	6.759e-4	
<i>LCP<sub>2</sub>: Manufacturing</i>			
Design alternatives: $A_{211}, A_{222}, A_{232}, A_{242}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Electricity TN	9.59e-6	4.01e-6
	Water TN	2.192e-6	9.168e-7
	Insurance	1.102e-8	4.611e-9
	Labor cost	1.149e-4	4.808e-5
	Service charge (i.e. internet, phone..etc.)	1.598e-5	6.685e-6
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	1.17e-5	4.88e-5
	Phosphoric acid emissions	4.02e-8	1.68e-8
	Plastic products TN	2.882e-7	1.205e-7
Wastewater, unpolluted	2.44e-9	1.02e-9	
<i>LCP<sub>3</sub>: Distribution</i>			
Design alternatives: $A_{312}, A_{321}, A_{331}$	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Transport nec TN	2.2e-5	9.3e-6
<i>LCP<sub>4</sub>: Use</i>			
Design alternatives: $A_{414}, A_{433}$	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Petroleum, coal products TN	5.659e-3	2.367e-3

Table A.25: Social flows related to  $OS_9$ 

Operational Scenario $OS_9$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{141}$	Metal products CN	5.284e-4	2.21e-4
	Chemical products CN	3.669e-5	1.534e-5
	Plastic products TZ	2.183e-4	9.132e-5
	Metal products TZ	9.135e-5	3.821e-5
	Plastic products TN	1.535e-5	6.422e-6
	Chemical products TZ	1.504e-5	6.293e-6
	Paper products TN	7.277e-8	3.044e-8
	Transport nec CN	2.544e-5	1.064e-5
	Transport nec TZ	7.258e-9	3.036e-9
	Transport nec TN	1.749e-6	7.315e-7
	Water transport CN	3.349e-3	1.4e-3
	Water transport TN	7.542e-5	3.155e-5
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{212}, A_{221}, A_{232}, A_{241}$	Electricity TZ	3.99e-4	1.67e-4
	Water TZ	1.334e-4	5.58e-4
	Insurance	3.67e-8	1.54e-8
	Labor cost	3.83e-4	1.6e-4
	Service charge (i.e. internet, phone..etc.)	5.33e-5	2.23e-5
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	3.89e-5	1.63e-5
	Sulfuric acid emissions	6.94e-8	2.9e-8
	Plastic products TZ	4.764e-10	1.992e-10
	Wastewater, unpolluted	1.48e-6	6.2e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{311}, A_{321}, A_{333}$	Transport nec TZ	1.5e-7	6.4e-8
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{411}, A_{432}$	Petroleum, coal products TZ	1.27e-5	5.32e-6

Table A.26: Social flows related to  $OS_{10}$ 

Operational Scenario $OS_{10}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{112}, A_{123}, A_{131}, A_{132}, A_{142}$	Metal products CN	2.11e-4	8.842e-5
	Chemical products CN	1.523e-5	6.371e-6
	Plastic products TZ	8.773e-5	3.653e-5
	Metal products TZ	3.654e-5	1.528e-5
	Plastic products TN	6.141e-6	2.569e-6
	Chemical products TZ	1.056e-5	4.418e-6
	Paper products TN	2.911e-8	1.218e-8
	Transport nec CN	1.027e-5	4.295e-6
	Transport nec TZ	2.695e-9	1.127e-9
	Transport nec TN	6.995e-7	2.926e-7
	Water transport CN	1.351e-3	5.654e-3
	Water transport TN	3.017e-5	1.262e-5
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{212}, A_{222}, A_{233}, A_{242}$	Electricity TZ	1.59e-4	6.67e-5
	Water TZ	5.34e-4	2.23e-4
	Insurance	1.47e-8	6.15e-9
	Labor cost	1.53e-4	6.41e-5
	Service charge (i.e. internet, phone..etc.)	2.13e-5	8.91e-6
		<b>Outputs</b>	<b>Total cost per FU (TND)</b>
	Lead emissions	1.56e-5	6.51e-6
	Phosphoric acid emissions	5.36e-8	2.24e-8
	Plastic products TZ	1.905e-10	7.971e-11
	Wastewater, unpolluted	5.93e-7	2.48e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{312}, A_{321}, A_{333}$	Transport nec TZ	5.7e-8	2.4e-8
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{413}, A_{434}$	Petroleum, coal products TZ	1.18e-5	4.94e-6

Table A.27: Social flows related to  $OS_{11}$ 

Operational Scenario $OS_{11}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{111}, A_{121}, A_{131}, A_{132}, A_{142}$	Metal products TR	5.284e-4	2.21e-4
	Chemical products TR	3.669e-5	1.534e-5
	Plastic products TZ	2.183e-4	9.132e-5
	Metal products TZ	9.135e-5	3.821e-5
	Plastic products TN	1.535e-5	6.422e-6
	Chemical products TZ	1.504e-5	6.293e-6
	Paper products TN	7.277e-8	3.044e-8
	Transport nec TR	1.734e-5	7.254e-6
	Transport nec TZ	7.258e-9	3.036e-9
	Transport nec TN	1.749e-6	7.315e-7
	Water transport TR	1.29e-3	5.398e-4
	Water transport TN	7.542e-5	3.155e-5
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{212}, A_{221}, A_{232}, A_{241}$	Electricity TZ	3.99e-4	1.67e-4
	Water TZ	1.334e-4	5.58e-4
	Insurance	3.67e-8	1.54e-8
	Labor cost	3.83e-4	1.6e-4
	Service charge (i.e. internet, phone..etc.)	5.33e-5	2.23e-5
		<b>Outputs</b>	<b>Total cost per FU (TND)</b>
	Lead emissions	3.89e-5	1.63e-5
	Sulfuric acid emissions	6.94e-8	2.9e-8
	Plastic products TZ	4.764e-10	1.992e-10
	Wastewater, unpolluted	1.48e-6	6.2e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{311}, A_{321}, A_{333}$	Transport nec TZ	1.5e-7	6.4e-8
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{411}, A_{432}$	Petroleum, coal products TZ	1.27e-5	5.32e-6

Table A.28: Social flows related to  $OS_{12}$ 

Operational Scenario $OS_{12}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{112}, A_{123}, A_{131}, A_{132}, A_{142}$	Metal products TR	2.11e-4	8.842e-5
	Chemical products TR	1.523e-5	6.371e-6
	Plastic products TZ	8.773e-5	3.653e-5
	Metal products TZ	3.654e-5	1.528e-5
	Plastic products TN	6.141e-6	2.569e-6
	Chemical products TZ	1.056e-5	4.418e-6
	Paper products TN	2.911e-8	1.218e-8
	Transport nec TR	1.027e-5	6.999e-6
	Transport nec TZ	2.695e-9	1.127e-9
	Transport nec TN	6.995e-7	2.926e-7
	Water transport TR	5.208e-3	2.178e-3
	Water transport TN	3.017e-5	1.262e-5
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{211}, A_{222}, A_{233}, A_{242}$	Electricity TZ	1.59e-4	6.67e-5
	Water TZ	5.34e-4	2.23e-4
	Insurance	1.47e-8	6.15e-9
	Labor cost	1.53e-4	6.41e-5
	Service charge (i.e. internet, phone..etc.)	2.13e-5	8.91e-6
		<b>Outputs</b>	<b>Total cost per FU (TND)</b>
	Lead emissions	1.56e-5	6.51e-6
	Phosphoric acid emissions	5.36e-8	2.24e-8
	Plastic products TZ	1.905e-10	7.971e-11
	Wastewater, unpolluted	5.93e-7	2.48e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{312}, A_{321}, A_{333}$	Transport nec TZ	5.7e-8	2.4e-8
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{413}, A_{434}$	Petroleum, coal products TZ	1.18e-5	4.94e-6

Table A.29: Social flows related to  $OS_{13}$ 

Operational Scenario $OS_{13}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{111}, A_{122}, A_{131}, A_{132}, A_{141}$	Metal products CN	5.284e-4	2.21e-4
	Chemical products CN	3.669e-5	1.534e-5
	Plastic products TZ	1.212e-4	5.069e-5
	Metal products TZ	9.135e-5	3.821e-5
	Plastic products TN	1.535e-5	6.422e-6
	Chemical products TZ	1.504e-5	6.293e-6
	Paper products TN	7.277e-8	3.044e-8
	Transport nec CN	2.544e-5	1.064e-5
	Transport nec TZ	7.164e-9	2.996e-9
	Transport nec TN	1.749e-6	7.315e-7
	Water transport CN	3.349e-3	1.4e-3
	Water transport TN	7.542e-5	3.155e-5
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{212}, A_{221}, A_{234}, A_{241}$	Electricity TZ	2.79e-4	1.17e-4
	Water TZ	1.334e-4	5.58e-4
	Insurance	3.67e-8	1.54e-8
	Labor cost	3.83e-4	1.6e-4
	Service charge (i.e. internet, phone..etc.)	5.33e-5	2.23e-5
		<b>Outputs</b>	<b>Total cost per FU (TND)</b>
	Lead emissions	3.89e-5	1.63e-5
	Sulfuric acid emissions	6.94e-8	2.9e-8
	Plastic products TZ	3.945e-10	1.65e-10
	Wastewater, unpolluted	1.48e-6	6.2e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{311}, A_{321}, A_{333}$	Transport nec TZ	1.5e-7	6.2e-8
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{411}, A_{432}$	Petroleum, coal products TZ	1.24e-5	5.18e-6

Table A.30: Social flows related to  $OS_{14}$ 

Operational Scenario $OS_{14}$	Life cycle phases of the lead acid battery		
	<i>LCP<sub>1</sub>: Extraction of raw materials</i>		
	<b>Raw materials</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{112}, A_{124}, A_{131}, A_{132}, A_{141}$	Metal products CN	2.11e-4	8.842e-5
	Chemical products CN	1.523e-5	6.371e-6
	Plastic products TZ	4.847e-5	2.027e-5
	Metal products TZ	3.654e-5	1.528e-5
	Plastic products TN	6.141e-6	2.569e-6
	Chemical products TZ	1.056e-5	4.418e-6
	Paper products TN	2.911e-8	1.218e-8
	Transport nec CN	1.027e-5	4.295e-6
	Transport nec TZ	2.657e-9	1.111e-9
	Transport nec TN	6.995e-7	2.926e-7
	Water transport CN	1.351e-3	5.654e-3
	Water transport TN	3.017e-5	1.262e-5
	<i>LCP<sub>2</sub>: Manufacturing</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{214}, A_{222}, A_{234}, A_{242}$	Electricity TZ	1.12e-4	4.67e-5
	Water TZ	5.34e-4	2.23e-4
	Insurance	1.47e-8	6.15e-9
	Labor cost	1.53e-4	6.41e-5
	Service charge (i.e. internet, phone..etc.)	2.13e-5	8.91e-6
	<b>Outputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
	Lead emissions	1.56e-5	6.51e-6
	Phosphoric acid emissions	5.36e-8	2.24e-8
	Plastic products TZ	1.578e-10	6.6e-11
	Wastewater, unpolluted	5.93e-7	2.48e-7
	<i>LCP<sub>3</sub>: Distribution</i>		
	<b>Transport</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{312}, A_{321}, A_{333}$	Transport nec TZ	5.5e-8	2.3e-8
	<i>LCP<sub>4</sub>: Use</i>		
	<b>Inputs</b>	<b>Total cost per FU (TND)</b>	<b>Total cost per FU (USD)</b>
Design alternatives: $A_{413}, A_{434}$	Petroleum, coal products TZ	1.15e-5	4.8e-6

Table A.31: Results of the impact assessment for each scenario

OS	Environmental attributes (EA)		Economic attributes (ECA)		Social attributes (SA)				
	EA <sub>1</sub> : Human health	EA <sub>2</sub> : Ecosystem quality	ECA: Net costs	Net	SA <sub>1</sub> : Labor rights and decent Work	SA <sub>2</sub> : Human rights	SA <sub>3</sub> : Health and safety	SA <sub>4</sub> : Governance	SA <sub>5</sub> : Community infrastructure
OS <sub>1</sub>	3.228e-7	1.309e-2	1.207e-2		1.718e-2	4.742e-2	7.217e-2	2.691e-2	4.576e-2
OS <sub>2</sub>	4.02e-7	1.352e-2	1.4e-2		2.331e-2	6.297e-2	9.711e-2	3.466e-2	5.682e-3
OS <sub>3</sub>	1.758e-7	1.156e-2	8.829e-3		1.098e-2	2.178e-2	3.171e-2	1.383e-2	2.308e-3
OS <sub>4</sub>	2.078e-7	1.173e-2	6.336e-3		9.319e-3	2.523e-2	3.891e-2	1.386e-2	2.308e-3
OS <sub>5</sub>	3.222e-7	1.305e-2	1.207e-2		4.81e-3	8.966e-3	8.84e-3	7.905e-3	1.096e-3
OS <sub>6</sub>	1.755e-7	1.155e-2	8.829e-3		4.127e-3	6.38e-3	6.2e-3	6.175e-3	8.635e-4
OS <sub>7</sub>	3.165e-7	1.251e-2	1.172e-2		1.653e-2	4.566e-2	6.942e-2	2.694e-2	4.41e-2
OS <sub>8</sub>	1.718e-7	1.113e-2	8.588e-3		7.985e-3	2.096e-2	3.035e-2	1.329e-2	2.174e-2
OS <sub>9</sub>	4.547e-7	1.361e-2	8.385e-3		2.821e-2	5.856e-2	6.687e-2	4.716e-2	1.332e-2
OS <sub>10</sub>	2.256e-7	1.1789e-2	4.274e-3		2.836e-2	5.892e-2	6.736e-2	4.741e-2	1.339e-2
OS <sub>11</sub>	4.502e-7	1.358e-2	8.385e-3		2.231e-2	3.4629e-2	2.255e-2	3.548e-2	1.109e-2
OS <sub>12</sub>	2.255e-7	1.1759e-2	4.274e-3		2.242e-2	3.48e-2	2.269e-2	3.563e-2	1.113e-2
OS <sub>13</sub>	4.251e-7	1.286e-2	8.156e-3		2.647e-2	5.6e-2	6.554e-2	4.401e-2	1.226e-2
OS <sub>14</sub>	2.16e-7	1.13e-2	4.182e-3		2.695e-2	5.686e-2	6.632e-2	4.485e-2	1.251e-2