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CICLO XXVII

Innovative approaches and models for Green Supply Chain Management: from Design for Environment to Reverse Logistics

Approcci e modelli innovativi per il Green Supply Chain Management: dal Design For Environment alla Reverse Logistics

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ABSTRACT

Emerging environmental, social and economic issues have attracted increasing global concern over the course of the last decade. Many entities, such as governments and companies have taken on the label of “sustainable” to attempt to conciliate the public or try to gain a competitive advantage in the marketplace, but still struggle in effectively integrating sustainability principles into their project or development.

Green Supply Chain Management (GSCM) is a comprehensive philosophy developed in the last years to support companies and governments to improve their environmental sustainability. Green Supply Chain Management implies the pursuit of eco-efficiency for supply chains in their entirety, as a global purpose shared by all stakeholders. Topics like Green Purchasing, Design for Environment (DfE), Closed-Loop Supply Chain (CLSC), Life Cycle Assessment (LCA), Green Manufacturing, Waste Management, Reuse, Remanufacturing, Refurbishment, and Reverse Logistics (RL) fall under the main umbrella of GSCM.

The objective of this research is the study, adaptation, integration, development and application of innovative approaches and models for decision-making support in the context of GSCM. Such methodologies are expected to lead decision-makers, in particular companies, in the management of product and service design. In particular, this thesis focuses on the integration of LCA methodology in the DfE of prototypal devices and mechanical plants, on application and integration of LCA and Life Cycle Costing (LCC) in the analysis of economic and environmental performances of supply chains, on the modelling by single- and multi-objective optimisation problems in the design and planning of CLSCs.

In this research, the role of LCA as methodological central thread clearly emerges. As a start, LCA has been adopted as supporting tool in DfE of products. Then, combined with LCC, as part of a comprehensive economic-environmental evaluation of multiple options in the logistics of the distribution of products. Finally, through the implementation in a Multi-objective optimisation model, LCA has been included in a decision support tool for the optimal design and planning of a CLSC. In summary, this research can be also understood as a path, in which LCA has evolved from *ex post* assessment method, to *ex ante* optimisation tool.

SOMMARIO

L’ultimo decennio è stato caratterizzato dalle emergenti questioni ambientali, sociali ed economiche che hanno attirato una crescente preoccupazione globale. Molte organizzazioni, come governi ed imprese, hanno assunto l'etichetta di "sostenibile" per tentare di conciliare l’opinione pubblica o cercare di ottenere un vantaggio competitivo sul mercato, ma non sono riusciti a integrare efficacemente i principi della sostenibilità nel loro progetto di sviluppo.

Green Supply Chain Management (GSCM) è una filosofia globale sviluppata negli ultimi anni per sostenere imprese ed organizzazioni governative nel miglioramento della loro sostenibilità ambientale. GSCM implica il perseguimento dell’ eco-efficienza delle Supply Chain nella loro interezza, come obiettivo globale, condiviso da tutte gli stakeholder coinvolti. GSCM contiene temi cruciali quali Green Purchasing, Design for Environment (DfE), Closed-Loop Supply Chain (CLSC), Life Cycle Assessment (LCA), Green Manufacturing, Waste Management, Reuse, Remanufacturing, Refurbishment, e Reverse Logistics.

L'obiettivo di questa ricerca è lo studio, l'adattamento, l'integrazione, lo sviluppo e l'applicazione di approcci e modelli innovativi per il supporto decisionale nel contesto di GSCM. Tali metodologie sono orientate a guidare i decision-makers, in particolare le imprese, nella progettazione e gestione di prodotti e servizi. In particolare, questa tesi si concentra sulla integrazione della metodologia LCA nel processo di DfE di dispositivi prototipali e impianti meccanici, sull'applicazione e l'integrazione di LCA e Life Cycle Costing (LCC) nell'analisi delle prestazioni economiche e ambientali di supply chain, sulla modellazione di problemi di ottimizzazione singolo e multi-obiettivo per la progettazione e pianificazione di filiere ad anello chiuso.

In questa ricerca, il ruolo di LCA come filo conduttore metodologico emerge chiaramente. Dapprima, LCA è stato adottato come strumento di supporto nel DfE di prodotti. A seguire, in combinazione con LCC, come parte di una valutazione economica-ambientale globale delle diverse opzioni nella logistica della distribuzione di prodotti. Infine, attraverso la realizzazione di un modello di ottimizzazione multi-obiettivo, la metodologia LCA è stato inclusa in uno strumento di supporto alle decisioni per la progettazione e la pianificazione ottimale di una filiera a ciclo chiuso. In sintesi, questa ricerca può essere inteso come un percorso che guida l’evoluzione della metodologia LCA da metodo di valutazione *ex post*, a strumento di ottimizzazione *ex ante*.

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Innovative approaches and models for Green Supply Chain Management: from Design for Environment to Reverse Logistics

by

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“Growth for the sake of growth
is the ideology of the cancer cell.”
Edward Abbey

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1 INTRODUCTION

Emerging environmental, social and economic issues have attracted increasing global concern over the course of the last decade. Many entities, such as governments and companies have taken on the label of “sustainable” to attempt to conciliate the public or try to gain a competitive advantage in the marketplace, but have failed in effectively integrating sustainability principles into their project or development. One additional feature does not make a house sustainable. Several of these houses do not create a sustainable community and, a few of these communities do not produce a sustainable society. Misrepresentations of sustainability meaning and its principles have tended to diminish its perceived importance and reduce its potential as a vehicle for creating a new development ethic for individuals and communities. Sustainability must be considered from a holistic point of view and this get its understanding an arduous challenge. Therefore, sustainability can be pursued effectively and consciously only through the adoption of a comprehensive scientific approach.

Green Supply Chain Management is a comprehensive philosophy developed in the last years to support companies and governments to improve their environmental sustainability. Green Supply Chain Management implies the pursuit of eco-efficiency for supply chains in their entirety, as a global purpose shared by all stakeholders. Topics like Green Purchasing, Design for Environment, Closed-Loop Supply Chain, Product Life Cycle Assessment, Green Manufacturing, Waste Management, Reuse, Remanufacturing, Refurbishment, and Reverse Logistics fall under the main umbrella of Green Supply Chain.

The objective of the research here presented is the study, adaptation, integration, development and application of innovative approaches and models for decision-making support in the context of Green Supply Chain Management. Such methodologies are expected to lead decision-makers, in particular companies, in the management of product and service design. In particular, this thesis focuses on the integration of Life Cycle Assessment methodology in the Design for Environment of prototypal devices and mechanical plants, on application and integration of Life Cycle Assessment and Life Cycle Costing in the analysis of economic and environmental performances of supply chains, on the modelling by single- and multi-objective optimisation problems in the design and planning of closed-loop supply chains.

1.1 RESEARCH FRAMEWORK

The research presented in this dissertation has been developed according to a structured framework (Figure 1.1.1). Such a framework is organised according to a main issue, i.e. Green Supply Chain, a set of sub-topics, a set of tools and methodologies, and a series of applications, obtained by the combination of topics and methodologies on industrial case studies.

Green Supply Chain Management is defined as the integration of Sustainability, Life Cycle Engineering and Supply Chain Management. Among the several issues that fall under the umbrella of Green Supply Chain Management, in this thesis the topics of Design for Environment, Reverse Logistics and Closed-Loop Supply Chain, the triple R (Reuse, Remanufacturing and Refurbishment), Green Supply Chain design and planning have been considered as particularly relevant and of greatest interest, as supported by several authors (Ageron et al., 2012; Ahi and Searcy, 2013; Ashby et al., 2012; Brett-Crowther, 1983; Carter and Rogers, 2008; Elkington, 1998; Graedel and Allenby, 2009; Hauschild et al., 2005; Jeswiet, 2003; Meadows, 1972; Rosen and Kishawy, 2012; Sarkis, 2003; Seuring and Müller, 2008; Srivastava, 2007; Tsoulfas and Pappis, 2006).

The methodologies and tools considered in this research are Life Cycle Assessment, Life Cycle Costing, Multi-scenario and sensitivity analysis, Mixed Integer Linear Programming and Multi-Objective Mixed Integer Linear Programming. Dotted lines in Figure 1.1.1 indicates the combination and integration of different methodologies: Life Cycle Costing and Mixed Integer Linear Programming; Life Cycle Costing, Life Cycle Assessment and Multi-Objective Mixed Integer Linear Programming.

Topics and methodologies find their intersection in applications. This research has been addressed on two main areas: the integration of Life Cycle Assessment methodology in Design for Environment of certain prototypical devices and mechanical plants; the development of decision support tools for the supply chain design and planning in the automotive and fresh food sectors.

The choice of a so extended range of applications is explained by the will of presenting a comprehensive set of problems in the context of Green Supply Chain Management. Since there is no solution that fits for every problem, depending on the specific issue, different approaches and methodologies have been selected, adapted and applied. In a few cases, the integration of several methods have been required in order to approach to certain issues from different viewpoints. As a result, this research shows an evolutionary itinerary in the evolution and application of methodologies for Green Supply Chain management: from the mere application of Life Cycle Assessment, to its completion with multi-scenario and sensitivity analysis, to its combination with Life Cycle Costing, to the final integration of economic and environmental Life Cycle analyses in multi-objective optimisation. During this path, Life Cycle Assessment, that represents one of the cores of the research, evolves from ex-post assessment method to an ex-ante optimisation support tool.

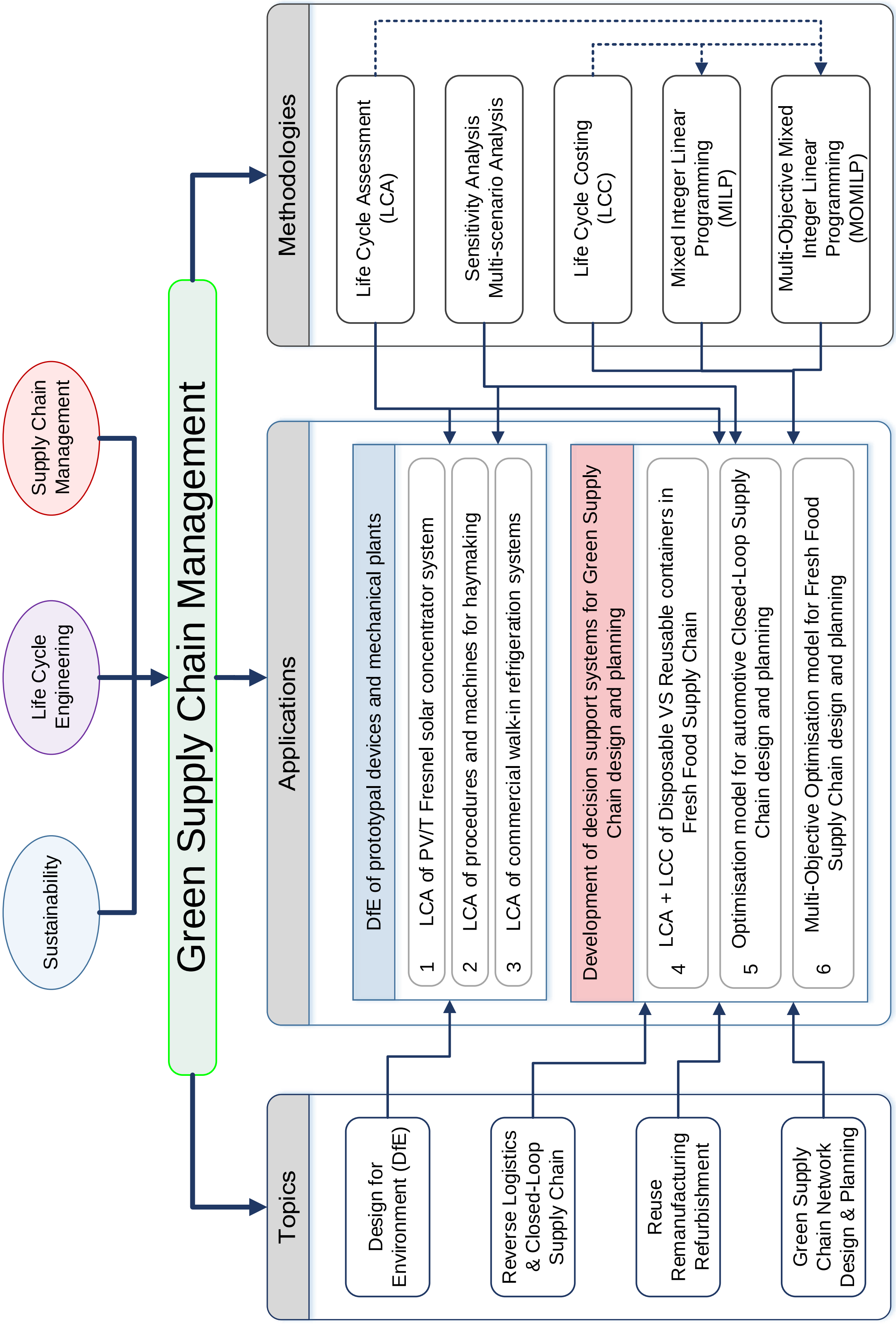

Figure 1.1.1 - Research framework

1.2 THESIS OUTLINE

This thesis has been developed in accordance with the research framework presented above. For the sake of linearity, topics, methodologies and applications have been debated and arranged in a sequence of chapters, as shown in Figure 1.2.1.

After an introduction on purpose and structure of this research, the triple bottom line of sustainability, the ideas of life cycle approach and life cycle engineering are presented in Chapter 2.

Chapter 3 is focused on the presentation of Green Supply Chain Management. The different definitions of Green Supply Chain Management proposed by the literature are discussed and the main topics that fall under its umbrella are presented and classified in a hierarchy, in which two research areas, i.e. Green Design and Green Operations, are distinguished. A survey on the meanings of Green Design and Green Operations is reported and a set of sub-topics are discussed for each area.

Because of the importance of Life Cycle Assessment in this research, a whole chapter, i.e. Chapter 4, is dedicated to the introduction to this methodology, to its combinations with Life Cycle Costing and to its extension in Social Life Cycle Assessment.

As a result of the classification proposed in Chapter 3, applications in the context of Green Design and Green Operations are presented in Chapter 5 and Chapter 6, respectively.

In Chapter 5, the integration of Life Cycle Assessment in Design for Environment of prototypal devices and mechanical plants is discussed. The section presents studies on the environmental impact associated with the life cycle of an innovative hybrid solar system equipped with Fresnel lenses and bi-axial sun-tracking system, standalone and multifunctional machines for haymaking, walk-in commercial refrigeration systems for medium- and low-temperature food preservation. Through the application of Life Cycle Assessment methodology on different cases, pros and cons, benefits and limits of this tool are discussed step by step.

According to the classification adopted and described in Chapter 3, Chapter 6 presents the research on the area of Green Operations, in particular in the design and planning of Closed-Loop Supply Chain networks according to the principles of Green Supply Chain Management. The cases of the automotive closed-loop supply chain and the closed-loop supply chain of containers for fresh food distribution are assumed as representative of the various industrial sectors on which the research on decision-support tools for supply chain design and planning can be useful. A combination of methodologies is here presented. Life Cycle Assessment and Life Cycle Costing are adopted as support to strategic and tactical decisions in fresh food distribution system. A Mixed Integer Linear Programming model is used as support for the design and planning of a network for end-of-life vehicles recovery, remanufacturing of parts and their reuse, with the purpose of minimising vehicle life cycle cost, i.e. costs bearing on Original Equipment Manufacturers and customers.

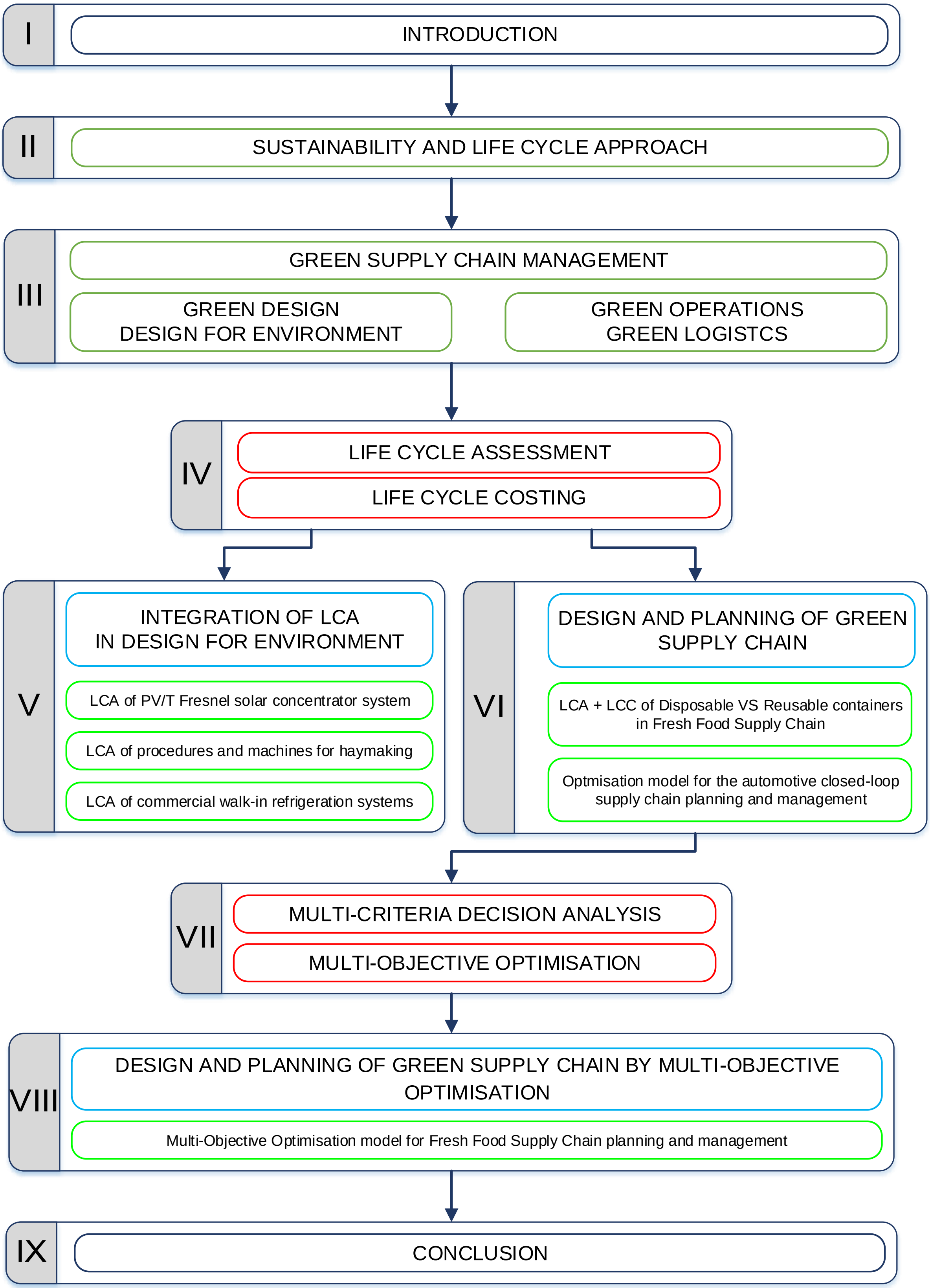

Figure 1.2.1 - Thesis outline structure

As a result of the conclusions presented in the previous chapters, Chapter 7 introduces the family of Multi-Criteria Decision Analysis methodologies, among which particular attention is paid to Multi-objective optimisation methods.

Chapter 8 focuses on the issue of Multi-objective optimisation. In particular, a Multi-objective Mixed Integer Linear Programming model for the design and planning of a closed-loop supply chain network for the distribution of fresh food is presented. The study resumes the main results presented in Chapter 6 and represents the final step of the methodological evolutionary path presented in this thesis: Life Cycle Assessment, Life Cycle Costing and Mixed Integer Linear Programming are combined in a comprehensive decision-support tool. The chapter presents the developed model and the results of its application on an illustrative case study.

Results of the research presented in this dissertation are then resumed in Chapter 9.

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2 ENVIRONMENTAL SUSTAINABILITY AND LIFE CYCLE APPROACH

2.1 SUSTAINABILITY

2.1.1 Definition for Sustainable Development

In the last decades, one has witnessed an increasing investigation of the factors characterising the development processes of industrialised countries. It emerged that the environmental and social risks that are implicit in an industrial development are affected exclusively by economic mechanisms.

However, the comprehension of the scarcity of natural resources and of the vulnerability of biosphere health induced a deep re-thinking of the concept of development, as a process harmonised with the environment, in the interests of present and future generations.

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987).

With this definition, in 1987 the World Commission on Environment and Development (WCED) , also known as Brundtland Report, established the guiding objective of the current process of economic and technological development: to ensure that the use of environmental resources to satisfy present demands is managed in a way that they can be exploited also by future generations.

This definition, which was first formulated in (Brett-Crowther, 1983), was also intended as a response to the worrying conclusions reached in 1972 by the so-called Club of Roma. Analysing the provisional results of a mathematical model of the world development system, based on the interaction between five key factors, i.e. population growth, food production, industrialisation, resource depletion, and pollution, the Club of Roma concluded that economic and industrial growth would come to a stop in the near future due to the exiguity of natural resources, with a consequent decline in the population level and in the industrial system: “If the actual line of development continues unchanged in these five principal sectors, humanity is destined to reach the natural limits of development within the next 100 years” (Meadows, 1972).

Alternative definitions for sustainability and sustainable development have been proposed over time.

“Improving the quality of human life while living within the carrying capacity of supporting eco-systems” (IUCN/UNEP/WWF, 1991).

“Sustainability is the ability to achieve continuing economic prosperity while protecting the natural systems of the planet and providing a high quality of life for its people” (U.S. Environmental Protection Agency, n.d.)

Sustainability is the "long-term, cultural, economic and environmental health and vitality" with emphasis on long-term, "together with the importance of linking our social, financial, and environmental well-being". (Sustainable Seattle, n.d.)

"Sustainable development involves the simultaneous pursuit of economic prosperity, environmental quality and social equity. Companies aiming for sustainability need to perform not against a single, financial bottom line but against the triple bottom line." (World Business Council on Sustainable Development, n.d.)

The majority of the proposed definition claims that sustainability is based on three dimensions, i.e. economy, environment and society, which are defined as "the three pillars of sustainability".

2.1.2 The three Pillars of Sustainability

According to Rosen and Kishawy (2012), sustainability "is simply the ability to endure or survive". Sustainability describes the productivity and diversity over time of biological systems, from an ecological perspective, and the potential for long-term welfare, from a human perspective. The latter depends on the wellbeing of the natural world, including the responsible use of natural resources and disposal of wastes. At its core, sustainable development is the view that social, economic and environmental concerns should be addressed simultaneously and holistically in the development process of any human society. Figure 2.1.1 represents the three dimensions of sustainability.

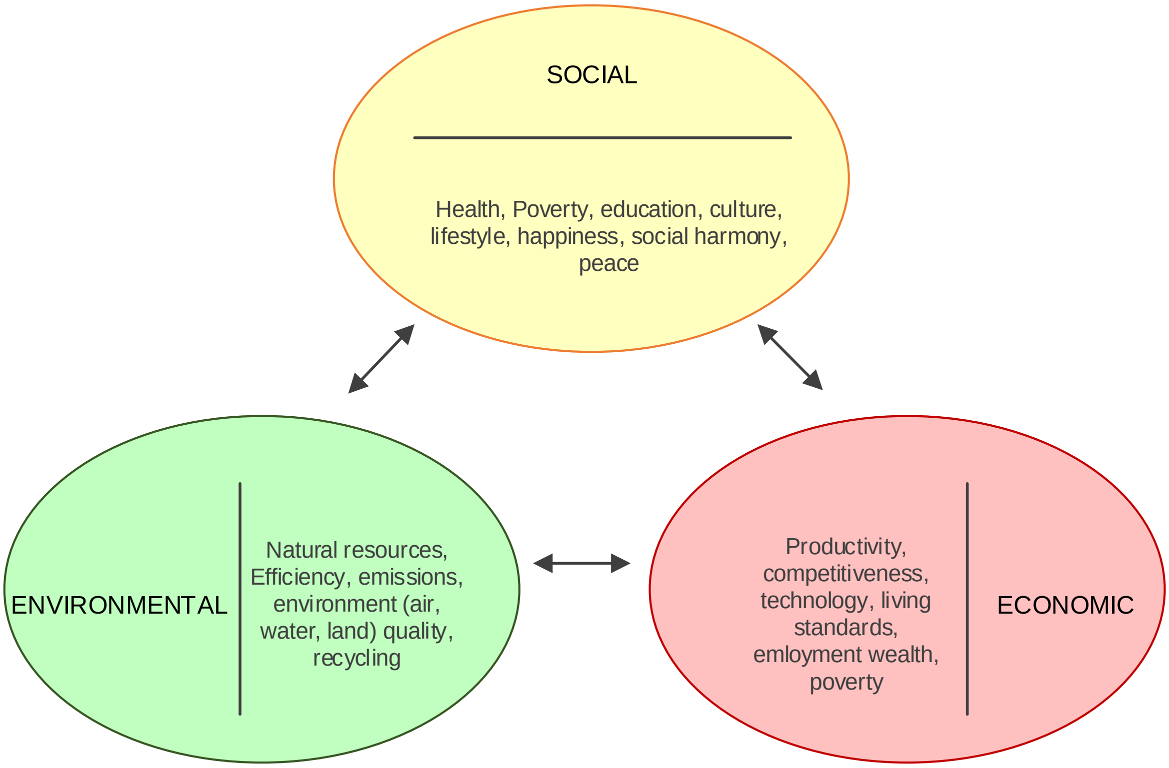

Figure 2.1.1 - The three pillars of sustainability. Adapted from Rosen and Kishawy (2012)

As a consequence, achieving sustainability requires an integrated approach and multi-dimensional indicators that link a community's economy, environment and society (Elkington, 1998; Rosen and Kishawy, 2012). The so-called "triple bottom line" concept of sustainability is given in Figure 2.1.2.

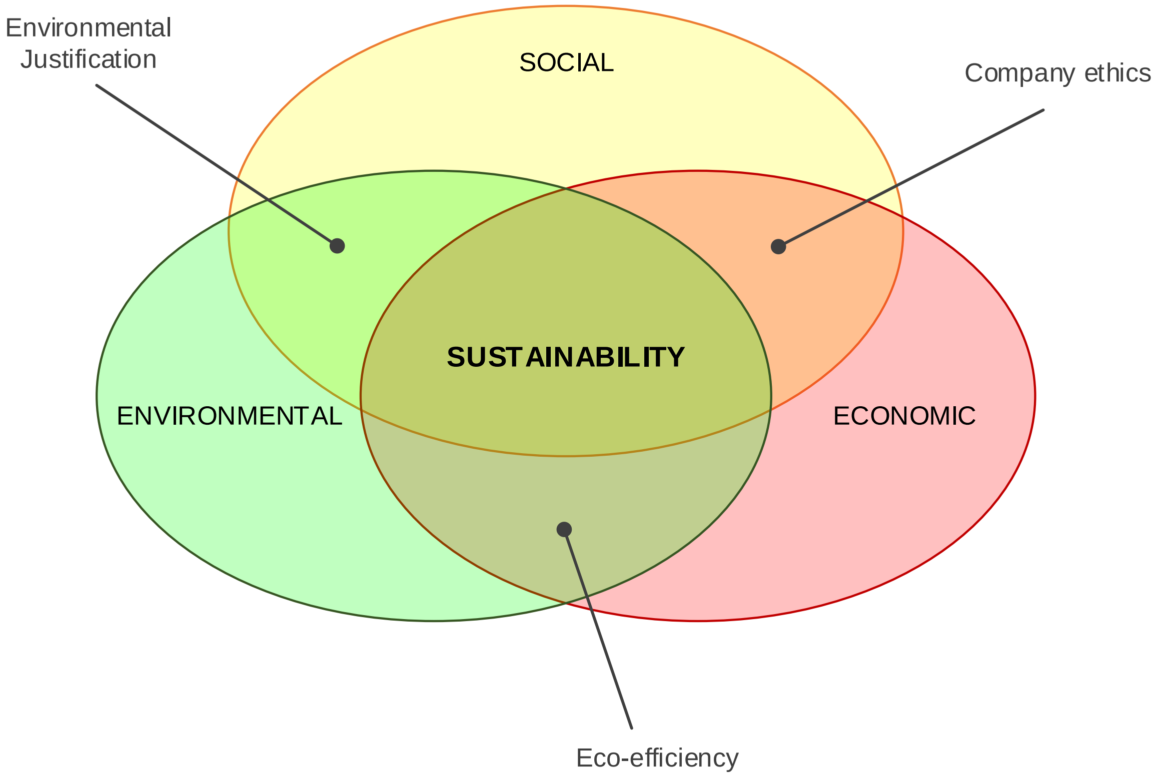

Figure 2.1.2 - The triple bottom line concept of sustainability. Adapted from Hauschild et al. (2005)

In the intersection between the economic and the social dimension of sustainability lies the “company ethics” concerning the way in which the company behaves towards the people and the community, e.g. employees, suppliers, neighbours. For a sustainable industrial company, the traditional focus on the shareholders is broadened to include a wide range of stakeholders along its product chain, and issues like discrimination, child labour, corruption and fair working conditions all reflect the company ethics at the intersection between the economic and social dimensions of sustainability.

The “justification of the product” represents the intersection between the environmental and the social dimensions. Industry should address the environmental justification of the product demonstrating the relevance of the product to society. Companies should ask themselves whether the impacts caused by their product is justified by the service it provides to the user, and whether society have a real need for their product or the function it serves could be fulfilled in a more sustainable way.

This research focuses on the intersection between economic and environmental sustainability, i.e. the so-called eco-efficiency.

2.1.2.1 Eco-efficiency

In the intersection between the environmental and the economic dimension lies the “eco-efficiency”. Graedel and Allenby (2009) express, in their “master equation”, the impact on the environment as a product of:

- Global population
- The material standard of living, expressed as Gross Domestic Product (GDP) per capita
- The environmental efficiency of our society and technology, expressed as the ratio between the total environmental impact and the total economic activity

$$Environmental\ impact = Population\ \times GDP\ per\ capita\ \times \frac{Environmental\ Impact}{GDP}$$

The first two factors are ruled by social and economic factors, while the third term represents the reciprocal eco-efficiency.

Therefore, eco-efficiency is defined as follows:

$$Eco - efficiency = \frac{GDP}{Environmental\ Impact}$$

Optimistic population forecasts predict that the world population may stabilise around twice the current number in the second half of XXI century. On the same period, a doubling in the global average material standard of living must therefore be expected, particularly in the developing countries.

According to the master equation, global eco-efficiency must increase by more than a factor of four just to keep the current level of environmental impact. Despite some local promising improvements, the general picture shows a situation that is clearly not sustainable. According to Schmidt-Bleek (1995), Elkington (1998) and Hauschild et al. (2005), considering a desirable reduction in total environmental impacts and uncertainties in the growth of population and economic parameters, the challenge to the eco-efficiency for our society and manufacturing industry is presented as a factor ten improvement.

2.1.3 Life Cycle Approach

Increasing the eco-efficiency of the global economy, which means decreasing the environmental impact associated with the anthropogenic processes that determine the degree of development of civilisations that co-exist on our planet, is a crucial goal with highest priority. In the definition of eco-efficiency, companies are explicitly mentioned as one of the key players in the pursuit of a more sustainable society.

Jeswiet (2003) defines the “Life Cycle Engineering” (LCE) as: “the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimising the product life cycle and minimising pollution and waste.”

Hauschild et al. (2005) summarise the same concept with “LCE covers the engineering activities addressing industry’s environmental impacts in a product life cycle perspective.”

Jeswiet (2003) also defines LCE as a multitude of topics such as: sustainability, economics, market, economic progress, social concern, environment, protect the environment, minimise pollution/waste, resource conservation, engineering activities, optimisation, ecodesign, green design, product life cycle, product/process assessment. Aim of LCE is to improve the eco-efficiency of the industrial activities, defined as the ratio between the service that is provided by the activities and the environmental impacts associated with providing such a service.

Starting from the classification of Wenzel and Alting (2004), Rosen and Kishawy (2012) define three levels on which LCE can address the eco-efficiency:

- Product: the manufacturing strategy for environmentally benign products involves a design process that accounts for environmental impacts over the life of the product. Product design is usually associated with Design for Environment (DFE) and Life Cycle Assessment (LCA), which are presented in the following chapters.

- Process: environmental improvements related to manufacturing processes are linked to reduction, reuse, recycling and remanufacturing. Closed-loop manufacturing system considers the manufacturing system as an industrial ecosystem, in which wastes or by-products are reused within the manufacturing system. Therefore, closed-loop manufacturing requires capabilities for pollution prevention and waste reuse.

- Practices: organisational manufacturing practices can be used strategically to improve manufacturing, through such other activities as benchmarking and performance measurement, since such schemes assist companies in developing and maintaining new environmental programs and technologies.

In other terms, according to this classification, Life Cycle Engineering addresses the eco-efficiency by focusing on the design of product and its manufacturing process by using organisational practices. Even though such a classification takes into account the whole life cycle of a product, it seems that eco-efficiency strategies are limited to the industrial activities of product development and manufacturing. On the contrary, product life cycle is characterised also by material procurement, operations, logistics marketing, regulatory compliance and waste management (Srivastava, 2007). Often, also product use by final customer affects the life cycle impact. Westkämper et al. (2001) defines LCE as only a part of Life Cycle Management (LCM), which considers the product life cycle in a more holistic way.

2.1.4 Towards a more holistic idea of product life cycle

Sarkis (2003) revolutionises the conventional concept of “life cycle” by subverting the viewpoint. Sarkis introduces the concept of “operational life cycle” (or value chain) of an organisation as “a more tactical set of organisational elements that will influence how the supply chain is to be managed (either internally or externally)”, in which the operational life cycle includes procurement, production, distribution, packaging life cycle, and reverse logistics. Such a definition is a further step towards the connection between the concepts of product Life Cycle and Supply Chain. According to Handfield and Nichols (1999) “the Supply Chain encompasses all activities associated with the flow and transformation of goods from raw materials stage (extraction), through to the end user, as well as the associated information flows, material and information flow both up and down the supply chain.” Seuring and Müller

(2008) completes with “Supply Chain Management is the integration of these activities through improved supply chain relationships to achieve a sustainable competitive advantage”.

In summary, eco-efficiency can be defined as the ratio between the capability of offering a service and the environmental impact associated with it. Therefore, increasing eco-efficiency means decreasing its denominator. “Offering a service” includes also “providing a product” in case, as usual, a physical object is the means for a need fulfilment. Product life, in turn, is not limited to its use by the final user. Nor it is limited to its design and manufacturing. Product life cycle is understood as the crossing through a series of life stages, from design, to the supply of raw materials, to its manufacturing, distribution, use, maintenance, collection, to its end-of-life and, in case, to its recycle/reuse/remanufacture/recovery. During its life, a product moves from one to another, along the steps of a Supply Chain, or rather, along a Closed Loop Supply Chain: from raw material suppliers, to feedstock transformers, to product manufacturers, assemblers, distributors, users, waste collectors and managers, recyclers, and then again to raw material suppliers. Such an awareness brings to a broadened view of product life cycle as a conjoint activity of different stakeholders then, in turn, to the definition for Sustainable Supply Chain Management and Green Supply Chain Management.

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3 GREEN SUPPLY CHAIN MANAGEMENT

There is an increasing recognition that organisations must address the issue of sustainability in their operations. Different definitions for sustainability are presented in Chapter 2. The term “sustainability” has been interpreted in a variety of ways, ranging from an inter-generational philosophical position to a multi-dimensional term for business management. The most recent definitions agree in the adopting of a triple bottom approach: economic, environmental, and social. In the previous chapter, according to the main intent of this research, the intersection between environmental and economic sustainability, defined eco-efficiency by Graedel and Allenby (2009), has been deepened. In addition, the relationship between eco-efficiency and product life cycle has been discussed, and the parallelism between product life cycle and supply chain management introduced. In this chapter, the concepts of Green Supply Chain Management and Sustainable Supply Chain Management are presented. Particularly, the meaning of Green Supply Chain Management is investigated through an extended literature review. Finally, the main topics in Green Supply Chain, which are faced in the research presented in this thesis, are integrated in a research framework. Ecodesign, Design for Environment, Green Design, Green Logistics, Green Operations, and Reverse Logistics are presented and organised as components of Green Supply Chain Management.

3.1 FROM SUSTAINABLE SUPPLY CHAIN MANAGEMENT TO GREEN SUPPLY CHAIN MANAGEMENT

Supply chain contemplates the product from initial processing of raw materials to distribution to the user, and then, if the loop is closed, from collection to the reintroduction in a new supply chain. A focus on supply chains is a step toward the wider adoption and development of sustainability. The topic of sustainability in the context of Supply Chain Management (SCM) has been discussed using a number of terms in the literature. Sustainability and SCM are two concepts that have created many debates over the last decade (Seuring and Müller, 2008). The two terms used that most closely link sustainability and SCM concepts are Green Supply Chain Management (GSCM) and Sustainable Supply Chain Management (SSCM) (Ashby et al., 2012). Ahi and Searcy (2013) propose a survey on the published definitions for GSCM and SSCM.

3.1.1 Definitions for Sustainable Supply Chain Management

Table 3.1.1 reports some definitions for SSCM

Source	Definition
Carter and Rogers (2008)	The strategic, transparent integration and achievement of an organisation's social, environmental, and economic goals in the systemic coordination of key inter-organisational business processes for improving the long-term economic performance of the individual company and its supply chains.
Seuring and Müller (2008)	The management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements.
Seuring (2008)	The integration of sustainable development and supply chain management [in which] by merging these two concepts, environmental and social aspects along the supply chain have to be taken into account, thereby avoiding related problems, but also looking at more sustainable products and processes.
Ciliberti et al. (2008)	The management of supply chains where all the three dimensions of sustainability, namely the economic, environmental, and social ones, are taken into account.
Haake and Seuring (2009)	The set of supply chain management policies held, actions taken, and relationships formed in response to concerns related to the natural environment and social issues with regard to the design, acquisition, production, distribution, use, reuse, and disposal of the firm's goods and services.

Table 3.1.1 - Definitions for Sustainable Supply Chain Management

There is full agreement on the multi-dimensionality of sustainability. All definitions explicitly take into account the three pillars of sustainability. On the other hand, with reference to the meaning of supply chain management different versions are proposed: from the integration and achievement of goals, to the management of material information, capital flows and cooperation, to the set of policies held, actions taken and relationships formed with regard to the design, acquisition, production, distribution, use, reuse, and disposal of goods and services. We consider this last, from Haake and Seuring (2009), the most comprehensive definition for SSCM.

3.1.2 Definitions for Green Supply Chain Management and main topics

Table 3.1.2 reports a list of definitions for GSCM

Source	**Definition**
Handfield et al. (1997)	Application of environmental management principles to the entire set of activities across the whole customer order cycle, including design, procurement, manufacturing and assembly, packaging, logistics, and distribution.
Zhu et al. (2005)	An important new archetype for enterprises to achieve profit and market share objectives by lowering their environmental risks and impacts while raising their ecological efficiency.
Hervani et al. (2005)	Green Purchasing + Green Manufacturing/Materials Management + Green Distribution/Marketing + Reverse Logistics
Wee et al. (2011)	Integration of environment considerations into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, and end-of-life management of the greening products.
Gnoni et al. (2011)	An approach that aims to integrate environmental issues into SC management procedure starting from product design, and continuing through material sourcing and selection, manufacturing processes, the final product delivery and end-of-life management.
Srivastava (2007)	Integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life.

Table 3.1.2 - Definitions for Green Supply Chain Management

The definitions for GSCM are more focused than those for SSCM are, and have a greater emphasis on the topic of environmental sustainability. Though some definitions of SSCM show considerable overlap with definitions of GSCM, it is clear that SSCM is essentially an extension of GSCM.

Zhu et al. (2005) mention the achieving of profit while raising eco-efficiency as the main goal of GSCM. Different from the case of SSCM, for GSCM there is large agreement on the extension of SCM activities, with a few differences. Handfield et al. (1997) consider the product life cycle from design to distribution to customer, Wee et al. (2011) include also reverse logistics, as well as Hervani et al. (2005) who, however, do not consider product design.

The most comprehensive definitions are given by Gnoni et al. (2011) and Srivastava (2007), who consider GSCM as the integration of SCM activities from product design to end-of-life management of the product after its useful life. According to this point of view, product life cycle, from cradle to gate, is the subject of all activities of GSCM, so that there is a full matching between the two concepts.

Figure 3.1.1 shows a schematic representation of product life cycle and at the same time, its integration in the supply chain activities. Blue arrows represent the flow of product life cycle: from the extraction of raw materials, through their transformation in feedstock, the manufacturing and assembly of the final product, its distribution and use and, finally, the collection and the end-of-life management. In green the reverse logistics of the product after the end of its useful life and its reintegration in the life cycle of a new product, in a closed loop supply chain. In yellow, the energy flow absorbed by the product during the life cycle and, in red, the waste flow of waste generated along the steps of the supply chain. Above all, we consider the GSCM as the combined action of product design and process design, according to the definitions given by Rosen and Kishawy (2012).

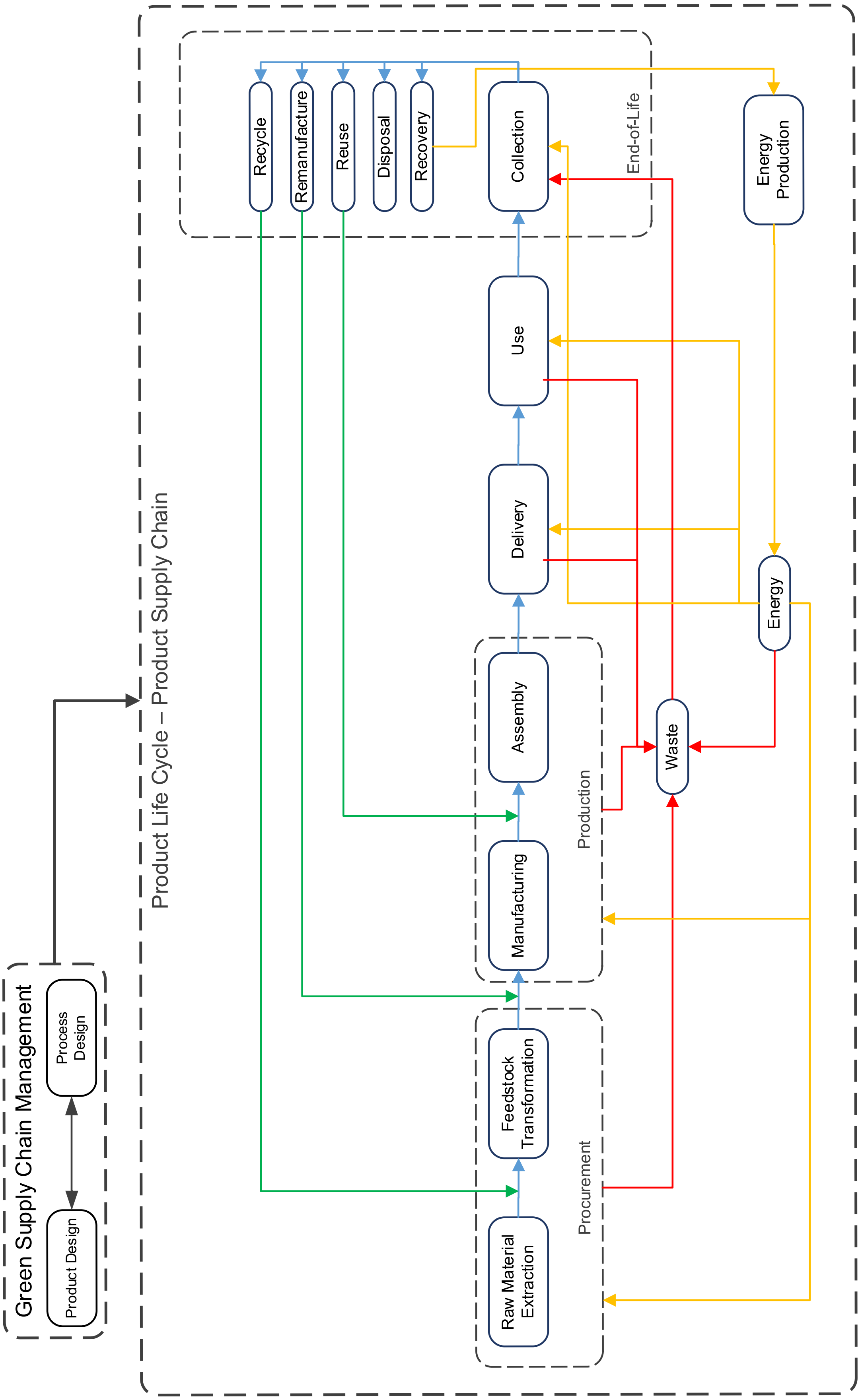

Figure 3.1.1 - Product Life Cycle in the Green Supply Chain. Readapted from Sarkis (2003)

Product design involves the design of a product having regard for every effect that the selection of materials, shape, physical characteristics, function, durability and handleability, has downstream, on the following life cycle steps, and upstream, when the life cycle start from the scraps of a previous product life. Operation design, also referred as process design, involves every single choice and evaluation of alternatives about the selection and definition of how to perform, ceteris paribus, a certain service; e.g., the selection of the packaging, the design of a delivery process, the distribution network design, the selection of a process for waste classification, the energy source selection, the strategy for reverse logistics, the policy for component remanufacturing. Product design and process design reciprocally influence each other and affect every single step of product life cycle and product supply chain. For this reason, we consider the GSCM as the combination of product design and process design along the whole product/service life cycle from a closed loop perspective. Such a definition matches with the meaning expressed by Srivastava (2007). Srivastava proposes a classification of current problem contexts in GSCM, i.e. importance of GSCM, Green Design, and Green Operations, and articulates these main topics in classes of subtopics. Figure 3.1.2 represents GSCM topic hierarchy. The topics on which this research focuses on are highlighted by red boxes.

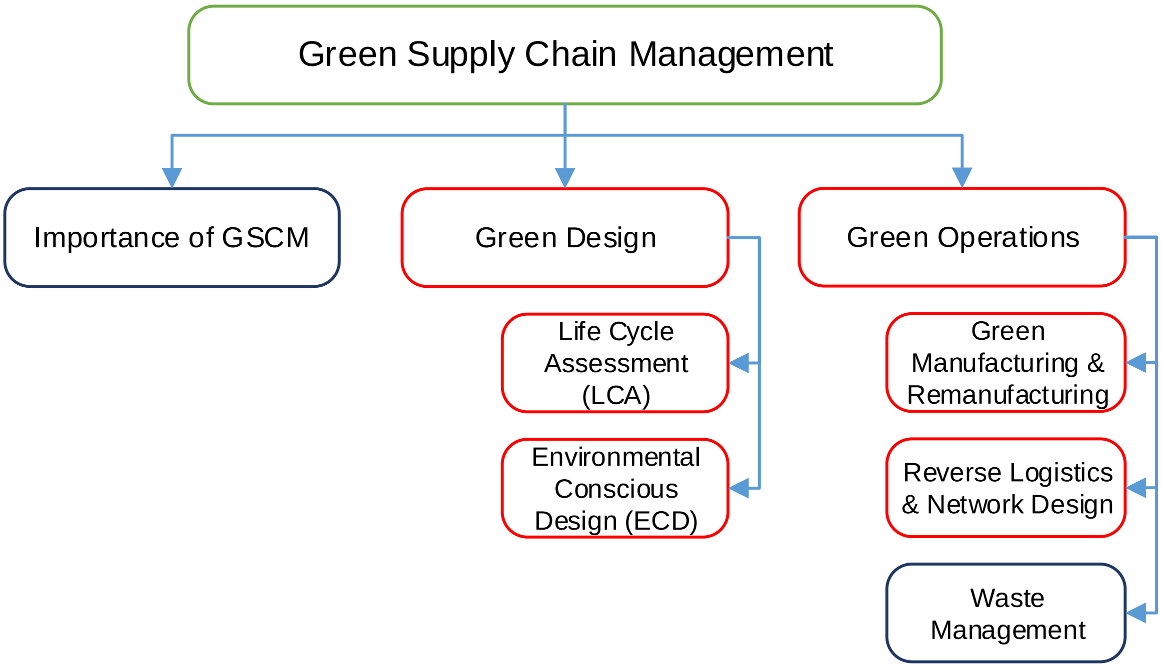

Figure 3.1.2 - Classification of GSCM main topics. Readapted from Srivastava (2007)

In addition to “importance of GSCM”, Srivastava (2007) identifies two main topics, i.e. Green Design and Green Operations, which matches the definition of GSCM adopted in this study and depicted by Figure 3.1.1. The term “Green” is used a synonym of “environmental focused”, or rather, “eco-efficiency focused”, since the dual objective of economic and environmental sustainability pursuit is implicitly declared.

3.1.2.1 Green Design

Green Design is used to denote the systematic consideration of design issues associated with environmental safety and health over the full product life cycle during new production and process development (Fiksel, 1993). The meaning of Green Design will be deeply analysed in Chapter 3.2, in which overlaps and parallelisms with Design for Environment, Ecodesign are discussed.

The two main subtopics proposed by Srivastava (2007) are Life Cycle Assessment (LCA) and Environmental Conscious Design (ECD). Srivastava neglects the interaction and the hierarchy between the two topics. On the contrary, such an argument is discussed Chapter 3.2. Particularly, the LCA approach is deepened in Chapter 4 and its integration in Green Design is discussed in Chapter 5, by reporting real applications of LCA in the design of prototypal mechanical plants.

3.1.2.2 Green Operations

Green Operations are related to product manufacturing/remanufacturing, use, handling, logistics and waste management and reverse logistics once the design has been finalised. Srivastava (2007) proposes three main subtopics related to Green Operations: Green Manufacturing and Remanufacturing, Reverse Logistics and Network Design, and Waste Management.

Green manufacturing aims at reducing the environmental burden by using appropriate material and technologies, while remanufacturing refers to the restoration to as-good-as-new condition of consumed products. Tibben-Lembke (2002) defines Reverse Logistics as “the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal”. Network design aims at accommodating product returns and remanufacturing, and the re-use of such parts and components (closed loop supply chain network design). For example, the physical location of facilities and the selection of best optimal routes helps in turning reverse logistics profitable for the whole supply chain and, in turn, in conveying used products from their former users to a producer and to future markets again (Fleischmann et al. 2001). Chapter 3.3 focuses on the concept of Green Operations and explores the meanings of Green Logistics, Reverse Logistics, and Supply Chain Network Design. Particularly, Chapter 8 discusses the application and integration of different methodologies (e.g. Life Cycle Assessment, Life Cycle Costing and Mixed Integer Linear Programming) for the Closed Loop Supply Chain Network Design in different sectors.

3.2 GREEN DESIGN, ECODESIGN AND DESIGN FOR ENVIRONMENT

3.2.1 Definitions

During the 1990s the need of introducing the practice of a design action directed at reducing the environmental impact of products has been emphasised by many authors (Allenby, 1994; Ashley, 1993; Billatos and Basaly, 1997; Brezet and van Hemel, 1997; Dowie, 1994; Fiksel, 1996; Graedel and Allenby, 1998; Zhang et al., 1997). However, this new design practice/procedure/philosophy has been presented in literature through a plethora of different terms and related definitions.

Navinchandra (1991) defines “Design for Environmentability” as “the study of and an approach to product and process evaluation and design for environmental compatibility that does not compromise products' quality or function."

Zhang et al. (1997) define “Environmental Conscious Design & Manufacturing (ECD&M)” as “a view of manufacturing that includes the social and technological aspects of the design, synthesis, processing, and use of products in continuous or discrete manufacturing industries. ECD&M is a proactive approach to minimise the product's environmental impact during its design and manufacturing, and thus to increase the product's competitiveness in the environmentally conscious market place.”

Fiksel (1996) defines “Design for Environment (DfE)” as “the systematic consideration of design issues associated with environmental safety and health over the full product life cycle during new production and process development.”

Also Billatos and Basaly (1997) propose a definition for DfE as “a design process that must be considered for conserving and reusing the earth’s scarce resources; where energy and material consumption is optimised, minimal waste is generated and output waste streams from any process can be used as the raw material (inputs) of another.”.

According to Giudice (2006) “DFE can be defined as a methodology directed at the systematic reduction or elimination of the environmental impacts implicated in the whole life cycle of a product, from the extraction of raw materials to disposal.”.

In their survey, Karlsson and Luttropp (2006) declare: “Ecodesign focuses on the integration of environmental considerations in product development”.

According to Giudice (2006), Hauschild et al. (2004) and Lagerstedt (2003), Design for Environmentability, Environmental Conscious Design, Design For Environment, but also Ecodesign, Clean Design, Life Cycle Engineering, Life Cycle Design and Green Design have the same meaning and can be used as synonyms.

Since the most common term used in literature is Design for Environment, in this thesis, in order to easier the reading, we refer to Design for Environment (DfE) for Green Design, Ecodesign, Life Cycle

Design, Environmental Conscious Design. In case of citation, the original term used by the authors, is preserved.

3.2.2 Principles of DfE - Green Design

According to Billatos and Basaly (1997) and Fiksel (1996), DfE is based on 10 main principles to adopt during the product development process:

- Reducing the use of materials, using recycled and recyclable materials, and reducing toxic or polluting materials;
- Maximising the number of replaceable or recyclable components;
- Reducing emissions and waste in production processes;
- Increasing energy efficiency in phases of production and use;
- Increasing reliability and maintainability of the system;
- Facilitating the exploitation of materials and recovery of resources by planning the disassembly of components;
- Extending the product's useful life;
- Planning strategies for the recovery of resources at end-of-life, facilitating reuse, remanufacturing and recycling, and reducing waste;
- Controlling and limiting the economic costs incurred by design interventions aimed at improving the environmental performance of the product;
- Respecting current legal constraints and evaluating future regulations in preparation.

Lagerstedt et al. (2003) expands the list by introducing:

- Using structural features and high quality materials, to minimise weight, these should not interfere with flexibility, impact strength or functional properties;
- Using better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear;
- Minimising joining elements, using screws, adhesives, welding, snap fits, geometric locking, etc.

Anastas and Zimmerman (2003) define 12 principles, some of which complete the lists above, in particular:

- Using products, processes, and systems that “pull the output” rather than “push the input” through the use of energy and materials;
- Minimising material diversity in multicomponent products, in order to promote disassembly and value retention;
- Designing products, processes, and systems for performance in a commercial “afterlife”.

Although these principles appear as simple measures suggested by common sense, important limitations in their application reside. In some cases, certain principles come into conflict with each other, as in the following examples:

- Reducing product weight by dematerialising product components may affect product durability;
- Extending product durability results in increasing the risk of obsolescence in product efficiency;
- Using toxic materials or pollutant substances may reduce energy consumption;
- Using high performance components may decrease energy consumption during the use phase at the cost of increasing the energy consumption during the manufacturing phase;
- Minimising joining elements eases product disassembly but may reduce product reliability.

Therefore, DfE is not limited to the application of rules, but deals with the management of the trade-offs caused by conflicting effects of design choices. In case of conflicting actions, a support to the decision-making in the design is given by appropriate assessment methods, e.g. Life Cycle Assessment, which is presented in Chapter 4.

3.2.3 DfE Hierarchy and DfX disciplines

The scope of DFE encompasses many disciplines, including environmental risk management, product safety, occupational health and safety, pollution prevention, ecology, resource conservation, accident prevention, and waste management. A classification of DfE disciplines is proposed by Fiksel (1996) and presented in Figure 3.2.1. According to the hierarchy Fiksel proposes a distinction between “Design for Sustainability”, which includes all the actions aimed at the minimisation of the damage on the biosphere and aimed at avoiding natural resources depletion; and “Design for Health and Safety”, related to the measures aimed at the prevention of damages on human beings.

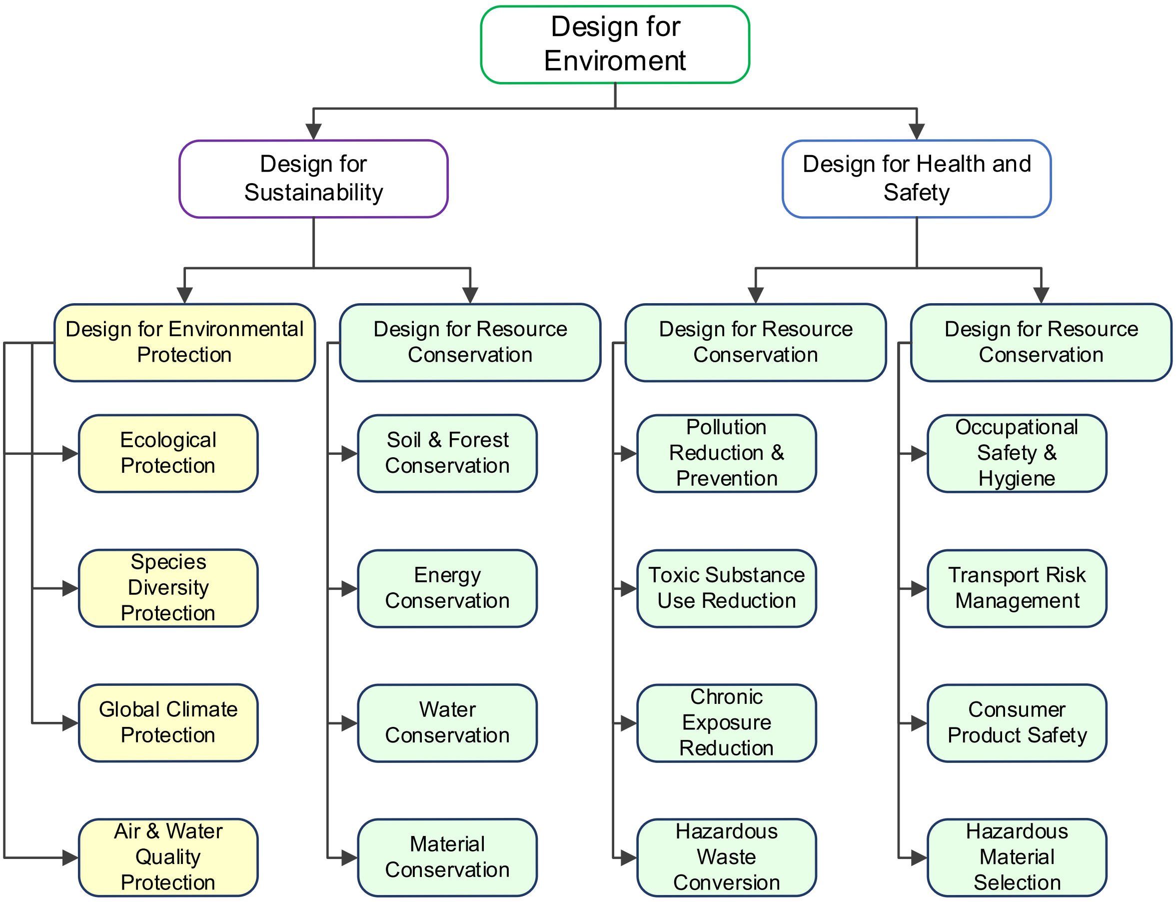

Figure 3.2.1 - Hierarchy of DfE disciplines. From Fiksel (1996)

As suggested by the proposed hierarchy, different DfE strategies can be adopted, each of which focuses on a specific aspect of product life. Hauschild et al. (2005) mentions DfE in a panel of so-called “DfX” strategies, which includes also Design for Disassembly (DfD), Design for Recycling (DfR), Design for Assembly (DfA), Design for Manufacture (DfM), Design for Manufacture & Assembly (DfMA). Ljungberg (2007) introduces also Design for Material Substitution, Modular Design, Design for Disposability, Design for Reusability, Design for Energy Recovery, and Design for Life Extension. After having rearranged the classification of Fiksel (1993), and having merged the contributions Hauschild et al. (2005) and Ljungberg (2007), we propose a DfE taxonomy, represented in Figure 3.2.2. The scheme presented shows a DfE classification, according to which we distinguish the DfX strategies: Design for Recovery and Reuse, Design for Material Conservation, Design for Waste Reduction, Design for Disassembly, Design for Energy Conservation, Design for Health and Safety. For each strategy, a number of sub-strategies or practices are listed. This thesis discusses some of these practices. In particular: Design for component recovery, Design for Remanufacturing, Design for Closed-Loop Reuse, Design for source reduction, Design of multifunctional products, Reduce device power consumption, Reduce energy use in distribution, Use renewable forms of energy.

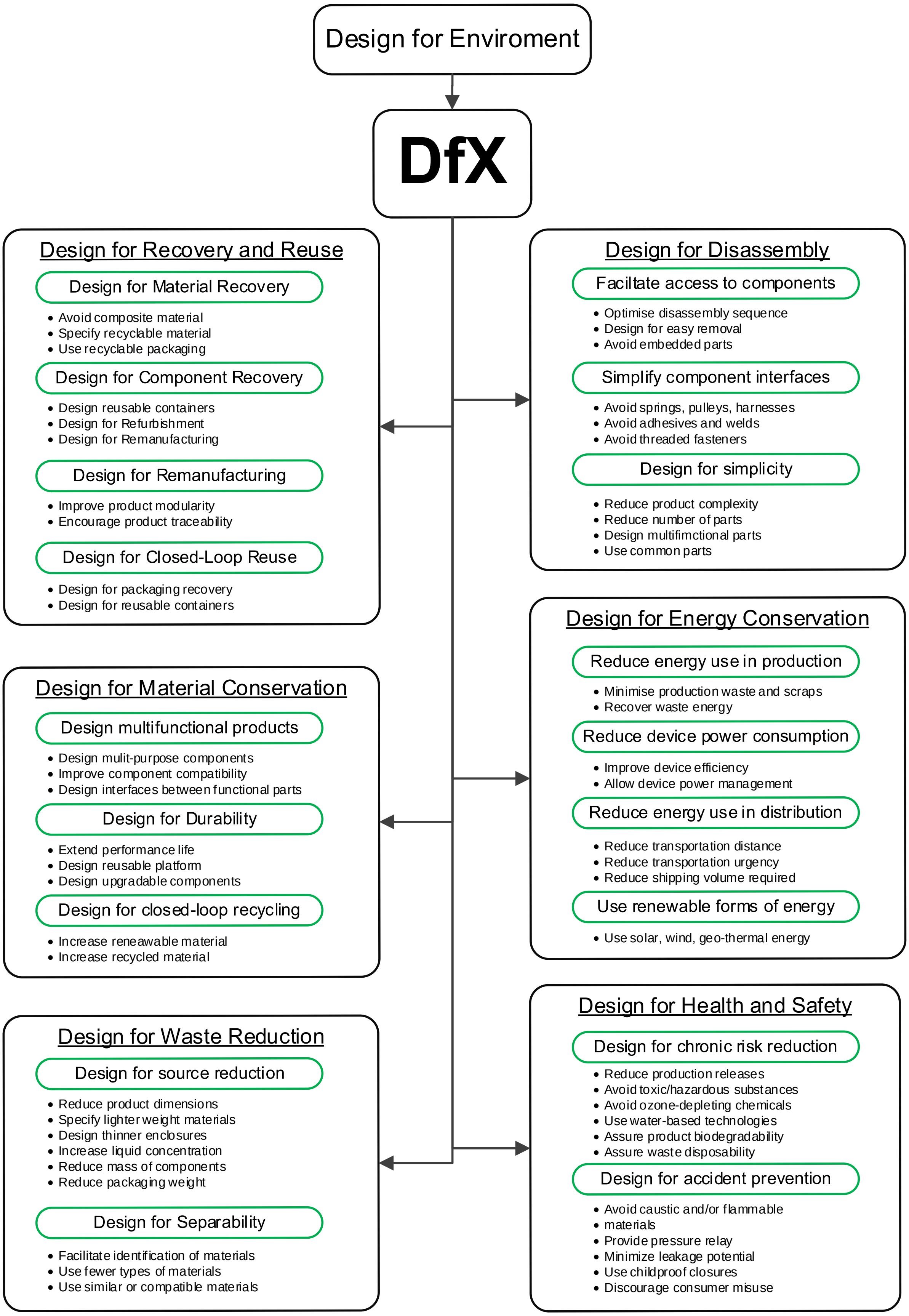

Figure 3.2.2 - Classification of DfX approaches

3.2.4 Tools of DfE

Many methods have been developed for integrating environmental considerations in the design of new products. Many authors have developed approaches to design for environment. The variety of methods and tools ranged from the general to the specific, focusing on parts of the life cycle (typically use and disposal) or on certain types of products or services. Some methods were intended for use early in the design process while others were aimed at use during the detailed design phase. Classifications of DfE tools are proposed by Byggeth and Hochschorner (2006), Knight and Jenkins (2009), and Ilgin and Gupta (2010). The most update taxonomy on DfE tools is proposed by Bovea and Pérez-Belis (2012). According to the authors, DfE tools aims at integrating environmental aspects into the design process, and are defined as the combination of "methods for integrating environmental and other traditional requirements" and "methods for evaluating the environmental aspect".

3.2.4.1 Methods for integrating environmental and other traditional requirements

This group considers methods like Design Matrix, Quality Function Deployment (QFD), Value Analysis (VA), and Failure Mode and Effect Analysis (FMEA).

Tools based on design matrix are descriptive techniques that concern the qualitative evaluation of the design team for different requirements of a product (including the environmental one) throughout its life cycle. QFD is applied in order to consider environmental requirements during the early stages of product development. These tools are applied to check that the product satisfies the customer requirements, including the environmental requirements. VA and allow a product to be designed or redesigned at low cost, while including all the functions for which the customer is willing to pay in order to obtain perceived environmental benefits. The Failure Mode and Effect Analysis is a methodology usually used to identify, assess and prevent deficiencies related with product safety. However, component failure safety factors can be replaced by environmental issue factors.

3.2.4.2 Methods for evaluating the environmental aspect

These methods are dedicate to the measurement of the environmental performance of products. These techniques range from environmental indicators focused on specific environmental problems, to more comprehensive methods that consider a wide range of environmental categories throughout the whole product life cycle. This group can be classified in three main categories: qualitative, semi-qualitative, and quantitative techniques. This classification is reported in Table 3.2.1. Qualitative or semi-quantitative methods are simple to use, fast, and offer advantages in situations where the environmental performance of the product is easy to evaluate. According to Bovea and Pérez-Belis (2012), they are, however, not very reliable. Quantitative methods are proper whether a detailed environmental profile of a product is needed. On the other hand, qualitative techniques require a large amount of data on the analysed product. Therefore, these methods have a tendency to enter the design process at a late stage, such as in the prototypal phase, when only minor changes can be made. This conflict defines the so-called "design process paradox" (Hauschild et al., 2005; Lagerstedt, 2003), described in 3.2.5.

Tool	Reference	Description
	Qualitative techniques	
Checklists	Keoleian et al. (1995)	Series of questions formulated to help designers work in addressing environmental issues during design process.
Matrix Element Checklist for ERP	Graedel and Allenby (1998)	Combination of questions that generates a relation between environmental problems and the product life stages.
MET-Matrix	Brezet and van Hemel (1997)	Method based on two matrices. The first considers three environmental concern categories (materials cycle, energy use and toxic emissions) and three life cycle stages (production, use and disposal). The second matrix indicates the severity of the abovementioned environmental effects.
Ten Golden Rules	Luttropp and Lagerstedt (2006)	It is a summary of main guidelines. This tool shows ten rules that should be applied into the product development process
	Semi-quantitative techniques	
Environmentally Responsible Product/Process Assessment Matrix (ERP)	Graedel and Allenby (1998)	Method based on two matrices: one for products and another for processes. Rows represent life cycle stages, columns indicate environmental concerns on a numerical scale. The overall rating is computed as the sum of the matrix element values.
Environmental Product Life Cycle Matrix (EPLC)	Gerstakis et al. (1997)	Similar to the ERP matrix. No distinction is made between processes or products and environmental concern columns are replaced by proper impact categories.
Ecodesign Checklist Method (ECM)	Wimmer (1999)	A checklist is applied at three different levels: parts, product and function. A semi-quantitative assessment is then applied quantify the fulfilment of Ecodesign requirements.
Streamlined Life Cycle Assessment (SLCA)	Bennett and Graedel (2000)	Tool for identifying hot spots and highlighting key opportunities to effect environmental improvements. It is particularly helpful when comparing different products.
Product Investigation, Learning and Optimization Tool (PILOT)	Wimmer et al. (2004)	New multimedia tool based on ECM. PILOT includes more Ecodesign guidelines then ECM.
	Quantitative techniques	
Environmental Indicators	Navinchandra (1991)	These environmental parameters allow different alternative designs to be evaluated from the environmental point of view, thus facilitating the decision-making process during product development.
Oil Point Method (OPM)	Lenau and Bey (2001)	Indicators in the OPM are defined as the energy consumption or energy content measured in kilograms of crude oil (1 Oil Point [OP] = energy content of 1 kg crude oil = 45 MJ).
Life Cycle Assessment (LCA)	ISO 14040-44 (2006)	LCA considers the entire life cycle of the product, usually from cradle-to-grave, and allows to obtain environmental indicator obtained for each impact category or to calculate a single indicator grouping all the impact categories considered.

Table 3.2.1 - Classification of DfE tools: qualitative, semi-quantitative and quantitative techniques

3.2.5 Design process paradox

At the early phase of product design, the knowledge about new product is scarce but the freedom in its rethinking or redesign is almost total, as nothing is still established. Information about the product increases as the product develops, but at the cost of design freedom. By the end of the process, the possibilities for changing the design are reduced. Global design decisions are already taken and only minor changes can be made. Major changes can be made but have high costs. However, at this stage the knowledge of the product is greatest. Data on its composition and manufacturing process are known and reliable forecasts on product use phase, e.g. on product durability, energy efficiency, maintenance, and on EoL can be proposed. Such a conflict is defined by Lagerstedt (2003) "design process paradox" and discussed also by Hauschild et al. (2005) and (Bevilacqua et al., 2012). Figure 3.2.3 gives a schematic representation of the design process paradox.

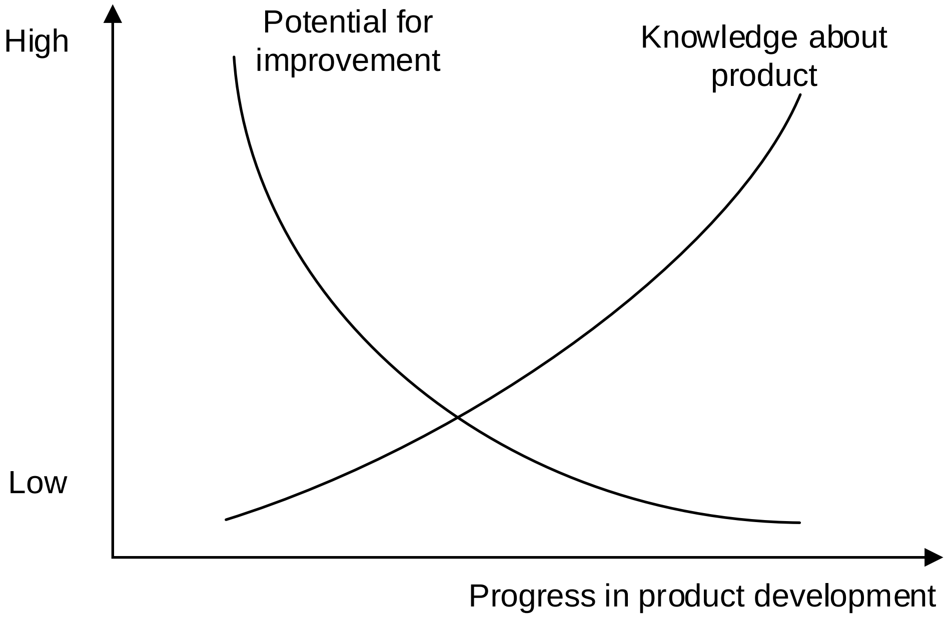

Figure 3.2.3 - Design process paradox

As well as the generic design process, also DfE and LCA are affected by the paradox between potential for improvement and knowledge about the product. At the early stage of product development, only a few data on product characteristics are known. Therefore, performing a detailed LCA when there is almost no information about the product life cycle is not convenient, and should be postponed at the final steps of design process. However, once the environmental profile of the product starts to be clear, interventions on product design becomes more and more inconvenient in terms of cost and time. This paradox is the basis for the systematic integration of LCA in DfE process.

3.2.6 DfE and LCA

In this section, the integration of LCA in the DfE process is discussed. An extended explanation of LCA methodology is proposed in Chapter 4.

Life Cycle Assessment is used to quantify the environmental impact associated with the product life cycle. In comparison to more qualitative approaches, LCA focuses on the quantification of potential environmental impacts by an analysis of material and energy consumption, waste generation, and emissions from the materials acquisition, manufacturing, distribution, use and end-of-life steps of the product life. The advantage of this “environmental accounting” is that if it is modelled in enough detail, it can help in:

- Developing a systematic evaluation of the environmental consequences associated with a given product;
- Analysing the environmental trade-offs associated with one or more specific products/processes and, in turn, to help the acceptance from stakeholders for a planned action;
- Quantifying the environmental emissions in air, water, and land in relation to each life cycle stage and/or major contributing process;
- Assisting in the identification of significant shifts in environmental impacts between life cycle stages;
- Identifying impacts to one or more specific environmental areas of concern;
- Assessing the human and ecological effects of material consumption and environmental releases to the local community, region, and worldwide;
- Comparing the health and ecological impacts between two or more rival products/processes or identify the impacts of a specific product or process.

Many authors discussed the issue of the integration between LCA, as a quantitative method for evaluating the environmental aspect, into the environmental concerned design process. Keoleian and Menerey (1994) propose a “Life Cycle Design Framework”, according to which, the processes of needs analysis, requirement analysis, design phase and design implementation are integrated in a concurrent design loop and supported by environmental analysis tools (LCA). The framework shows the relationship between the design phases and the role of LCA but does not explain the hierarchy and the logical sequence of the design steps. In Bevilacqua et al. (2012), a more realistic approach is presented. The authors define the developing of a new product as composed by the steps: “project definition”, “concept development”, “prototype assembly test” and “field test”. During each phase, aspects such as technical, ergonomic, economic, health, and environmental properties of the product are taken into account and the final product usually comes out as a compromise between the different priorities. According to this framework Figure 3.2.4, DfE is performed in the phase between concept development and prototype assembly testing, and supported by continuous LCA analyses. According to the authors, LCA can be used in any phase, although the major potential exists in the early stage of the process, preferably downstream of concept development stage. Such a conclusion refers to a common problem, discussed in section 3.2.5: the design process paradox.

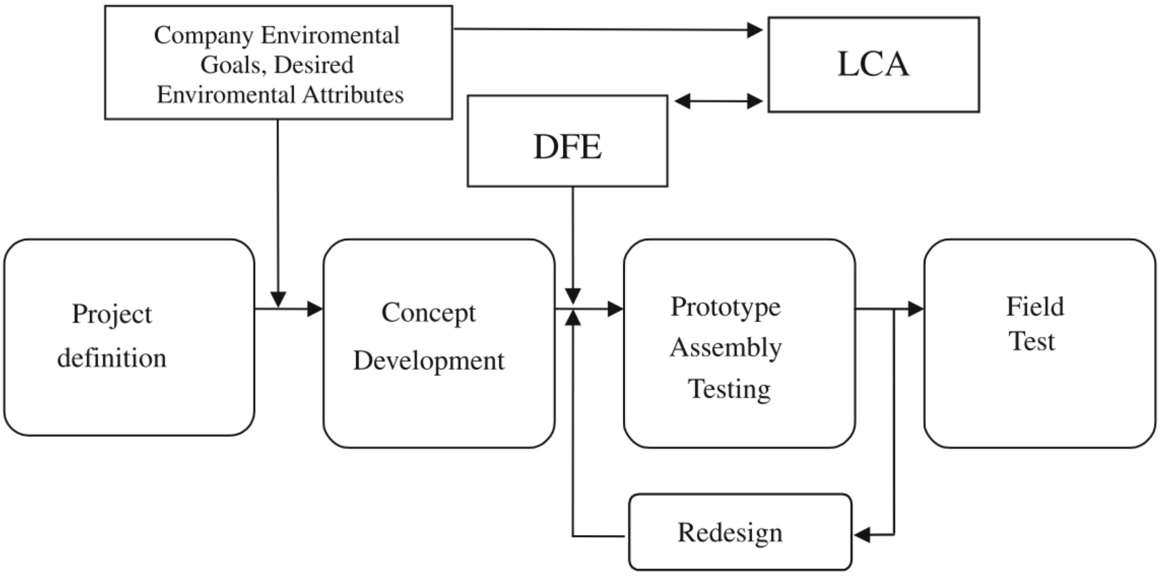

Figure 3.2.4 - Integration of LCA and DfE (from Bevilacqua et al., 2012)

Also Nielsen and Wenzel (2002) studied the issue of the integration of environmental regards in product development. They define the product development as the sequence of “idea generation”, “analysis”, “goal definition”, “concept development”, “detail development”, “establishment of production”. They agree with Bevilacqua et al. (2012) that LCA can be used in any phase of product development and that the major potential exists in the early stages but, conversely, identify three different phases in which LCA can return a real support to Ecodesign. In particular during: analysis, concept development and detail development. Figure 3.2.5 shows the integration of LCA in the product development. The framework suggests incremental updates of LCA to account for increased knowledge on the product under development. The approach considers the product development as a forward flow that does not consider product rethinking or product redesign. From this point of view, we consider the approach proposed by Bevilacqua et al. (2012) closer to the concurrent development process adopted in industry.

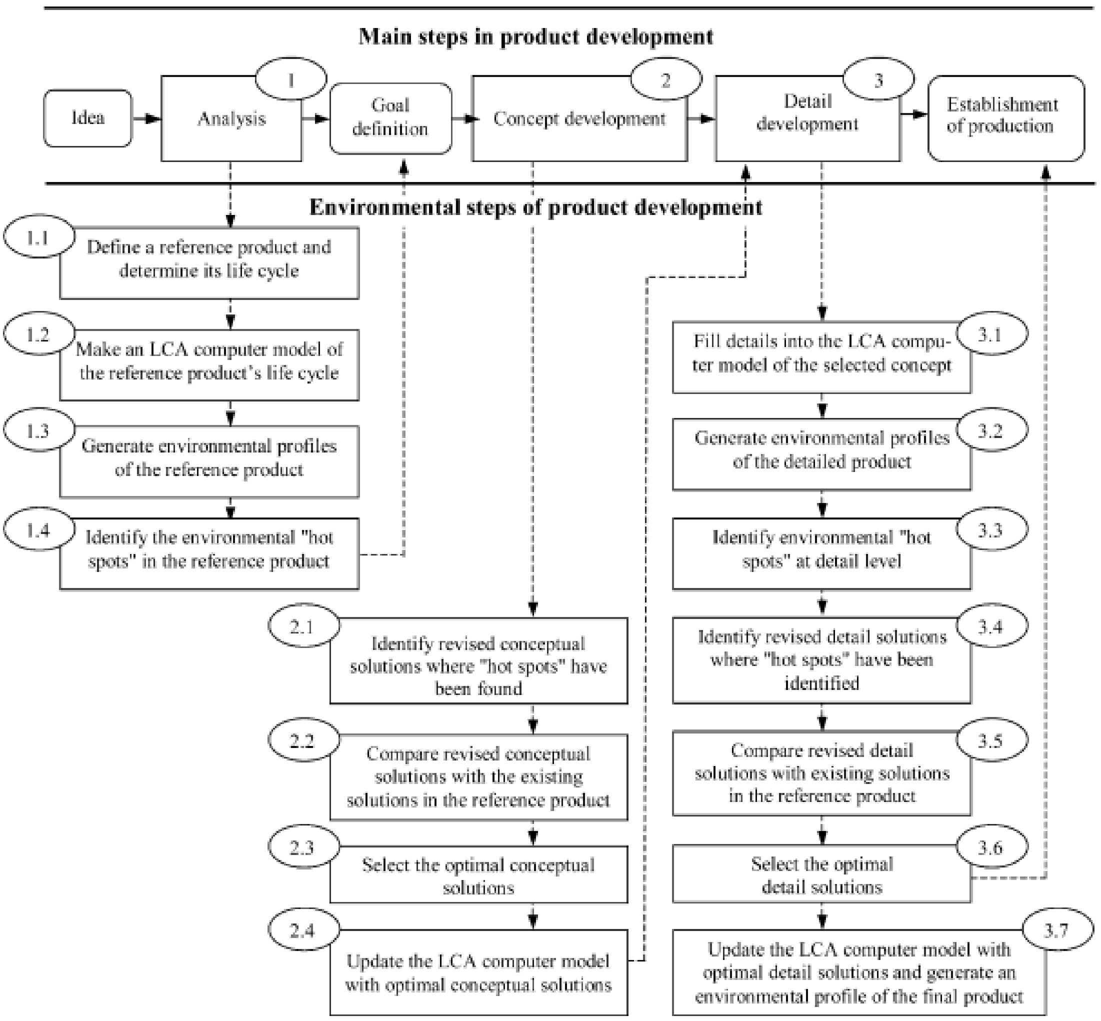

Figure 3.2.5 - Environmental performance assessment integrated into product development (from Nielsen and Wenzel, 2002)

3.2.7 A new framework for integration of LCA and DfE

In response to the weaknesses identified in the approaches presented above, we propose a general design approach, which considers the application of DfE tools, in different stages of product development. This approach consider the issue expressed by the design process paradox and define a DfE process flow chart (Figure 3.2.6) that associates the most appropriate method for the evaluating the environmental aspect to each design phase. As demonstrated, there is no agreement in a unique definition of product development stages. Therefore, we define five general steps: idea, conceptual design, detailed design, prototype development and pilot production. These steps are arranged in cascade: each progress depends on the fulfilment of design requirements, which are not limited to but considers environmental specifications. Redesign loops are iterated in closed feedback cycle: design, environmental assessment, requirement fulfilment check, redesign, etc. With each step, an assessment method (or class of methods) is associated. In particular, the conceptual design should be assisted by a qualitative assessment method. Detailed design and prototype development should be supported by streamlined (semi-qualitative method) and detailed LCA (qualitative method), respectively.

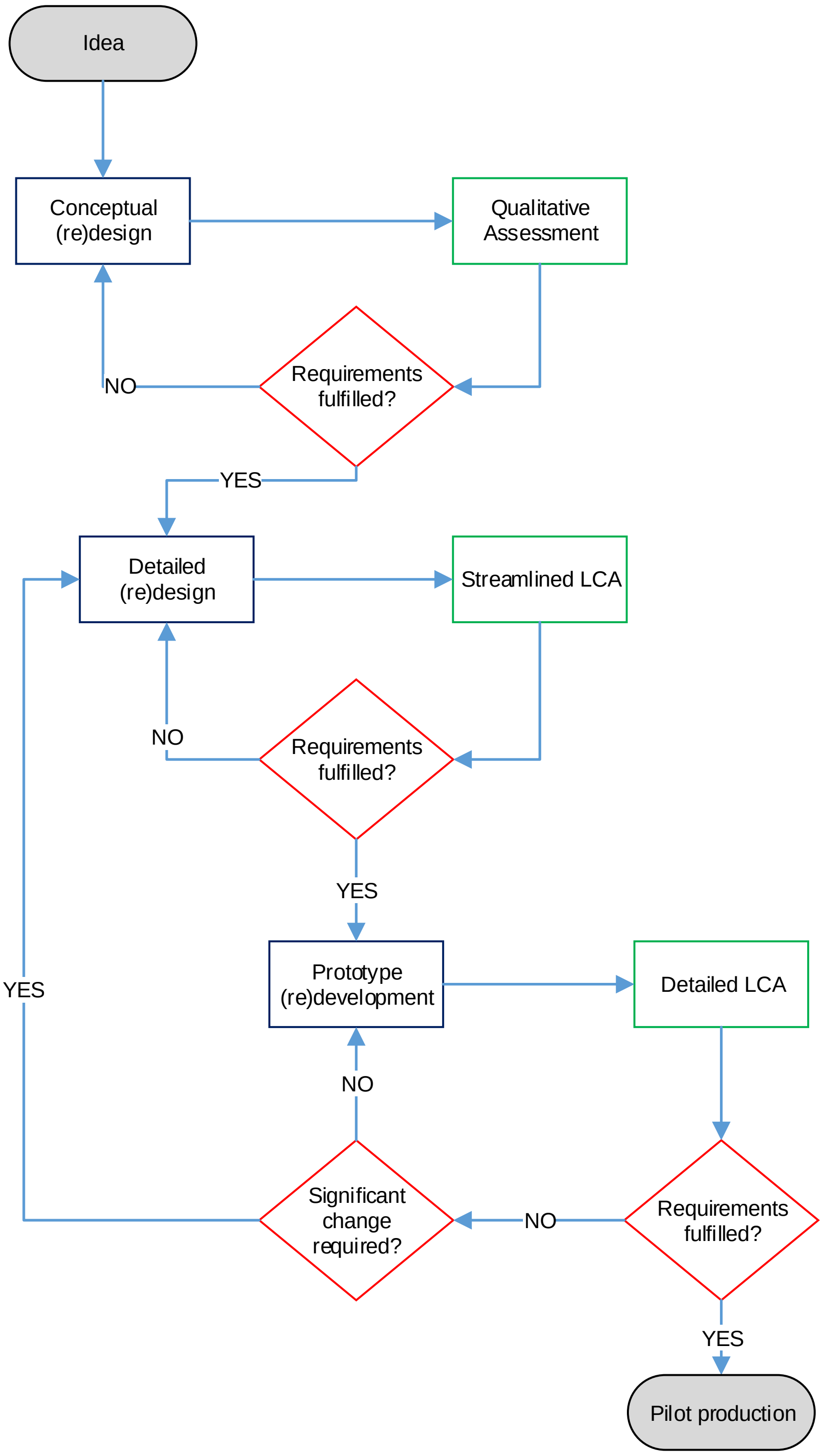

Figure 3.2.6 - DfE process flow chart

This thesis focuses on a section of this flow chart. In particular, Chapter 5 is dedicated to the presentation of the application of detailed LCA on three mechanical prototypal plants.

3.3 GREEN OPERATIONS, GREEN LOGISTICS, REVERSE LOGISTICS, CLOSED LOOP SUPPLY CHAIN AND SUPPLY CHAIN NETWORK DESIGN

In this chapter Green Operations, Green Logistics, Reverse Logistics, Closed Loop Supply Chain and Supply Chain Network Design are discussed. These terms assume different meanings in literature. In addition, although many authors discussed about these topics, there is no agreement about a unique taxonomy. In the next sections, we analyse the definitions proposed by the literature and introduce the main hot spots.

3.3.1 Definitions for Green Operations, Green Logistics, Reverse Logistics, Closed Loop Supply Chain and Supply Chain Network Design

According to Wong et al. (2012), Green Operations “spans from product development to management of the entire product life cycle involving such environmental practices as ecodesign, clean production, recycling, and reuse with a focus on minimising the expenses associated with manufacturing, distribution, use, and disposal of products”. The authors include Reverse Logistics in Green Operations by stating: “In process management, Green Operations emphasises closed-loop operations involving practices like recuperation and recycling with the objective to reduce waste, capture residual value of products and deploy environmental technology and cleaner transportation in the downstream supply chain for pollution prevention.”

Srivastava (2007) defines “Green Operations” as the activities connected to "all aspects related to product manufacture/remanufacture, usage, handling, logistics, and waste management once the design has been finalised.”. The author considers Reverse Logistics a separate topic and adopt the definition of Tibben-Lembke (2002): “RL is the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal.” Srivastava (2007) also states that “Green operations involve all operational aspects related to RL and network design (collection; inspection/sorting; pre-processing; network design), green manufacturing and remanufacturing (reduce; recycle; production planning and scheduling; inventory management; remanufacturing: re-use, product and material recovery) and waste management (source reduction; pollution prevention; disposal).”

Unlike Wong et al. (2012), Srivastava (2007) explicitly mentions “logistics” as a component of Green Operations. A definition of the term “logistics” is given by the Council of Logistics Management (CLM, 2002): “Logistics is that part of the supply chain process that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customers' requirements". According to Abukhader and Jönson (2004): "a logistical system includes four main processes: transportation, warehousing, inventory management and order processing".

According to Sarkis (2003), Green Logistics can be considered the tactical component of Green Supply Chain Management and represents the categories of: procurement, distribution, packaging and reverse logistics. There is a good overlapping in the hierarchy proposed by González-Benito and González-Benito (2006), in which logistics includes: supply/purchasing, transportation, warehousing and distribution, and reverse logistics and waste management. The authors define a list of environmental logistics processes, such as green purchasing, supplier selection, shipments consolidation, selection of cleaner transportation methods, use of recyclable/reusable packaging/containers, and responsible disposal of waste.

The above presented investigation on the definitions of Green Operations, Green Logistics, Reverse Logistics, Closed Loop Supply Chain and Supply Chain network Design shows that there is lack of agreement about the meaning of these terms and, therefore, there is not a unique headachy that defines their relationship.

In this thesis we mostly refer to the taxonomy proposed by Srivastava (2007), who considers reverse logistics, network design, green manufacturing and remanufacturing and waste management as components of Green Operations (see Figure 3.1.2). In particular, in this thesis Reverse Logistics, Closed Loop Supply Chain, Supply Chain Network Design, Reuse and Remanufacturing are the topics considered the most.

The following sections present a survey and a literature review on these topics.

3.3.2 Remanufacturing, Refurbishment and Reuse

Remanufacturing, Refurbishment and Reuse allows product to start, after their EoL, a new life cycle. Remanufacturing and reuse, together with repair, cannibalisation, and recycling belong to the product recovery process (Thierry et al., 1995). Johnson and Wang (1995) define it as a combination of Remanufacturing, Reuse and Recycling. Whatever are the boundaries of recovery, product recovery refers to the broad set of activities designed to reclaim value from a product at the end of its useful life.

The preferred option when a product reaches the EoL is to reuse the product as a whole, either for the same or for a new application (Zbicinski et al., 2006). The more the product retains its original form, the greater is the environmental benefit achieved. The reuse option is also valid for parts of a product. A product may be reused if parts are replaced, and parts in a product may be reused even if the product has to be scrapped. It is useful to consider whether these components can be reused, either for the original purpose or for a new one. Remanufacturing and Refurbishing are then usually necessary. Hoshino et al. (1995) define "remanufacturing" as "recycling-integrated manufacturing". The purpose of remanufacturing is to return used products to 'working order'. The quality of remanufactured products is generally lower than the quality of new products, while the purpose of refurbishing is to bring used products up to a specified quality.

3.3.3 Reverse Logistics and Closed-Loop Supply Chain

In the last years, Reverse Logistics and Closed-Loop Supply Chain issues have attracted attention among public opinion, academia and industry. The focus on Reverse Logistics and Closed-Loop Supply Chain originated from public awareness, then faced by governmental legislation with the aim of forcing producers to take-back and manage their EoL products, e.g. Directive 2002/96/EC (now Directive 2012/19/EU) on Waste Electrical & Electronic Equipment (WEEE), and Directive 2000/53/EC on end-of-life Vehicles (ELV). Now, in many industrial sectors, Reverse Logistics and Closed-Loop Supply Chain are considered an opportunity for supply chain cost minimisation (Guide and Van Wassenhove, 2009).

Traditionally, a supply chain is understood in its “forward” form, which corresponds to “a combination of processes to fulfil customers’ requests and includes all possible entities like suppliers, manufacturers, transporters, warehouses, retailers, and customers themselves.” (Chopra and Meindl, 2010).

Reverse Logistics is defined by Tibben-Lembke (2002) as “the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal”. The integration of Forward and Reverse supply chains, simultaneously, results in the creation of a Closed-Loop Supply Chain. In Guide et al. (2003) the Closed-Loop Supply Chain Management is defined as “the design, control, and operation of a system to maximise value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time”.

According to Govindan et al. (2014b), the contributions from the literature to the issues of Reverse Logistics and Closed-Loop Supply Chain can be classified as follows:

- Network Designing and Planning: the aim of designing is to determine strategic decision variables, such as facility location and facility capacity. In the planning stage, the most important decision variables are the quantities of flows between supply-chain network entities known as mid-term decision variables. Some studies regard designing and planning stages simultaneously, and some concentrate on one of them in depth. The topic of Supply Chain Network Design is deepened in 3.3.4.
- Network Planning: it is a sub-category of the previous one, in which the planning level decisions, such as quantity of flows between network entities, are studied without regarding any strategic or operational decisions.
- Vehicle Routing Problems: Vehicle Routing Problem (VRP) is an effective issue in RL and CLSC. Some studies directly consider this problem mostly in proposing efficient algorithms. VRP is a typical example of an operational decision-making problem.

- Production planning and Inventory Management: management issues such as finding reorder point, base stock, and economic order quantity without regarding production-planning subjects.
- Price and Coordination: this category includes studies that focus on the determination of the price of products and the coordination of win-win strategies to balance profit margins between two entities of a supply chain network (e.g. a remanufacturer and a retailer of second market). Usually, in such problems, optimum price and coordination strategies are determined.
- Decision-making and performance evaluation: this category includes the research on the evaluation of the performance of various networks and recovery strategies in Closed-Loop Supply Chain.

Depending on the specific topic, different tools, techniques and methodologies are adopted in literature for the design, planning, optimisation and control of Reverse Logistics operations and Closed-Loop Supply Chain Management.

3.3.3.1 Tools/Techniques/Methodologies in Reverse Logistics and Closed-Loop Supply Chain

Both Reverse Logistics and Closed-Loop Supply Chain have been faced by many authors in recent years. Srivastava (2007) presents an extended review of these issues. The author focuses on studies related to the mathematical modelling for network design and planning problems. The author builds a taxonomy based on mathematical tools/techniques. Results show that the methodologies applied the most in this context are the following: Mixed Integer Linear Programming, simulation, sensitivity analysis, algebraic equations, heuristics and meta-heuristics, dynamic programming, Markov chains, and game theory. Although to a lesser degree, also Petri-net, Analytic Hierarchy Process, Fuzzy reasoning, and neuro-fuzzy are used. Classifying them on the basis of the decision level they deal with, it is possible to notice that 35%, 33% and 32% is the portion of studies having operational, tactical and strategic focus, respectively.

3.3.3.1.1 Linear Programming

Govindan et al. (2014b) analyse studies published between 2007 and 2013 on Reverse Logistics and Closed-Loop Supply Chain. According to the survey, 18.8% of papers deal with the Design and Planning of Closed-Loop Supply Chains, and the 69.4 % of these researches are based on linear modelling, such that it is possible to claim that the Linear Programming approach can be introduced as the dominating modelling approach for the design and planning problems of Reverse Logistics and Closed-Loop Supply Chain.

3.3.3.1.2 Exact solutions VS heuristics and meta-heuristics

The authors propose a further classification of methodologies, according to which methods leading to extract solutions and heuristics and meta-heuristics are split in two categories. The survey shows that in case of large complex problem, utilising heuristic and meta-heuristic algorithms is unavoidable, but these methods do not ensure knowledge about the quality of the found solutions. Despite the fact that analytical and exact methods are rarely applicable to real-sized instances of a problem, they are still largely studied and proposed in literature (41.6% against 11.2% of heuristics and meta-heuristics).

3.3.3.1.3 Single VS Multi period, product and objective

A further classification can be made based on the number of periods, products and objectives considered in the problem modelling. Govindan et al. (2014b) classified recent papers on the basis of single- and Multi-objective models, for Single and multi-period, and for single- and multi-product problems. The trend in recent literature is shown in Figure 3.3.1, Figure 3.3.2 and Figure 3.3.3, in which the incidence of each approach is measured by the number of papers per period.

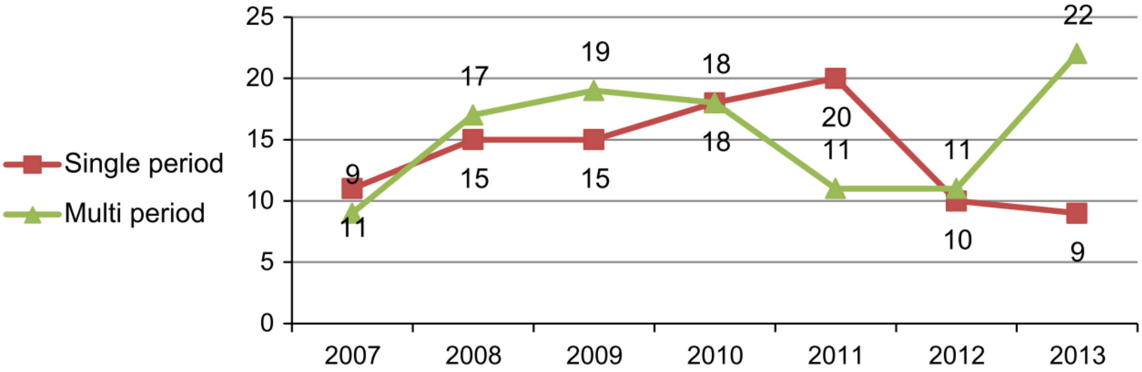

Figure 3.3.1 - Trend of Single- and Multi-Period problem modelling (from Govindan et al. (2014b))

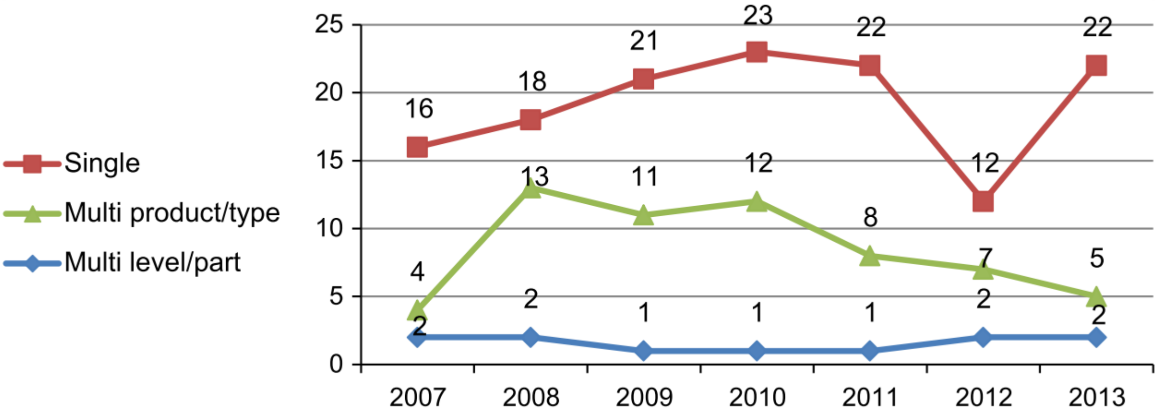

Figure 3.3.2 - Trend of Single- and Multi-Product problem modelling (from Govindan et al. (2014b))

There is a balance between Single- and Multi-Period problems. That proves the equilibrium in the ratio of strategic and planning models: the former are characterised by single-period problems, the latter by multi-period modelling. However, a negative trend for Single-period approaches has been recently noticed, which demonstrates that dynamic approaches are more representative of the reality. Finally, the majority of recent papers present single-product models (65.4%) and only few studies consider multi-part products (just 5.4%). This result is probably caused by the computational difficulties that Multi-product problems usually involve.

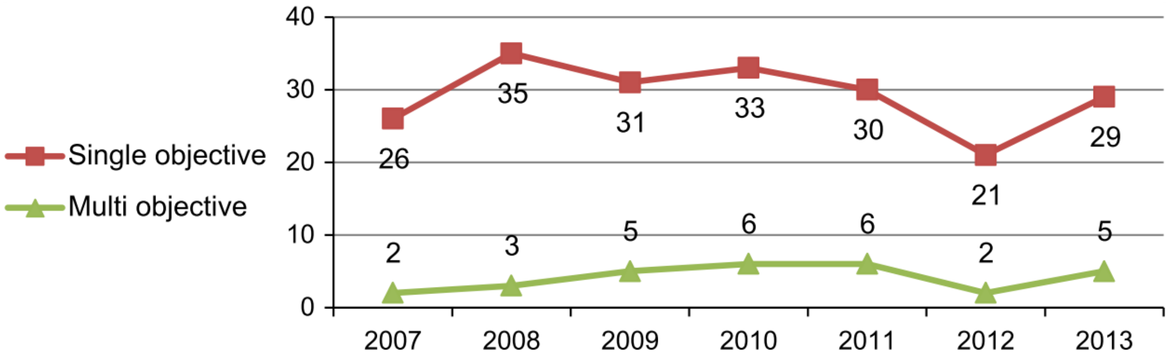

Figure 3.3.3 - Trend of Single- and Multi-Objective modelling (from Govindan et al. (2014b))

3.3.3.1.4 Reverse Logistics, Closed Loop Supply Chain and Multi-Objective problems

Multi-objective approaches are still a minor part in recent publications: 87.6% of papers deal with Single-objective approaches while only 12.4% present Multi-objective tools. These numbers demonstrate that Multi-objective decision-making is still a gap in literature (Govindan et al., 2014; Kumar and Kumar, 2013). Real world problems are rarely single objective, therefore implementing Multi-objective functions instead of single objective ones is a priority in research. The approaches for dealing with Multi-objective problems and achieving the optimal solutions (e.g. Pareto optimal solutions) need to be revised to produce more robust and applicable methods.

One of the most interesting extension in objective functions regards the introduction of sustainable and environmental objectives. According to Govindan et al. (2014b) “it is expected that researchers regard appropriate environmental, social, and green-based objectives in their analyses, which can be a critical future avenue for all entities in the Reverse Logistics and Closed-Loop Supply Chain network”, who concludes the paper with “the integration of different levels of decision-making and defining new decision variables are future opportunities for the decision variables category. Paying attention to multi objective problems, utilising new approaches, and applying more green, sustainable, and environmental objectives can be the future directions in single and multiple objective problems”.

Among the potential topics of Reverse Logistics and Closed-Loop Supply Chain, this research focuses on the issue of Network Design and Planning, which is discussed in the following section.

3.3.4 Supply Chain Network Design

In the context of Reverse Logistics and Closed-Loop Supply Chain, a relevant research is the classical Supply Chain Network Design and Planning problem. This topic considers strategic and tactical decision problems that need to be optimised for long-term efficient operations of the whole supply chain.

The Network Design problem determines a portfolio of configuration parameters including the number, location, capacity, and type of various facilities in the network. Survey dealing with the design problem of supply chains are in Vidal and Goetschalckx (1997), Beamon (1998), Erengüç et al. (1999), Srivastava (2007), and Govindan et al. (2014b).

Reverse Logistics and, in particular, Closed-Loop Supply Chain Networks Management deal the coordination requirement of two markets, supply uncertainty, returns disposition decisions, postponement and speculation (Fleischmann, 2001; Krikke, 2001). All these variables affect the network design to a considerable extent. In order to understand the complexity of the network design problem, it is necessary to define the operations that the Reverse Logistics includes in the Closed-Loop Supply Chain.

Reverse Logistics involves the recovery of a certain product. In case of reuse of products, compared to a traditional Supply Chain network, in closed-loop network three additional operations are required: collection, inspection/sorting, remanufacturing/refurbishment. Collection is the first stage in the recovery process in which product types are selected and products are located, collected and transported to facilities for remanufacturing/refurbishment or reuse. Used products originate from multiple sources and are brought to the product recovery facility in a converging process. Inspection/sorting illustrates the need for skill in the sorting of used products. This may be carried out either at the point/time of collection itself or afterwards, at collection points or at remanufacturing/refurbishment facilities. Finally, remanufacturing and refurbishment operations, if required, make the product, or parts of it, ready for a new cycle. Such loop allows an important saving from both environmental and economic point of view for all the stakeholders of the supply chain. Designing logistics networks to accommodate product returns, remanufacturing, and reuse of products (or parts/components), can be profitable and is more and more assuming importance in business as well as in research.

In a network design problem, the physical location of facilities and transportation links are the decision variables that allow used products to transfer from their former users to a producer and to future markets again (Fleischmann, 2001). Nowadays, one of the most discussed problem is the integration of Reverse Logistics activities within the forward logistics of an organisation. For traditional forward logistics environments, quantitative approaches such as Mixed Integer Linear Programming (MILP) models are widely adopted; however, a standard set of models is yet to be established for reverse networks. A survey by Fleischmann et al. (2000) discuss the applicability of traditional forward approaches in the Reverse Logistics of different industrial sectors: carpet recycling (Louwers et al., 1999), remanufacturing of electronic appliance (Jayaraman et al., 1999; Krikke et al., 1998), reusable packages (Kroon and Vrijens, 1995), sand recycling from demolition waste (Barros et al., 1998), and recycling of by-products from steel production (Spengler et al., 1997).

More recently, Akçalı et al. (2009) proposed and extended survey on models and approaches in Network Design for Reverse and Closed-Loop Supply Chains. The authors classify the research in two main branches: models and approaches for Reverse Logistics, which are concerned with establishing an infrastructure to manage the reverse channel only, and for Closed-Loop Supply Chain, which are concerned with establishing an infrastructure to manage both forward and reverse channels in a coordinated manner. Akçalı et al. (2009) establish a second classification based on: demand and supply modelling (deterministic versus stochastic demand), planning horizon (static versus dynamic models), network structure (single-level versus multi-level and two-stage versus multi-stage) and flow assumptions (single-item versus multi-item flows). With regards to Network Design in Reverse Logistics, the authors analyse Jayaraman et al. (1999), Schultmann et al. (2003), Lieckens and Vandaele (2007), Wang et al. (1995), Jayaraman et al. (2003), Min et al. (2006), Listeş and Dekker (2005), Realff et al. (2004). With reference to the Network Design for Closed-Loop Supply Chain, the authors reviewed Marín and Pelegrín (1998), Sahyouni et al. (2007), Fleischmann et al. (2009), Üster et al. (2007), Salema et al. (2005), Salema et al. (2007), Beamon and Fernandes (2004), Ko and Evans (2007).

The authors' conclusion can be summarised as follows.

Although the sources of uncertainties in reverse Logistics and Closed-Loop Supply Chain and CLSC networks (i.e., supply, recovery, and demand sources) are well known and the need to address these uncertainties is well established in the literature, the number of studies that address this concern is very limited. Moreover, uncertainties are not limited to quantity of demand and/or supply or to lead-time. The quality of returns can be highly variable. For instance, the conditions under which a particular product is used influences the remanufacturability of the product. In addition, the locations of demand and return and the timing of return can be uncertain. Quality, location, and timing uncertainties have not been considered in the literature to date, and there is a need to develop modelling approaches that adequately capture these uncertainties. For widespread adoption of recovery practices, the inclusion of regulatory constraints that are valid in different countries is crucial. In Europe, current environmental regulations prescribe collection and/or recovery targets for certain product categories (e.g. WEEE and ELVs). Models should consider the existence of regulatory constraints, which may lead to significantly different model variants that must be analysed carefully. The successful implementation of product recovery strategies relies on a set of carefully developed decision-making tools for transforming the supply chain to a closed-loop via optimal Network Design. Almost half of the published studies rely on the use of commercially available MILP software to obtain optimal solutions for the proposed MILP models (Beamon and Fernandes, 2004; Fleischmann, 2001; Jayaraman et al., 1999; Realff et al., 2004; Salema et al., 2005, 2007a; Schultmann et al., 2003; Wang et al., 1995). Such a result confirm the investigation conducted, more recently, by (Govindan et al., 2014).

In all surveys, there is full agreement on the fact that MILP models are commonly used for Network Design problems. Despite the fact that Fleischmann et al., (2000) and Akçalı et al. (2009) propose extensive studies of literature, they analysed only Single-objective models (cost/revenue objective functions) and do not mention neither the existence of Multi-objective problems, nor the need of focusing research efforts on such an issue, which is, on the contrary, what Srivastava (2007) and Govindan et al. (2014b) do.

3.3.4.1 Closed-Loop Supply Chain Network Design and Multi-Objective optimisation

As for the general topics of Reverse Logistics Network and Closed-Loop Supply Chain Management (section 3.3.3), recently, Multi-objective optimisation has been considered by different researchers in literature also for Supply Chain Network Design. For example, a Multi-objective programming model is proposed by Gabriel et al. (2006) who propose a model for simultaneously optimising the operations of both integrated logistics and its corresponding used-product reverse logistics in a close-looped supply chain. Alçada-Almeida et al. (2009) propose a Multi-objective Optimisation approach to identify the locations and capacities of hazardous material incineration facilities and balance social, economic, and environmental impacts, according to the three bottom line concept of sustainability. Paksoy et al. (2011) consider the environmental impact on a Closed-Loop Supply Chain network with the aim of preventing greenhouse gas emissions, and encourage the customers to use recyclable products by giving a small profit. The authors assume different transportation modalities between the network echelons and recyclability ratio of raw materials. Bouzembrak et al. (2011) develop a bi-objective (economic-environmental) MILP model for the design of a generic four-echelon supply chain. The model is then modified and applied in the design of a network for the recycling of waterways sediments. Chaabane et al. (2012) introduce a MILP model for Sustainable Supply Chain Design that considers Life Cycle Assessment principles in addition to the traditional material balance constraints at each node in the supply chain: the model is based on an economic and an environmental objective functions. The optimal network configuration is found through the conversion of the greenhouse gas emissions in economic cost according to an emission-trading scheme. Frota Neto et al. (2008), propose a Multi-Objective MILP for the design of a Closed-Loop Supply Chain. Unlike Chaabane et al. (2012), the authors opt for the calculation of Pareto optimal solutions, which preserve the different nature of environmental impact and economic cost. Multi-objective MILP models for Supply Chain and Closed-Loop Supply Chain Network Design are also in Hugo and Pistikopoulos (2005), Pinto-Varela et al. (2011) and Wang et al. (2011). In all these studies, the Network Design problem is faced via the application of Multi-Objective MILP, resulting in the calculation of the Pareto frontier of optimal solutions.

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4 LIFE CYCLE ASSESSMENT (LCA)

Chapter 3 presented the concept and principles of Design for Environment and the role of Life Cycle Assessment in the DfE process. In this chapter, an introduction to the LCA methodology is reported. The following sections present the definition of LCA, the standards that rule the tool, the history of the evolution of this method, the steps of which LCA is composed and the analytic framework on which the LCA relies. In addition, a discussion on the extension of LCA is discussed: Life Cycle Costing and Social Life Cycle Assessment are presented. Particularly, the potentiality of the integration of LCA and LCC is commented.

4.1 INTRODUCTION TO LIFE CYCLE ASSESSMENT

Life Cycle Assessment is an analytical tool developed to help to assess the environmental impacts associated with the life cycle of products and services. The life cycle of a product includes its development, manufacturing, assembly, distribution, use, and EoL. The life cycle of a product also includes the extraction of raw materials, their transformation in feedstock, the maintenance of the product, the recovery of part of it after its EoL and all the activities that allows the product, its components, or its materials to start a new life cycle (i.e. reuse, remanufacturing, refurbishment and recycling). The life cycle of a product also includes the production of energy used for its manufacturing, assembly, use, and the production/extraction of feedstock for energy generation, and so on. The same is for the transportation activities that occur during the product life cycle. The life cycle also includes the consumption of tools and instruments for the manufacturing of a product, and in turn their production, and the construction of the infrastructures where these activities are carried out, and so on. All these supportive activities consume resources and cause environmental impacts. In conclusion, a life cycle of a product has, in theory, no boundaries. However, when one refers to the product life cycle, usually refers to the cycle presented in Figure 3.1.1, which emphasises the overlapping between supply chain and product life cycle.

Decisions made by a company influence a number of stakeholders along the life cycle of its products. These actors are providing the needs of the company, using and servicing its products or taking care of the products when they are discarded. With the pursuit of sustainability, the responsibility of a company is extended to cover not only its own processes but also the other activities caused by company's demands to its suppliers and, in turn, their suppliers. Such a responsibility extends upstream in the product chain, but also downstream to include the impact that the company has on its products' behaviour during their EoL treatment. A company that has the aim to operate in a sustainable way needs broaden its thinking to the whole product chain, and not just on those links that belong to its own sphere of legal responsibility. Such a holistic perspective, also known as "cradle-to-grave" perspective, on which Life Cycle Assessment relies, allows companies to disclose the problem shifting that occurs when solutions to environmental problems at one place in a product's life stage create new problems elsewhere in the life cycle. In this context, the characteristics of LCA make the tool the proper instrument for a valuable decision support to companies that aim at developing their activities in a sustainable direction.

4.1.1 The evolution and standardisation of LCA

The development of Life Cycle Assessment methodology starts in the late 1960's and early 1970's. At that time, the environmental awareness was characterised by a particular concern for resource depletion as debated a few years earlier by Meadows (1972). In that early stage, the environmental impacts associated with industrial activities, energy systems and use of chemicals were still to be discovered. Therefore, a quantitative assessment of the environmental impacts, caused by the emissions from the product system, was not performed in the early studies: the focus was mainly on the consumption of energy and other resources, and the assessment technique, inspired from the substance flow analysis, was “Resource and Environmental Profile Analysis” (REPA) (Hunt et al., 1992). The first studies applying a life cycle perspective on a process system took place in the USA, focusing on environmental impacts from different types of beverage containers. In the early 1980’s, in Europe, the extensive use of resources for packaging of products received much public attention, and governments in a number of European countries commissioned analyses of the resource consumption and environmental emissions for different beverage container systems, e.g. milk containers (Franke, 1984; Lundholm and Sundström, 1985; Mekel and Huppes, 1990). Although the studies investigated on the same question, and despite the very similar packaging technologies (i.e. returnable bottles made from glass or PC, and milk cartons) were compared, the studies reached quite different conclusions on which system had the lowest environmental impact. Such an experience showed that the success of LCA as support tool for decision makers in government and industry, required the development of fundamental principles of the methodology, accompanied by international consensus.

The Society of Environmental Toxicology and Chemistry (SETAC) became the international organisation to host the global community of LCA researchers, and throughout the 1990’s, international SETAC working groups moved the methodology development (Consoli et al., 1993; Udeo de Haes, 1996). In parallel, the International Standards Organization (ISO) initiated a global standardisation process for LCA. Four standards were originally developed for LCA and its main phases and issued in the ISO 14000 series of standards for Environmental Management. The most updated releases are:

- ISO UNI EN 14040:2006: Principles and framework
- ISO UNI EN 14041:2004: Goal and Scope Definition and Life Cycle Inventory Analysis
- ISO UNI EN 14042:2001: A standard on Life Cycle Impact Assessment
- ISO UNI EN 14043:2001: A standard on Life Cycle Interpretation

All of them were then replaced in 2006 by ISO UNI EN 14044:2006 - Requirements and Guidelines.

ISO 14044 provides minimum requirements for the performance of LCA and define the framework for LCA as shown in Figure 4.1.1.

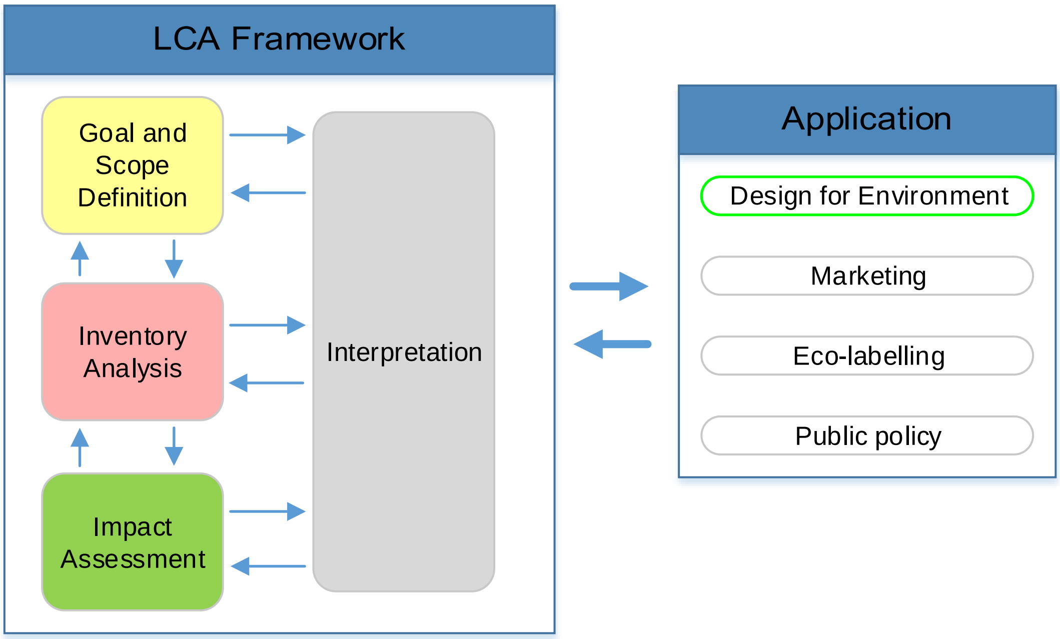

Figure 4.1.1 - LCA Framework according to ISO UNI EN 14044 standards

Aim of the standardisation was the harmonisation in the use of LCA methodology and the increase of the credibility of the results. As shown in Figure 4.1.1, LCA is interfaced with several applications, among which Design for Environment is probably the most discussed in this thesis (see Chapter 3): LCA is adopted by companies for focusing and comparison of alternatives in product development. However, LCA is also commonly used for documentation of environmental performance in marketing, and for decision support in environmental management, while governments use the tool for analysis of societal system choices (e.g. the comparison of waste management systems) and as the analytical backbone of the Integrated Product Policy, IPP, in eco-labelling schemes and for green public purchasing. A LCA, in accordance with the UNI EN ISO 14044 standard, proceeds iteratively through four phases. As shown in Figure 4.1.1, the use of LCA results in different applications is perceived as lying outside the framework, and the standards do not attempt to standardise these: LCA *per se* is perceived as a decision support tool, not a decision tool. The four phases of LCA are described in the following section.

4.1.2 LCA methodology

4.1.2.1 Goal and scope definition

In this first phase, the goal and intended use of the LCA is defined, and the assessment is scoped in terms of boundaries of the product system, temporal and technological scope of the processes in the product system, and assessment parameters to be considered in the assessment. The function to be provided by the system is meticulously described in qualitative terms and quantified in the “functional unit”, which defines the reference flow of products for the LCA, i.e. the number of product units for which the collection of data is done. It is a fundamental characteristic of LCA that its object is defined initially by the function, or service, that must be provided. This is in accordance with the comparative nature of most applications of LCA. For a fair comparison, it is essential that the systems, which are compared, actually provide the same function to the user.

4.1.2.2 Life Cycle Inventory (LCI)

After scoping the product system, the inventory analysis collects information on the input and output (environmental exchanges) for all the processes within the boundaries of the product system. The compilation of inventory data for each individual process quantifies the input and output associated with the reference flow of products as derived from the functional unit. The data is typically presented in an aggregated form for the whole product system, as total emissions of a certain substance or total use of a certain resource, per functional unit. This function- specificity is a fundamental characteristic of the life cycle inventory (LCI) and the resulting impact assessment, and consistent with the purpose of LCA to evaluate the environmental impacts associated with providing the service that is specified by the functional unit.

4.1.2.3 Life Cycle Impact Assessment (LCIA)

The purpose of the LCIA phase is to interpret the inventory results into their potential impacts on the so-called “areas of protection” of the LCA, i.e. the entities that the use of the LCA shall help to protect.

According to Hauschild et al. (2005) the areas of protection for LCIA are:

- Human health
- Natural environment
- Natural resources
- Man-made environment

LCIA applies a holistic perspective on environmental impacts. In principle, it attempts to model any impact from the product system that can be expected to damage one or more areas of protection. This means that LCIA addresses not only the toxic impacts from chemical emissions, as environmental risk assessment does, but also the other impacts associated with emissions of air pollutants (e.g. global warming, stratospheric ozone depletion, acidification, photochemical ozone and smog formation) or waterborne pollutants (eutrophication and oxygen depletion), as well as the environmental impacts from different forms of land use, from noise and from radiation, as well as the loss of renewable and non-renewable resources. Some LCIA methods also include the human health impacts from the occupational exposure from operating the processes in the life cycle.

If the LCI analysis for the product system has been thorough, the inventory will contain a multitude of substance emissions and input of different resources. Some of these exchanges are environmentally significant and even small amounts can be of importance, while others are of no significance.

For the environmental exchanges, the ambition with the impact assessment is hence to translate the emissions into their potential impacts on the areas of protection by applying the best available knowledge about causal relations between emissions and their effects in the environment as illustrated in Figure 4.1.2.

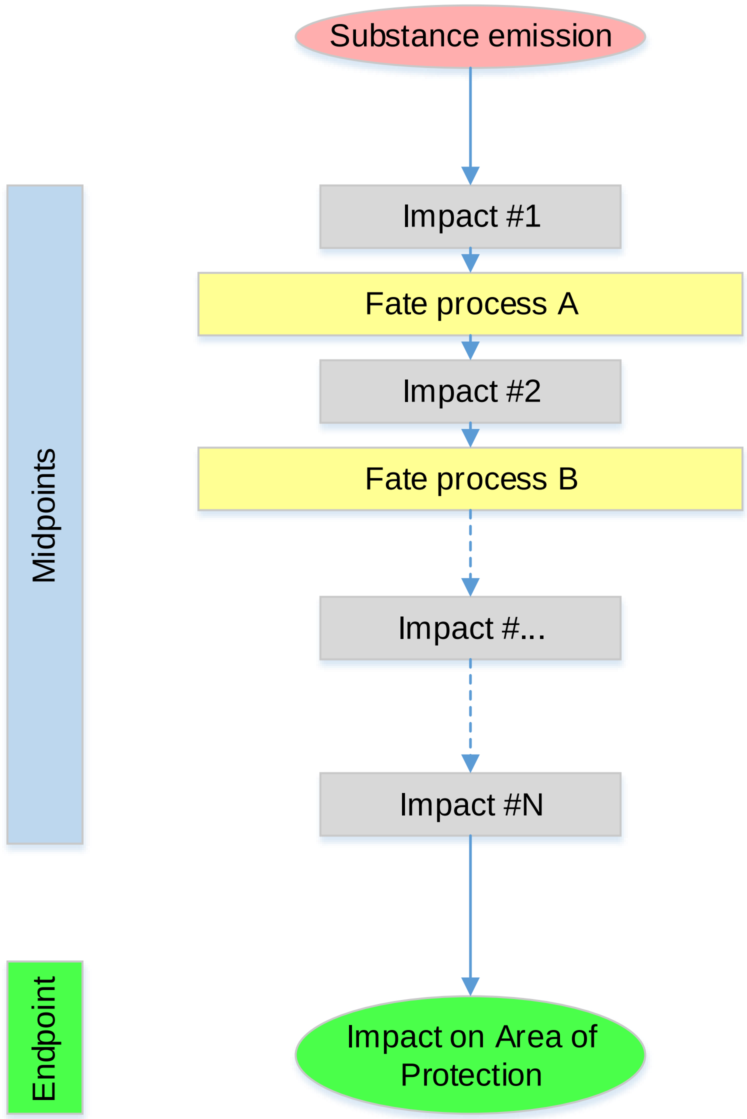

Figure 4.1.2 - The causal chain of the environmental impact in the LCIA framework

For greenhouse gases, the earliest impact in the causality chain is the increment in the atmosphere's ability to absorb infrared radiation. Later, impacts in the mechanism are the increase in the atmospheric heat content, propagating to the global marine and soil compartments causing changes in regional and global climates and sea-level rise, eventually damaging several of the areas of protection: human health, natural environment and man-made environment. In this case, the fate processes would be the degradation and transport of the gases in the troposphere, the stratosphere, and the global water and soil compartments, and they would be integrated in the chain of impacts all the way from emission to the areas of protection.

For the consumption of resources, the severity applied in the impact assessment is typically derived from the scarcity of the resource, i.e. the relationship between the economically feasible known reserve and the current consumption.

The LCIA proceeds through four steps (ISO 14044):

1. Selection of impact categories and Classification. Categories of environmental impacts of relevance to the study are defined. Next, the substance emissions from the inventory are assigned to the impact categories according to their ability to contribute to different environmental problems. ReCiPe 2008 method (Goedkoop et al., 2009) is one of the most comprehensive impact assessment method and considers, at midpoint level: global warming, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, fossil fuel depletion.
2. Characterisation. In this step where the impact from each emission is modelled according to the environmental mechanism (Figure 4.1.2) and expressed as an impact score in a unit common to all contributions within the impact category (e.g. kg CO_2-equivalent for all greenhouse gases). Following characterisation, the contributions from different substance emissions can be summed within each impact category, and the inventory data translated into a profile of environmental impact scores and resource consumptions.
3. Normalisation: Impact scores and resource consumptions from the characterisation are related to a common reference in order to facilitate comparisons across impact categories. Life cycle assessment is often used for comparative and comparison across impact categories is necessary when there are trade-offs between the categories, i.e. when improvements in one impact category are obtained at the expense of another impact category. Normalisation expresses the magnitude of the impact scores on a scale that is common to all the categories of impact. Typically, this scale is represented by the background impact from society's total activities. After normalisation, an impact can be measured in comparison with the annual impact from an average person and is useful for bringing the rather diverse environmental impacts on a common scale.
4. Weighting: A ranking or weighting of the different environmental impact categories reflecting the relative importance they are assigned in the study is performed.
5. Evaluation (or Single-score evaluation). The valuation is needed when trade-off situations occur as described under normalisation. Where normalisation expresses the relative magnitudes of the impact scores and resource consumptions, valuation expresses their relative significance considering the goal of the study.

According to the ISO 14044, the first two steps of the impact assessment are mandatory while normalisation and valuation are optional. The valuation step is the most normative part of the methodology since there is no objective way to perform the valuation and, therefore, not a unique correct set of ranks or weighting factors. The ISO standard for LCIA refrains from a standardisation of detailed methodological choices: over the last decades, several methodologies for LCIA have been developed (Goedkoop and Spriensma, 2000; Goedkoop et al., 2009; Steen, 1999).

LCIA is still under debate and apart from the global impact categories, i.e. global warming (leading to climate change) and stratospheric ozone depletion, no consensus has yet been reached on how to model the impacts.

In LCIA, two main modelling approaches are distinguished:

- Midpoint modelling: the impacts are modelled at some midpoint in the environmental mechanism. The midpoint is typically chosen as far as possible towards the areas of protection in the causality chain, i.e. at the point where further modelling is supposed too uncertain. The relation of the midpoint to the area of protection is then considered in the weighting.
- Endpoint modelling (or damage modelling): the impacts are modelled all the way to the effects, they cause on the areas of protection, using the best available environmental models. According to Endpoint modelling, the increased uncertainty in the impact modelling is warranted by the improved interpretation of the results. The only weighting needed here is the weighting between the areas of protection.

A valid example of LCIA endpoint method is given by Eco-Indicator 99 (EI99). The EI99 is an endpoint method that considers 11 environmental impact categories (characterisation). The burdens on impact categories are aggregated in damage categories by means of normalisation and weighting factors. In the present study, normalisation is performed at damage category level, and impacts in damage categories are normalised on the basis of the average impact of a European citizen. The impact categories are finally combined and quantified in three damage categories, i.e. Resources, Ecosystem quality and Human health, through single-score evaluation.

4.1.2.4 Interpretation

Interpretation is the phase of the LCA where the results of the other phases are interpreted according to the goal of the study. Typical studies performed at the interpretation phase are sensitivity and uncertainty analyses. The outcome of the interpretation may be a conclusion serving as a recommendation to the decision makers, who will normally consider the environmental and resource impacts together with other decision criteria (e.g. economic and social aspects). The interpretation may also lead to recommendation of a further iteration, reviewing and possibly revising the scope of the study, the collection of data for the inventory or the impact assessment.

As illustrated in Figure 3.2.6 and Figure 4.1.1, LCA is performed as an iterative exercise, and each phase may be revisited several times. With each iteration, the uncertainty is reduced, and the assessment is completed when the results can adequately answer the questions posed in the Goal and scope definition.

4.2 EXTENDING LCA: LIFE CYCLE COSTING AND SOCIAL LIFE CYCLE ASSESSMENT

According to the three bottom line framework, sustainability assessment includes not only environmental performances, but also social and economic performances. LCA is a tool developed for the evaluation of environmental impacts. Therefore, LCA in its traditional form, does not explicitly address trade-offs between environmental, social and economic performances in product life cycle. Hence, the effectiveness of LCA in supporting decision-making in companies is questionable.

4.2.1 Life Cycle Costing (LCC)

In the last decades, the need for the development of a methodology for the inclusion of economic impacts in LCA, in order to make LCA a more comprehensive tool, has emerged. Such a research need led to the adoption and integration of a well-known tool, i.e. Life Cycle Costing (LCC) methodology, as a support to LCA.

According to Woodward (1997), “The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life”. Alternative, but similar, definitions are in Ciroth et al. (2008), Jeswani et al. (2010) and Swarr et al. (2011).

LCC calculates the total costs of a product, process or an activity over its life span. In other words, LCC considers the economic implications to the supply chain stakeholders throughout the life cycle of a product. Traditionally, LCC has been applied to compare cost-effectiveness of different business decisions or investments from the point of view of a decision maker in a company or of a customer, and only those parts of the material life cycle of the product, where direct costs or benefits arise, are included in the product system. Although, life cycle management activities integrating the LCA results in business decision making have motivated ambitions of integrating cost assessments with the environmental assessment along the supply chain.

4.2.1.1 The integration of LCA and LCC

The theoretical principles of the integration of LCA and LCC are proposed in Carlsson Reich (2005) and Guinée et al. (2011). Gluch and Baumann (2004) discuss the theoretical assumptions and the practical usefulness of the LCC approach in making environmentally responsible decisions. The authors review the main corporate environmental accounting tools and propose three main research areas for the improvement of LCC as decision support tool, particularly in order to be used in combination with LCA. By applying LCC, it is possible to identify economic hot spots, as well as LCA does with environmental hot spots. In other terms, LCC is viewed as the economic counterpart of LCA (Jeswani et al., 2010). Therefore, the combination of the two methodologies enhances the application of a comprehensive life cycle approach for decision-making. The use of common data and models and many synergies between

LCA and LCC offer additional advantages of their combined use. The methodology of LCC is capable of fully integrating a LCI to provide monetary information as decision support. LCA and LCC, when carried out in an integrated manner and from a systems perspective, have a high potential for moving industrial practice towards sustainable development. Combining LCC and LCA also facilities eco-efficiency assessments, which can make understanding easier and further extend target audience for the use and interpretation of LCA. Basing LCA and LCC on the same information about the material and energy flows of the product system makes them more consistent and allows decision makers to weigh environmental and economic impacts against each other along the product chain, or to find a Pareto-efficiency. In fact, the comparable structure of the two methods also provides the possibility to combine their results in terms of eco-efficiency measure.

However, the integration of LCC into LCA can be encumbered by the lack of a standardised LCC methodology and difficulties in defining some of the cost factors. Although standardisation of LCC is a priority in research, as discussed by Ciroth et al. (2008) and represents a limit to its application, some important contributions in literature are found. Simões et al. (2013) proposes an innovative model for material selection in DfE process based on the integration of LCA and LCC: the model consists in applying the LCA methodology to the product system, incorporating, in parallel, its results into the LCC study, namely those of the LCI and the LCIA.

Another potential limit in the integration of LCA and LCC consists in the need of a result, able to lead the decision-maker through environmental and economic trade-offs. The use of monetisation methods or other forms of converting the two aspects into one indicator is a possibility discussed in literature. One of the most debated issue is whether and how external costs are to be included in the LCC. For designers aiming for sustainability, this would be a relevant option, and it would make LCC and environmental LCA results more compatible for most products (Senthil et al., 2003; Shapiro, 2001; Warren and Weitz, 1994). One well-known monetisation method, i.e. the so-called Environmental Life Cycle Costing (ELCC), consists in quantifying damage costs through costs due to some change, such as climate change due to greenhouse gas emissions. The existence of an actual market is an important issue for an externality to be considered (Swarr et al. 2011). Externalities from CO_2 equivalent, SO_2, NO_x and particulate emission, can be included in the LCC analysis. Costs of CO_2 equivalent emissions are obtained from a well-established market, such as the Europe Emission Trading Scheme (ETS). A valid example is in Chaabane et al. (2012). Whether there are no markets for pollutant emissions, e.g. for SO_2, NO_x and fine particle emissions, therefore the emission costs are considered as damage costs. Monetary valuation of externalities is a highly complex subject, and several approaches and methodologies have been applied (Ciroth et al., 2008; Swarr et al., 2011). However, so far, there is no consensus on how to convert environmental damages in an economic cost.

4.2.2 Social Life Cycle Assessment (SLCA)

Social life cycle assessment In our globalised economy, important stakeholder groups nowadays hold companies responsible for their social impacts through activities like child labour, corruption, discrimination of employees, and deprivation of employees of their right to organise and demand fair working conditions. Often these impacts occur far from the company headquarters, typically upstream in the product chain, but there are numerous examples where such cases have reached the media, and where globalised corporations have been held responsible for poor working conditions, not only in their own facilities, but also at their suppliers. The damage to their brand can be substantial, and for companies who claim to be sustainable, it can be devastating. Many companies understood the need of a tool that can help them make aware decisions about their social impacts throughout the life cycle of their products. The omission of social impacts from LCIA is also, to some degree, inconsistent with the defined areas of protection since social impacts will often lead to impacts on human health, and indirectly on the sustainable use of ecosystems. Nonetheless, very little work has so far been performed in Social LCA, but attempts are ongoing to develop LCIA for social impacts.

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5 APPLICATION OF LCA IN DESIGN FOR ENVIRONMENT OF PROTOTYPAL MECHANICAL PLANTS

In Chapter 3 the principles and the methodologies of Design for Environment (DfE) are introduces and discussed. Among the set of methodologies developed and adopted in industry and academy for the environmental concerned design purpose, Life Cycle Assessment is analysed in detail. In section 3.2.6, a complete approach for the integration of LCA in DfE is presented (Figure 3.2.6). This flow chart approach is based on a cascade of closed feedback cycles in which LCA and redesign are alternated in order to improve the environmental performances of a product during its whole development, from the product design to the prototype testing. According to the design paradox (section 3.2.5) the greater the knowledge about the product under development, the greater the level of detail that a LCA study can reach but, on the other hand, the lower the potential for further improvements.

In particular, when the product development reaches its last stages, LCA is considered the most appropriate instrument for the validation of the benefits caused by the application of DfE approach. Moreover, although it cannot lead to a complete redesign, LCA results can suggest minimal redesign operations and can indicate the best option in a set of possible product configuration.

In this chapter, the application of LCA in the area of prototypal machinery is presented. All the devices analysed through the LCA methodology have been design and/or developed and/or tested within the Department of Industrial Engineering of the University of Bologna. In studies the main purposes of the application of LCA methodology has been: the validation of the environmental benefit caused by the adoption of DfE rules; the comparison between standard/conventional systems, the identification of design hotspots and sensible components; the definition of redesign action proposal with the aim of improving the environmental performances of the analysed plants.

Chapter 5.1 presents an LCA on a prototypal photovoltaic/thermal cogeneration system with Fresnel lenses. In this study the prototype is analysed through the application of different impact assessment methods (Eco-Indicator 99, Cumulative Energy Demand, IPCC 2007 GWP 100a). The main life cycle hot spots, as well as the system components that introduce the greatest impact, are identified and discussed. The energy payback time of the device is calculated through a multi-scenario analysis. The system is then compared with alternative power plants from the environmental point of view. Finally, redesign proposals are discussed.

Chapter 5.2 introduces a comparative LCA study conducted on a multi-functional machinery and three standalone devices for haymaking. The life cycle of the multi-functional machine is modelled on the basis of the analysis of a fully functional prototype. The benefit introduced by the use of the multi-functional machine in replacement of the standalone system is estimated using an endpoint impact assessment method (ReCiPe 2008).

Chapter 5.3 presents a LCA study on two commercial walk-in refrigeration systems. The two vapour-compression refrigeration systems are designed for the preservation of food in cold-rooms at low- and medium-temperatures. Aim of the study is the evaluation of the Carbon Footprint associated with the life cycle of the system composed by device and refrigerant. In particular, the best configurations device-refrigerant-operating condition that minimise the Carbon Footprint of the refrigeration process is evaluated through a multi-scenario analysis. For both systems, the use of three hydrofluorocarbons (R-404A, R-410A, R-407F) in different use configurations is tested and assessed from the environmental impact viewpoint.

5.1 LCA OF A FRESNEL SOLAR CONCENTRATOR SYSTEM FOR MICRO-COGENERATION

5.1.1 Introduction

Due to the continuous increase of the fossil fuel cost, of the environmental pollution, of the global warming and also of the natural resource depletion, diversifying the power supply to include more and more renewable energy sources is starting to be considered a desirable and widely accepted strategy (Franke, 1984). The European Commission intent, which is formalised in the “20-20-20” climate and energy package, aims at reducing greenhouse gas emissions, decreasing primary energy use and increasing renewable energy consumption. In this context, the sunlight is considered one of the most “green” sources, since it represents a virtually unlimited supply and its direct exploitation causes no emissions (Tyagi et al., 2012). Even if the solar technologies, during its operational phase, can be considered non-polluting, evaluating the production process (as well as the end-of-life) of solar systems is important, in order to consider the emissions and the energy consumption during its whole life. For this reason, only a complete analysis can give a more correct basis to evaluate the real environmental sustainability of these plants.

There are different technologies that can be employed for the solar energy conversion, as well as there are different energy types (i.e. electric, thermal, mechanical etc.) that can be generated. The hybrid photovoltaic/thermal (PV/T) solar systems are an example and provide a simultaneous conversion of solar radiation into electricity and heat. In these devices, the PV module is integrated together with a water heat exchanger that recovers the thermal energy chilling the PV cells with a positive effect of increasing their efficiency. This advantage is particularly appreciated in solar concentrator systems in which, due to the converging of solar irradiance on a smaller surface, high temperature could negatively affect the electric energy production (Raugei and Frankl, 2009).

In this study, a hybrid PV/T concentrator prototype equipped with Fresnel lenses and mono-crystalline silicon cells is described. In particular, an environmental impact analysis applied to the system is presented. The adopted methodology used for this study is the LCA analysis, which is focused on evaluating the environmental impact of the PV/T system during its life cycle.

This section is organised as follows: the literature reviews about solar system cogeneration and micro-cogeneration and LCA studies applied on PV/T systems is presented in the next section, while section 5.1.3 introduces and describes the prototype object of this study. The following section 5.1.4 presents the related LCA analysis, and in 5.1.5 the Energy Pay Back Time of the system is evaluated. The conclusions and the outlooks end the manuscripts.

5.1.2 Literature review

Since the presented study focuses on a LCA analysis applied on a hybrid solar system, different literature contributions related to these topics are analysed. For the sake of brevity, the whole set of references is summarised and classified by topic in Table 5.1.1:

Topics	**References**
Micro-cogeneration with renewable energy	(Chemisana et al., 2011), Hasan and Sumathy (2010), Rosell et al. (2005), Smeltink and Blakers (2007), Tyagi et al. (2012), Zarza and Romero-Alvarez (2007), Zhang et al. (2012)
LCA of PV/Solar-Thermal modules/systems	Cavallaro and Ciraolo (2006), Celik et al. (2008), Chow (2010), Cucchiella and D'Adamo (2012), Desideri et al. (2012), Fthenakis and Kim (2011), Ito et al. (2009), Laleman et al. (2011), Mora et al. (2010), Raugei and Frankl (2009), Stoppato (2008), Tripanagnostopoulos et al. (2005)
LCA of PV cells (end-of-life)	Azzopardi et al. 2010, Fthenakis et al. 2008, Jungbluth 2005, Miles et al. 2005, Shibasaki 2005

Table 5.1.1 - Reference list classified by main topic

5.1.2.1 Survey on hybrid PV/T technology

Some contributions about hybrid PV/T systems (Chow, 2010; Hasan and Sumathy, 2010), review the most recent improvement sand technology advances in micro-cogeneration. (Chow, 2010; Hasan and Sumathy, 2010) introduce different hybrid solar solutions and applications, demonstrating their validity with various examples. Zhang et al. (2012) present economic and environmental performance indices, through which they compare different PV/T systems.

5.1.2.2 LCA applied to PV systems

With regard to LCA studies, the most recent investigations have to be reported. Fthenakis and Kim (2011) introduce a large survey on the environmental impact analysis of photovoltaic systems. A concentrator case study is also included: the Amonix High Concentrator PV (HCPV) 24 kWp system. By using different indices, e.g. Energy Payback Time (EPBT) and Greenhouse emissions (GHG), different PV systems and conventional power plants are compared. Greenhouse Gas per kilowatt hour (GHG/kWh), Energy Return on Investment (EROI), Greenhouse Gas Payback Time (GPBT) and Greenhouse Gas Return On Investment (GROI) are the indicators defined by (Cucchiella and D'Adamo, 2012) for the environmental performance evaluation of a building-integrated photovoltaic system located in Italy: a sensitivity analysis on different geographical locations is also proposed. (Cucchiella and D'Adamo, 2012) and Desideri et al. (2012) analyse large existing plants: the former, 200 kWp PV roof top plant, the latter 1778 kWp PV ground-mounted structure. Laleman et al. (2011) study the environmental impact of PV systems in low solar radiation regions. They introduce further performance indices, e.g. Eco-Indicator99 (EI99) and Cumulative Energy Demand (CED), through which they compare different power plants. In order to obtain a well-balanced evaluation, in fact, they recommend the use of a combination of various impact assessment methods.

5.1.2.3 LCA applied on HCPV systems

A Fresnel lenses HCPV system, i.e. FLATCON®, is described by Peharz and Dimroth (2005). Its sustainability is discussed by the evaluation of EPBT and CED. Mora et al. (2010) report a LCA study on a prototype of linear solar parabolic mirror concentrator, i.e. CHEAPSE, and analyse different design alternatives in order to minimise its life cycle environmental impact.

5.1.3 The Fresnel solar concentrator system

The Fresnel PV/T concentrator prototype analysed in this research, is designed and realised within the laboratory of Department of Industrial Engineering (DIN) of University of Bologna. The prototype is shown in Figure 5.1.1.

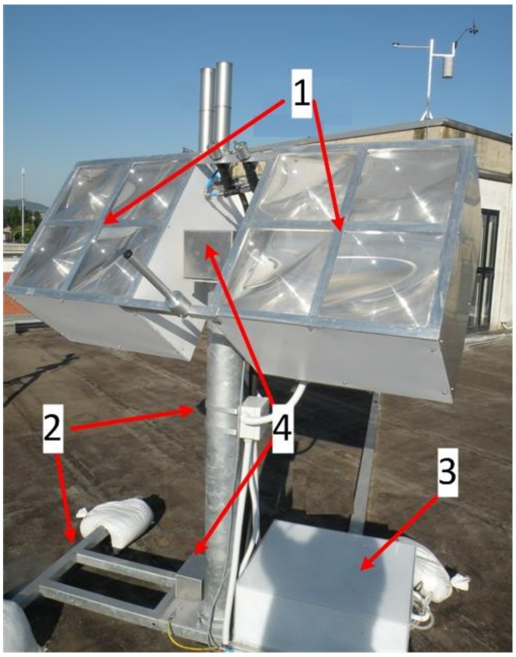

Figure 5.1.1 - The Fresnel PV/T concentrator prototype

5.1.3.1 Prototype description

The system is designed to produce both electric and thermal energy. The prototype is mainly composed by: eight solar collectors and receivers (1); support steel structure (2); heat recovery hydraulic circuit (3); motion transmission system (4). Thanks to the motion transmission system and the biaxial solar tracker, solar collectors are rotated along azimuthal and zenithal coordinates in order to keep the Fresnel lenses orthogonal to the sunlight direction. A high Concentration Ratio (CR) is obtainable (maximum 815x). The total receiving surface of Fresnel is 0.65 m^2. Mono-crystalline PV cells, located at the lens focus, are positioned on heat exchangers through which the exceeding thermal energy is recovered by a water circuit. The whole system is mounted on a galvanised steel structure.

5.1.3.2 System efficiency

The mono-crystalline PV cells are specifically designed for HCPV systems. They are manufactured by Fondazione Bruno Kessler (FBK) research centre. Although their rated efficiency is 20% with 160 CR, the whole system electric and thermal efficiency still need to be accurately evaluated. In this study, a system electric efficiency of 20% and a thermal efficiency of 30% are assumed.

5.1.4 LCA of the Fresnel solar concentrator system

The LCA is a useful tool for the evaluation of the environmental impact associated to a specific product life cycle. In this study, SimaPro 7.1 software is used and the life cycle impact assessment is carried out using three methods: Eco-indicator 99-H (Hierarchical version); IPCC 2007 GWP 100a; Cumulative Energy Demand (CED). The first method focuses on the evaluation of damage on human health, ecosystem quality and resource preservation. The IPCC evaluates the global warming potential due to gas air emissions over a 100-year period while the CED method aims to quantify all the energy that is consumed during the life cycle of a product. Topics and steps of the LCA methodology are regulated by ISO 14044. See Chapter 4 for further details.

5.1.4.1 Goal and scope definition

The goals of the study are mainly two: the first one is the environmental impact assessment of production, usage, and disposal of the prototype and the comparison between alternatives in the use of the prototype in different geographical locations. The second one is the comparison between the prototype and other energy production systems in terms of their environmental impact. System boundaries of the analysis are represented in Figure 5.1.2.

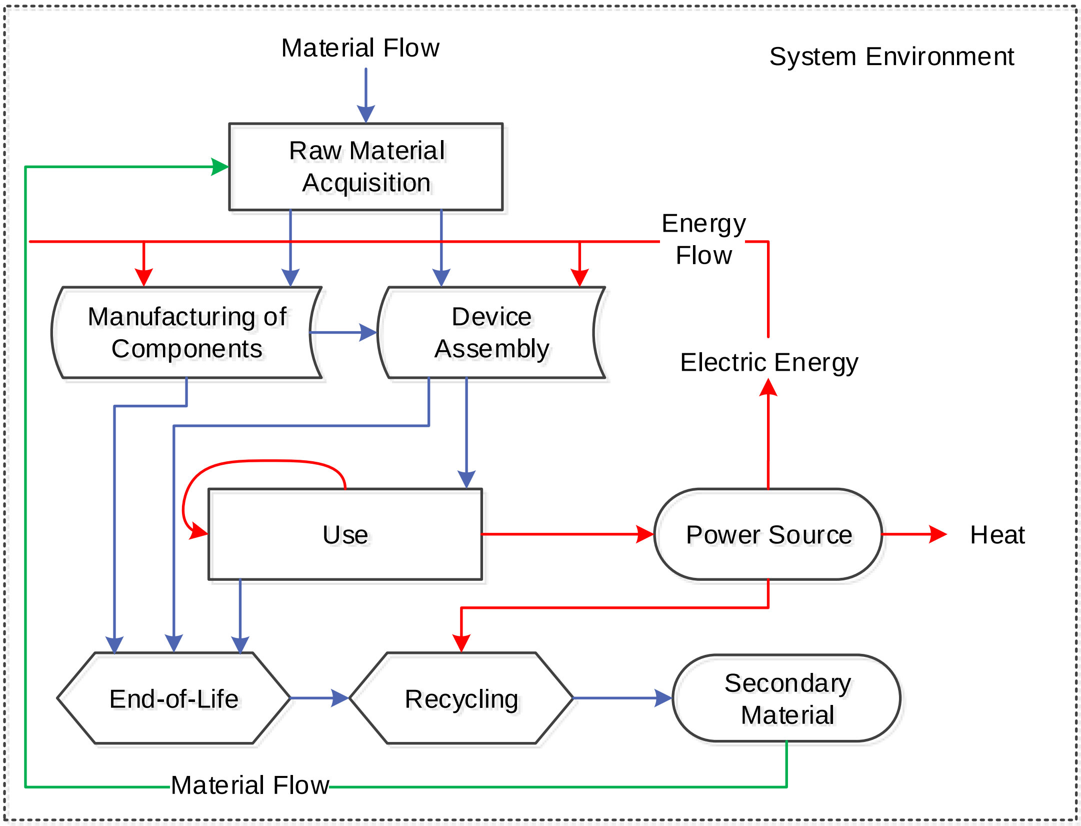

Figure 5.1.2 - System Boundaries

This LCA includes: raw material extraction processes; manufacturing and assembling of prototype components; transports; PV/T concentrator usage (i.e. electric and thermal energy production and electric energy consumption); waste treatment and disposal; component recycling and reuse. Because of the uncertainty on the system reliability (prototype), maintenance activities are neglected. In the same way, the environmental impact of the life cycle of the equipment used for the prototype assembly is not included in the boundary analysis. With these hypotheses, the presence of a Balance-Of-System (BOS) apparatus is also neglected.

The functional unit (FU) in the first part of the study is assumed the life cycle of the prototype, with the aim of defining its environmental impact, also related with its geographical location. In the second part of the study, the FU is assumed the production of 1 kWh of electric energy, in order to comparing the Fresnel concentrator to other energy production systems.

5.1.4.2 Inventory Analysis

All the data about environmental impact of manufacturing, assembly, usage and disposal processes related to the PV/T concentrator life cycle derive from SimaPro 7.1 data banks (BUWAL 250, Ecoinvent v.2.2, ETH-ESU, IDEMAT 2001, Industry data 2.0). In a few cases, in order to limit mismatches between data bank information and actual data on employed materials and processes, some simplifying hypotheses are made.

5.1.4.2.1 Materials

The main materials of which the PV/T prototype is composed are listed in Table 5.1.2:

Material	Weight [Kg]	Percentage by weight
Steel	78.67	61.18%
PVC	5.6	4.35%
PMMA	4.144	3.22%
Aluminium	39.67	30.85%
Copper	0.026	0.02%
Brass	0.29	0.226%
PE	0.18	0.14%
Silicon	0.0048	0.004%

Table 5.1.2 - PV/T concentrator material composition

Figure 5.1.3 represents the composition of each main component of the PV/T system.

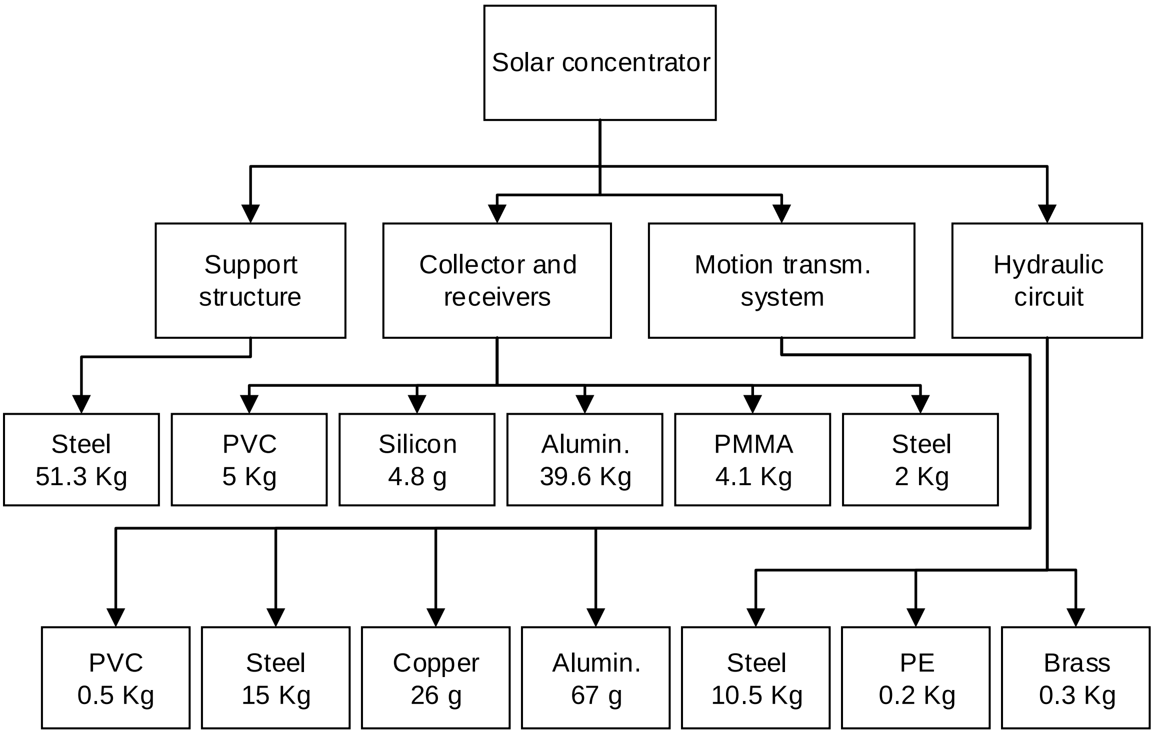

Figure 5.1.3 - Bill of Materials

5.1.4.2.2 Transports

Transportation of raw materials and semi-processed products is considered. In case of lack of accurate information about their geographical origin, average distances are adopted.

5.1.4.2.3 Energy consumption

With each manufacturing, assembly and disposal process, an energy consumption is associated. In case of lack of accurate data on manufacturing process input materials and pollutant emissions, the equivalent energy consumption is considered. In cell manufacturing process, the energy consumption of 6.4 kWh per single mono-crystalline cell (1 cm^2) is assumed. During the prototype use phase, estimated in 20 years, electric energy is needed for supplying tracking instruments, motion transmission system and hydraulic circuit: 876 kWh (43.8 kWh/year) of Low Voltage (LV) electric energy is the total estimated consumption during the use in the whole life cycle of the prototype. Environmental impact caused by LV electric energy production is calculated by consulting ETH-ESU data bank.

5.1.4.2.4 Energy Production

According to the solar radiation data obtained by the Photovoltaic Geographical Information System (PVGIS) database, the annual direct irradiation estimation in Bologna (Italy) is 1171 [kWh/(year·m^2]. Considering the above-mentioned hypothesis on system efficiency and assuming a PV cell electric productivity degradation of 1% per year, a 0.65 m^2 of receiving surface and a total life cycle of 20 year, an overall production of 2755 kWh of LV electric energy and 4133 kWh of thermal energy is estimated for the Bologna location. The energy generation by using the PV/T concentrator entails equivalent savings in production of LV electric energy and thermal energy by consuming conventional energy sources (e.g. oil, gas, coal, uranium). In particular, the production of electric energy by the PV/T system avoid an equivalent amount of energy generated by a mix composed of 19.49% from coal, 37.97% from crude oil, 24.15% from natural gas, 9.97% nuclear, 2.19% hydroelectric, 4.89% biofuel, 1.34% other sources. The generation of thermal energy by using PV/T system allows the saving of an equivalent amount of energy conventionally generated by burning natural gas. Respective pollutant emissions are consequently avoided.

5.1.4.2.5 End-of-life

For each module of PV/T prototype, different end-of-life scenarios are considered: reuse; recycling; landfill; incineration. Depending on the module material and on the degradation during its life, different possible end-of-life treatments are hypothesised. Table 5.1.3 summarises these assumptions:

	Support structure	**Collectors and receivers**	**Motion system**	**Hydraulic circuit**
% by weight	40%	39.5%	12%	8.5%
% of reuse	64%	-	26%	-
% of recycling	16%	72%	62%	40%
% in landfill	15%	18%	21%	31%
% of incineration	5%	10%	11%	29%

Table 5.1.3 - End-of-life treatment allocation by weight

5.1.4.3 Life Cycle Impact Assessment

Impact assessment is the stage in which data collected in LCI are converted in impact on impact categories and then in damage to areas of protection. In this phase, different impact assessment methods, i.e. Eco-Indicator 99, IPCC 2007 GWP and CED, are used and compared. At this stage, a main assumption is made. Since PV/T system allows the production of clean energy, the production of energy is assumed as an avoided impact, as explained in 5.1.4.2.4.

5.1.4.3.1 Eco-Indicator 99

By using Eco Indicator 99 Hierarchical version (EI99H), the environmental impact of PV/T manufacturing and assembly is calculated on impact categories (i.e. carcinogens effect, respiratory effect due to the emission of organic and inorganic substances, ionising radiation, ozone layer depletion, climate change effect, ecotoxicity, acidification and eutrophication, land use, mineral and fossil fuel depletion) and on areas of protection (i.e. human health, ecosystem quality and resource preservation). Impact and damage values are reported in percentage.

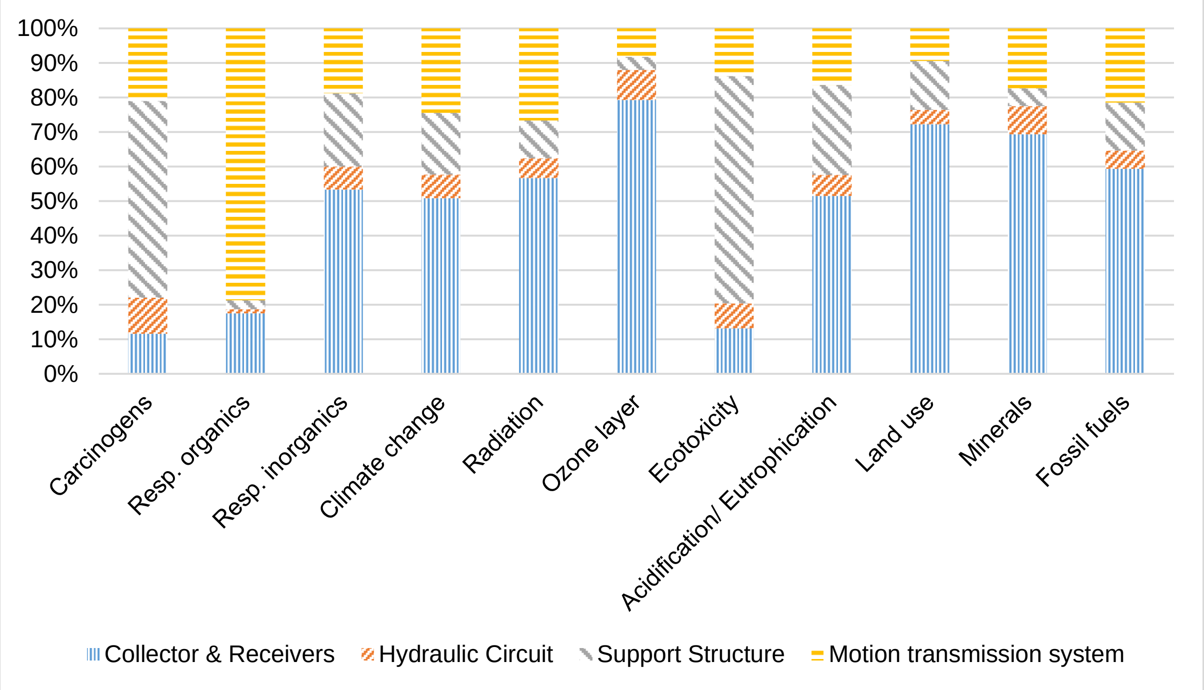

Figure 5.1.4 - PV/T prototype manufacturing and assembly Characterisation (EI99H)

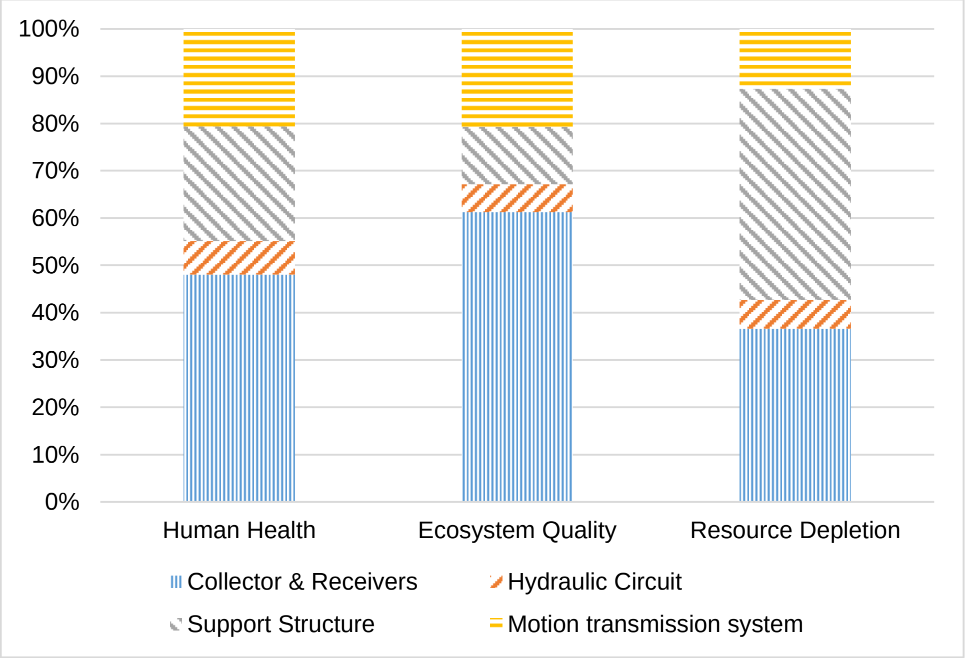

Figure 5.1.5 - PV/T prototype manufacturing and assembly Damage Assessment with EI99H

Figure 5.1.5 shows the characterisation of the impact of prototype manufacturing and assembly (from cradle-to-gate) on EI99H impact categories. Such categories are grouped in three areas of protection: Human Health (from carcinogens emissions to ozone layer depletion), Ecosystem Quality (from ecotoxicity to land use) and Resource Depletion (minerals and fossil fuels depletion). Figure 5.1.5 shows the Damage Assessment (DA), i.e. the non-normalised, non-weighted impact on the three areas of protection, of manufacturing and assembly processes for each module of the PV/T concentrator.

By using EI99H method, Characterisation of the whole PV/T concentrator life cycle is also evaluated and represented in Figure 5.1.6. Positive percentage values represent positive environmental impacts, while negative percentage values represent the amount of avoided environmental impact. Figure 5.1.7 shows the impact of PV/T life cycle on the three areas of protection. In both graphs, the life cycle is split in four steps: PV/T manufacturing and assembly, PV/T use (energy consumption and energy production), PV/T end-of-life. Since the energy production is affected by the site where the system is installed, as basic scenario, Bologna is assumed as the geographic site where the prototype is used.

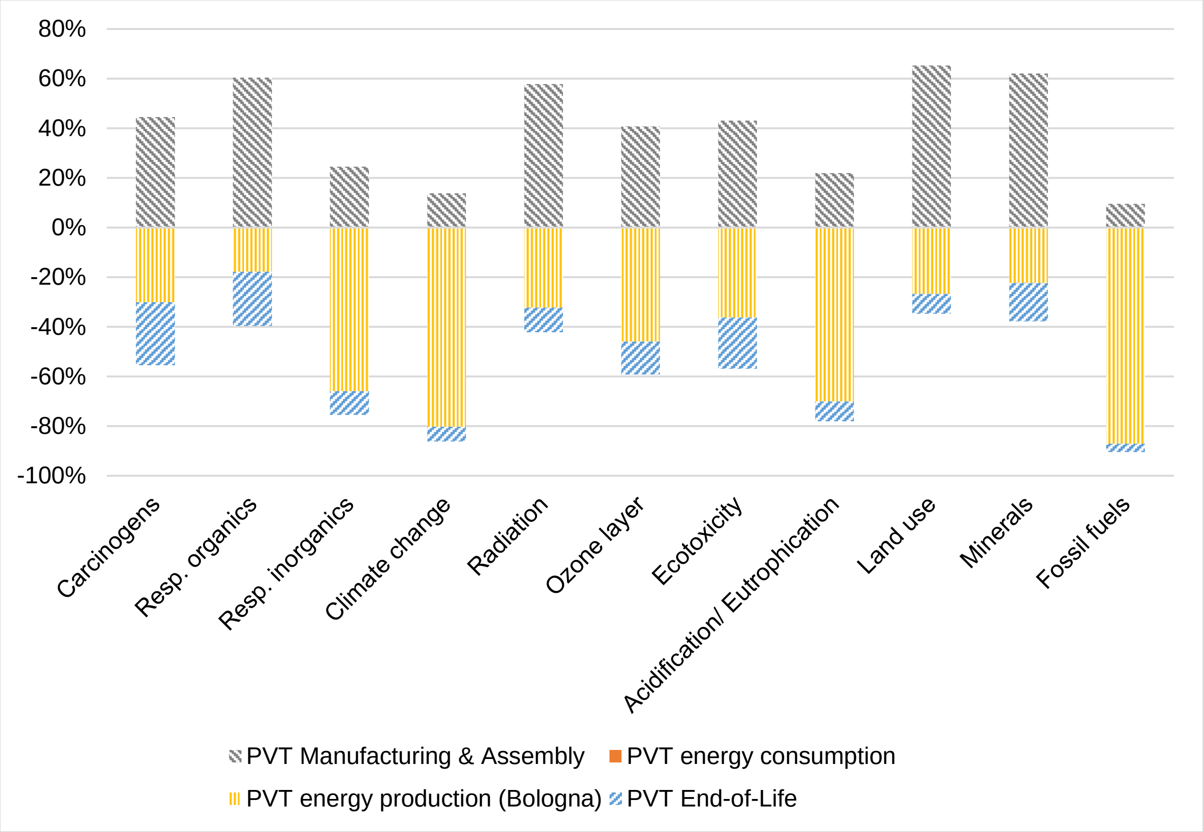

Figure 5.1.6 - Characterisation of PV/T prototype life cycle with EI99

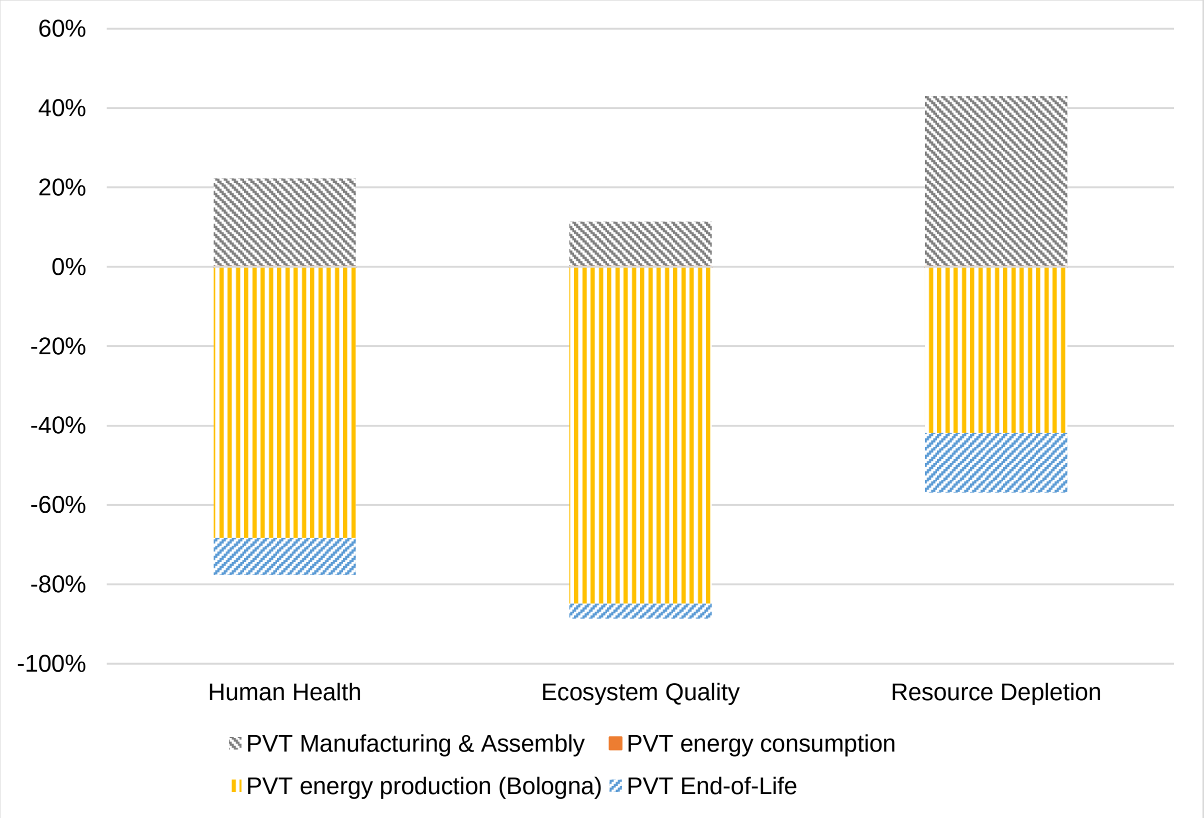

Figure 5.1.7 - Damage Assessment of PV/T life cycle on areas of protection (EI99H)

Details of the Characterisation of PV/T life cycle on EI99H impact categories are reported in Table 5.1.4.

Impact category	Unit	Total	PV/T Manufacturing & Assembly	PV/T Energy consumption	PV/T Energy production (Bologna)	PV/T end-of-life
Carcinogens	DALY	-1.51E-05	5.98E-05	-6.71E-09	-4.06E-05	-3.43E-05
Resp. organics	DALY	1.40E-06	4.06E-06	-1.57E-10	-1.20E-06	-1.47E-06
Resp. inorganics	DALY	-7.93E-04	3.79E-04	-1.63E-07	-1.02E-03	-1.49E-04
Climate change	DALY	-5.63E-04	1.07E-04	-7.49E-08	-6.24E-04	-4.62E-05
Radiation	DALY	4.06E-07	1.52E-06	-1.54E-10	-8.51E-07	-2.62E-07
Ozone layer	DALY	-7.01E-08	1.54E-07	-2.98E-11	-1.74E-07	-5.00E-08
Ecotoxicity	PDF*m^2*year	-1.80E+01	5.57E+01	-8.32E-03	-4.69E+01	-2.68E+01
Acidification/ Eutrophication	PDF*m^2*year	-2.88E+01	1.12E+01	-5.39E-03	-3.59E+01	-4.06E+00
Land use	PDF*m^2*year	1.50E+01	3.22E+01	-2.38E-03	-1.32E+01	-3.98E+00
Minerals	MJ surplus	5.57E+01	1.43E+02	-9.32E-03	-5.17E+01	-3.58E+01
Fossil fuels	MJ surplus	-5.05E+03	5.92E+02	-5.44E-01	-5.43E+03	-2.05E+02

Table 5.1.4 - Characterisation of PV/T life cycle - Absolute values (EI99H)

5.1.4.4 Carbon Footprint (IPCC GWP 2007 100a)

In order to extend the impact assessment of the PV/T life cycle, an additional impact assessment method is used: IPCC GWP 2007 100a. This method is used for the assessment of the Carbon Footprint associated with the life cycle of the prototype. The Carbon Footprint is measured in mass of equivalent carbon dioxide (kg CO_2e), and expresses the global warming potential, which implies climate change, of a process/life cycle. Figure 5.1.8 and Figure 5.1.9 show the impact assessment of the prototype during its life cycle calculated by using the IPCC GWP 100a method.

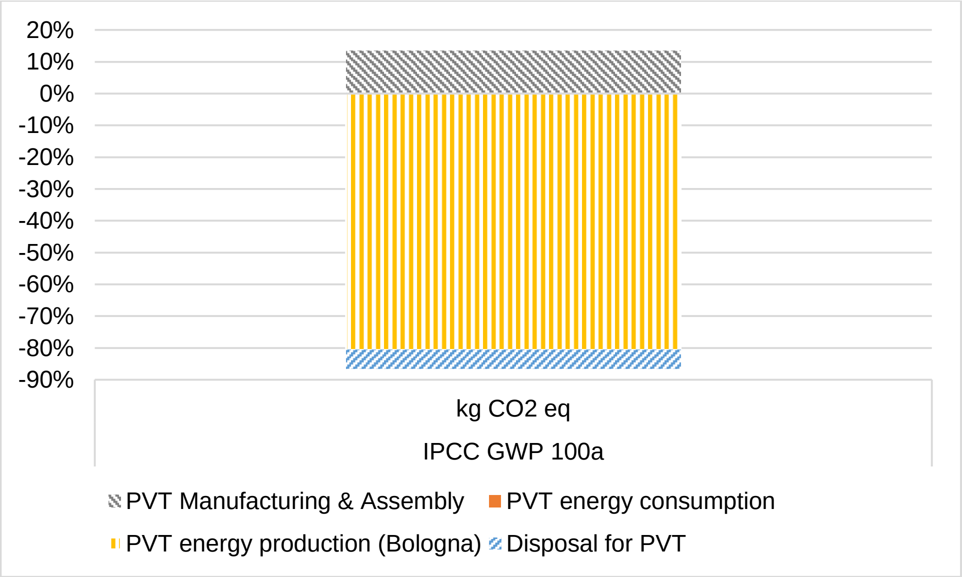

Figure 5.1.8 - PV/T prototype Carbon Footprint - Relative values (IPCC 2007 GWP 100 a)

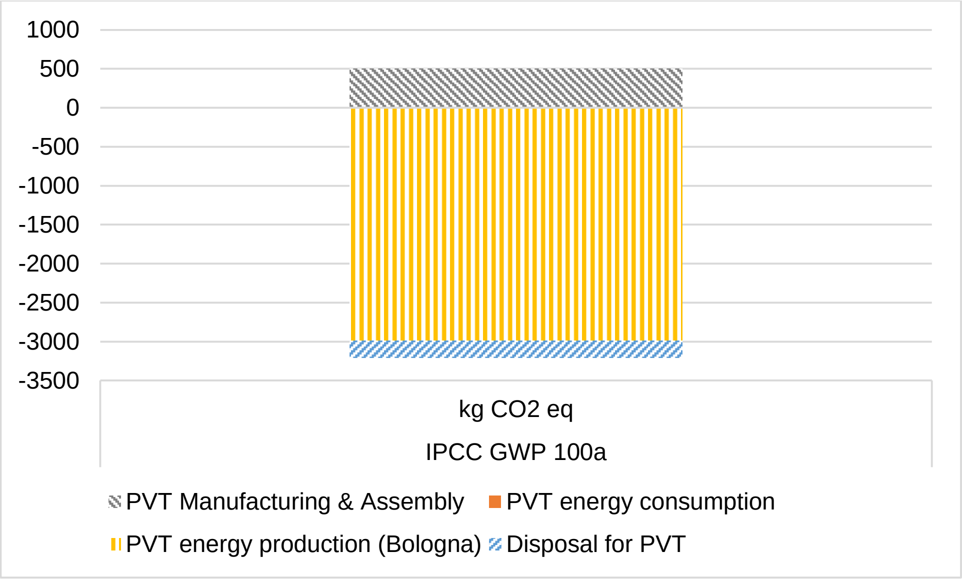

Figure 5.1.9 - PV/T prototype Carbon Footprint - Absolute values (IPCC 2007 GWP 100 a)

5.1.4.5 Interpretation of the results

In this section, some summarising comments on LCA analysis results are reported. Figure 5.1.6, Figure 5.1.7, Figure 5.1.8 and Figure 5.1.9 show that the prototype life cycle introduces a negative overall environmental impact. This result is due to the prototype use that allows important savings in terms of energy production by using conventional systems and, consequently, of fossil resource depletion and pollutant emissions. The avoided environmental impact widely counterbalances the impact caused by manufacturing and assembly activities for the PV/T concentrator prototype production. The prototype sustainability is furthermore increased by the recycling and reuse of a large portion of its modules. According to the main assumption that, each kWh produced by the PV/T system corresponds to the saving of 1 kWh produced conventionally by a mix of non-renewable and renewable sources (see 5.1.4.2.4), the Carbon Footprint associated with the life cycle of the PV/T system is estimated as -2700 $kgCO_{2e}$, which corresponds to a saving of almost 1 kg CO_{2e} per kWh of electric energy, and about 0.65 $kgCO_{2e}$ per kWh of thermal energy. By using EI99H method, with the life cycle of the PV/T system a total saving of 207 Pt (Points) is estimated. It is reminded that 1000 Pt is the average equivalent impact of one European citizen in one year. Referring this value to 1 kWh, the results is that for each kWh of electric energy produced by PV/t system a negative (less than 0) impact of 0.075 Pt is caused. Each thermal kWh generated results in the saving of an impact of 0.05 Pt.

Referring to the manufacturing and the assembly phase of the PV/T concentrator life cycle, the prototype modules that involve the greatest environmental impact are, as shown in Figure 5.1.5, collectors and receivers, which are mainly composed by aluminium and are subjected to noteworthy processes of welding. In addition, the use of PV cells prototype introduces a significant consumption of energy associated to their production, which could be minimised if cells were manufactured on a large scale.

5.1.5 Energy Payback Time

In order to provide a more exhaustive analysis on the prototype life cycle, a sensitivity analysis on its geographic installation site is conducted. EPBT index is calculated to compare the alternative scenarios. EPBT value of the PV/T prototype is given in (1).

$$EPBT_{PVT} = \frac{CED_{PVT}}{Esav_{PVT}} \tag{1}$$

Where CED_{PVT} is the total equivalent amount of energy consumed for manufacturing, assembly and disposal of the prototype. It is calculated by using CED method and its value is 3769 kWh_{eq}. $ESAV_{PVT}$ is the annual equivalent amount of energy production avoided thanks to the use of the PV/T prototype. Its value depends on the geographical location in which the system is installed. Three different locations, with different levels of annual direct irradiation are assumed and listed in Table 5.1.5:

Geographical location	**Annual direct irradiation** $\left[\frac{kWh}{year \cdot m^2}\right]$	**E_{SAV}** $\left[\frac{kWh_{eq}}{year}\right]$
Bologna	1171	646
Roma	1500	828.5
Palermo	1761	972

Table 5.1.5 - Annual direct irradiation and yearly $Esav_{PVT}$ for Bologna, Roma, Palermo

Figure 5.1.10 represents the $EPBT_{PVT}$ value for each geographical scenario: 3.9 years is the $EPBT_{PVT}$ of the system if installed in Palermo; 4.5 years if installed in Roma; 5.9 years if the prototype is located in Bologna.

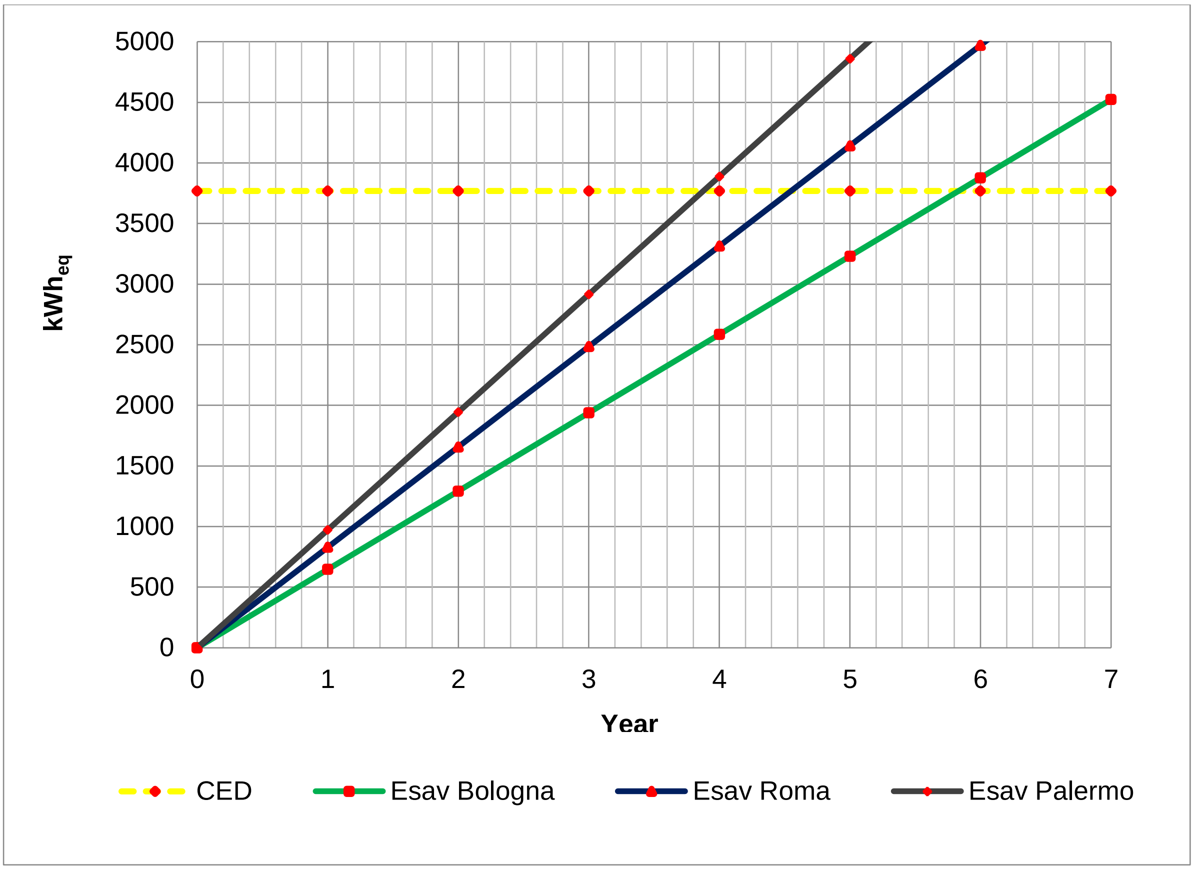

Figure 5.1.10 - Sensitivity analysis of $EPBT_{PVT}$ to the variation of plant geographical installation

5.1.6 Comparison between alternative energy production systems

In order to complete this study, it is necessary to compare the PV/T prototype with alternative energy production systems. For this comparison, the assumption according to which to the energy produced by using the PV/T system corresponds a negative impact must be removed. In this case, the impact associated with the energy production by the PV/T system is calculated as the ratio between the amount of energy produced during the machinery life cycle and the overall impact of manufacturing, assembly, energy consumption and EoL, then distributed on 1 kWh. As known, the PV/T prototype is a hybrid system, whose main purpose is the production of electric energy. For this reason, the comparison carried out on the basis of the generation of electric energy. In addition, EI99H is preferred to the other methods because of its comprehensiveness. Figure 5.1.11 shows the impact caused by the production of 1 kWh of electric energy by using different systems or technologies, i.e. Fresnel PV/T concentrator, conventional Italian low voltage Italian energy mix, electric energy production by biogas cogeneration and mixed photovoltaic electric energy production. Data on the environmental impact of these power systems are collected from Ecoinvent v.2.2.

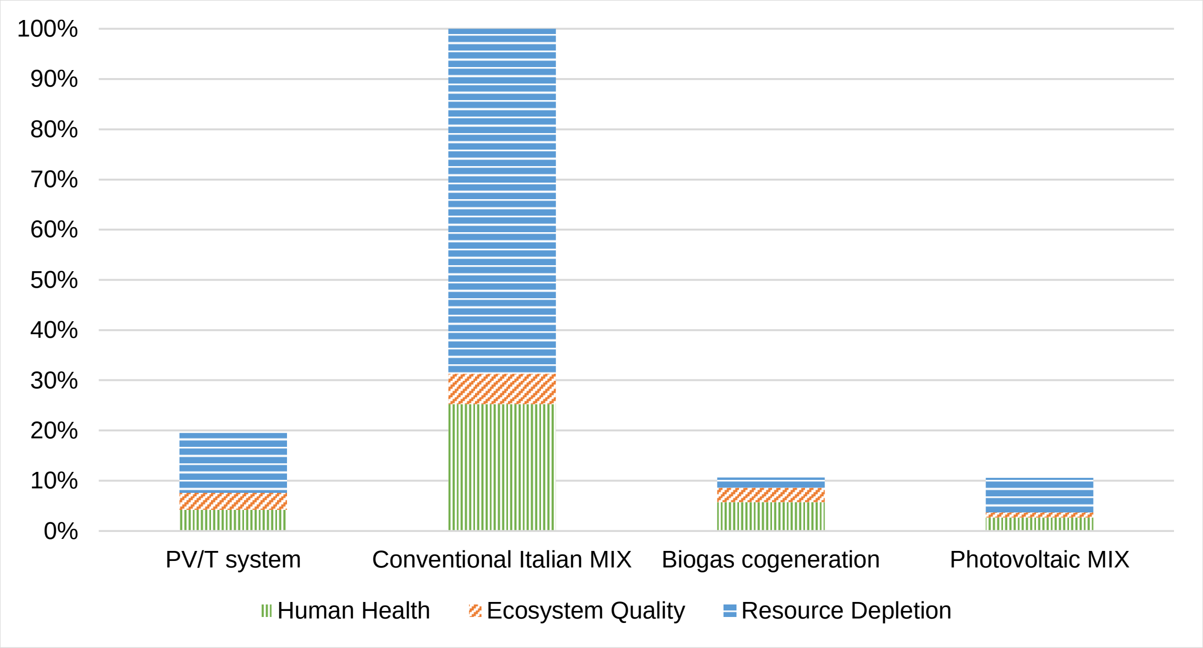

Figure 5.1.11 - Comparative impact assessment between different energy production systems - Single score - Relative values (EI99H)

Results show that the PV/T prototype introduces about one fifth than the average power system, here resented by the conventional Italian energy mix. However, the PV/T system is not yet competitive with the other renewable energy system here considered in terms of environmental sustainability. It is important to specify that, since the PV/T concentrator is a prototype, wide margins of improvement are still possible. Indeed, this study aims to guide the development of the prototype so that it can have a more sustainable life cycle.

5.1.7 Conclusion

Aim of the study is the evaluation of the environmental sustainability of a Fresnel PV/T concentrator prototype developed the laboratories of DIN of the University of Bologna. An LCA study on the prototype life cycle is conducted and its EPBT value is calculated. Finally, a comparison on environmental sustainability between alternative energy production systems is reported. The LCA demonstrates the system environmental sustainability and emphasises the life phases that introduce significant environmental impacts. Although the prototype manufacturing and assembly processes involve an important consumption of raw materials and energy, the hypothesised EoL treatments assure minimal environmental impacts. By conducting a sensitivity analysis, a significant dependence of the system EPBT from its geographical installation is demonstrated. The environmental impact of the production of 1 kWh of electric energy by using the PV/T prototype is calculated. This value is compared with the environmental impact of the same amount of energy by using alternative systems or technologies. The comparison demonstrates that the prototype is environmentally convenient if compared to the conventional electric energy mix but is not yet competitive in environmental sustainability with other renewable energy production systems. In order to reduce this gap, a partial redesign of the prototype must be considered: alternative materials and manufacturing processes, together with the selection of different PV cells, should be assumed and tested. In particular, system collectors are responsible for about the 50% of the cradle-to-assembly impact. The manufacturing of the 32 mono-crystalline PV cells is responsible for about 200 kWh of energy consumption, which represents about the 7.2% of the electric energy produced by the system during its life. High priority must then be given to the minimisation of the impact associated with the PV cells. The system is composed by about 80 kg of steel and 40 kg of aluminium. These materials compose the 92% by weight of the whole prototype. Therefore, the second action that can be applied in redesigning the prototype is its dematerialisation. A shape optimisation of collectors and support frame by conducting a finite element analysis can conduct to a significant reduction of prototype weight. These evaluations are left to future studies.

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5.2 COMPARATIVE LCA OF HAYMAKING MACHINERY

5.2.1 Introduction

The agricultural industry continues to experience a period of significant transformation. The industry’s ongoing sensitivity to increasing production costs has resulted in greater attention being paid to the development of more efficient processes (FAO, 2010). The use of chemical fertilisers, the over-exploitation of the soil and the adoption of intensive pesticides are legacy features, with long-term impacts that are subject to negative evaluation by the market (Dorais, 2007; Mózner et al., 2012). The international community frequently discusses the environmental sustainability of agricultural products and the effects of pollution on both the public health and product quality (Dorais, 2007; Mózner et al., 2012). This study contends that mechanised automation could play a crucial role in improving farm efficiency and reducing environmental impact. If the producer is able to reduce the economic costs and the environmental impact associated with the life cycle of the products offered to the final customers, a sustainable source of competitive advantage is possible with benefits for the agricultural production and the community. As a result, manufacturers are looking towards the design of effective methods based on both the environmental and mechanical efficiency of automated agriculture.

An Italian manufacturer of haymaking systems is developing an innovative single piece of Multi-Functional Machinery (MFM) able to perform, jointly, three operations that are usually conducted by three standalone devices, i.e. hay rake, round baler and a bale wrapper. Such a multi-functional system introduces significant modifications in the haymaking process where hay collection, hay baling and bale wrapping are carried out in a single step process requiring the MFM single device being towed by a tractor. Figure 5.2.1 represents the innovative concept behind the new MFM where three independent pieces of machinery are replaced by a single piece of machinery.

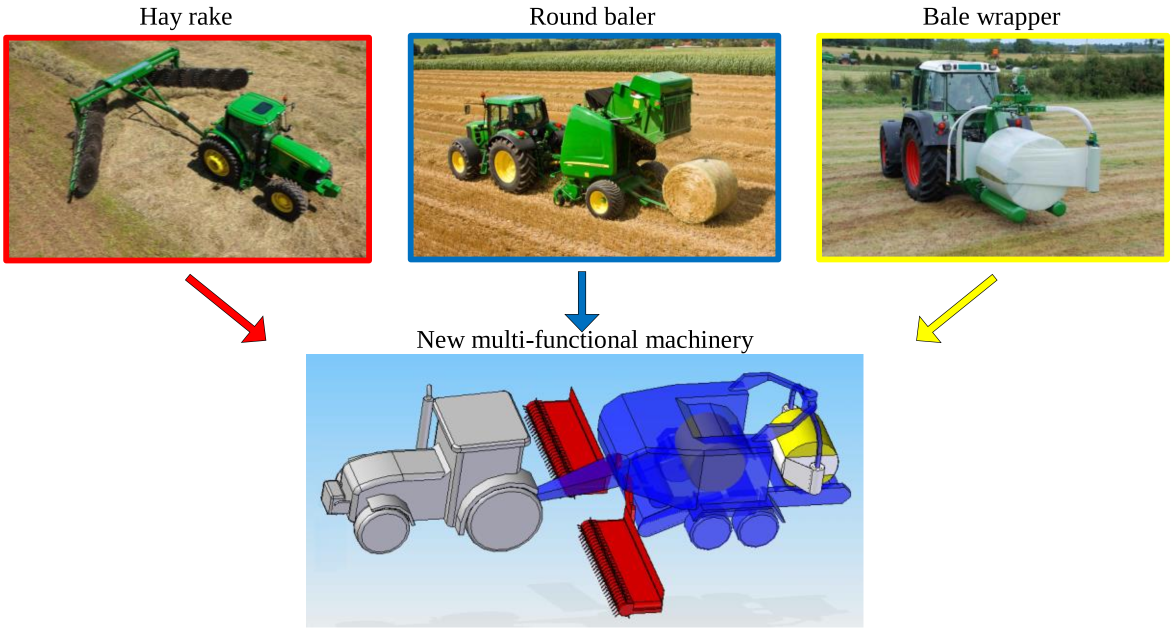


Figure 5.2.1 - New multi-functional machinery

Whilst the expected increase in efficiency is maybe predictable, the environmental benefit introduced by the use of the MFM compared to the corresponding three standalone machines is not obvious and requires evaluation. A comparative Life Cycle Assessment (LCA) is proposed to substantiate these efficiencies. The new MFM is compared to the standalone implement system on the basis of the environmental burden introduced across their life cycles. The assumed functional unit is the production of 98,700 wrapped hay bales, which corresponds to 3,000 machine working hours. The description of the haymaking process and the MFM features, developed during the machine design phase, are followed by the comparative LCA presentation. The results are, then, shown, both, aggregately and split by machine functional unit stressing their contribution to the global system environmental impact and highlighting the savings coming from the switch to the proposed MFM.

In the following discussion (section 5.2.2), we introduce a literature review on the most significant scientific contributions of LCA studies in the agricultural industry. Sections 5.2.3, 5.2.4, and 5.2.5 present a functional description of the haymaking process and the machinery analysed in this study. The LCA steps are fully described in 5.2.6 and 5.2.7, while the key results of the comparative LCA are reported in 5.2.8. Section 5.2.9 concludes with a comparative discussion on the environmental impacts associated with both machinery systems.

5.2.2 State of the art of LCA in agriculture and farming operations

5.2.2.1 LCA in agriculture

In recent years, the contribution of environmental impact assessment to agricultural production processes has grown significantly. From 2010 to date, more than two hundred articles, which have both “life cycle assessment” and “agriculture” as main issues, have been published. Such popularity is justified given the relevance of food production and environmental impact generation. Tukker et al. (2006) assessed that the food and beverage sector involves 20-30% of the total environmental impacts resulting from European Union food consumption, in which meat and dairy productions account for 4-12% and 2-4% respectively of the equivalent carbon dioxide emissions. Roy et al. (2009) proposed an extended review of LCA studies related to food production, classifying several contributions on the basis of food product features. Here a whole section is dedicated to LCA on dairy and meat production. According to the authors, the agricultural phases are reported to be the main hotspot in the life cycle of milk and semi-hard cheese production. Similar conclusions on the relevance of the agricultural phase in dairy and meat production impact were given by Berlin (2002) and Foster et al. (2006) . Hospido et al. (2003) analysed milk production in Spain and found that the feed production phase is a hotspot of the milk life cycle. In particular, the production of silage represents 21% by weight of the animal feed. Such a process is estimated to be responsible for 29% of global warming and acidification, and for 23% of the eutrophication effects of the total milk production. Some LCA studies adopted extended system boundaries and indicated that agriculture production is the main source of impacts in the life cycle of meat products (Foster et al., 2006; Mattsson et al., 2000; Roy et al., 2008) even if they are not directly related to the environmental impact resulting from silage production. (Foster et al., 2006; Mattsson et al., 2000; Roy et al., 2008) analysed beef production in the United Kingdom and calculated that the feed production, 41% of which was composed of forage, contributes 48% of the total carbon footprint of feed production. In addition (Ogino et al., 2007, 2004), demonstrated that the environmental impact of a beef-fattening system is strongly dependent on the silage production and type. Although the role of cattle feed and forage production in the life cycle of meat and dairy is well researched, there are few research contributions focusing specifically on the harvesting operation or on machinery efficiency and their sustainable design. (Ogino et al., 2007, 2004) and Meisterling et al. (2009) performed life cycle assessments of wheat production. The former estimated that on-farm operations (i.e., fertiliser, herbicide and seeds spraying, and harvesting) contribute 44% to the carbon footprint of wheat production life cycle. The latter determined that farming operations account for 29-32% of the production of wheat, 4% of which result from farm machinery production. Saer et al. (2013) discussed the hotspots of food waste composting operations. The authors concluded that the fuel combustion and electricity consumption created by machinery use (i.e., grinding, tractor drawing, mixing, loading, screening, stacking and turning operations) were the hotspots in the production of compost and proposed the calculation of the contribution for each individual piece of machinery in order to introduce effective efficiency improvement actions. Dyer and Desjardins (2006) proposed a model aimed at the quantification of the energy consumed in farming operations. According to their study, the energy required to manufacture farm machinery is comparable to the total amount of fossil fuel energy consumed during farm field work. Mousazadeh et al. (2011) presented a solar hybrid electric tractor and analysed its life cycle economic cost and environmental profile. The electric tractor prototype was compared to a conventional tractor highlighting the advantages and disadvantages. Lee and Park (2012) focused on the minimisation of the environmental impact introduced by agricultural machinery during their use phase. The greenhouse gas and atmospheric pollutant emissions introduced annually by agricultural machineries for rice production were estimated. Lee et al. model was developed to, then, identify the optimal combination of the agricultural machinery relative to environmental impact and then applied to a case study.

The issue of environmental impacts created by agricultural food production is widely published. It includes several contributions focused on the production of goods derived from livestock. However, these analyses do not discuss specifically the environmental burden created by the production of livestock silage. The aim of this study is to thoroughly assess the silage production process, determining the environmental impact contribution of each piece of machinery, as suggested by Saer et al. (2013) and to present an LCA analysis on a prototypal piece of hay making machinery which may be able to reduce significantly the environmental burden associated with the production of silage.

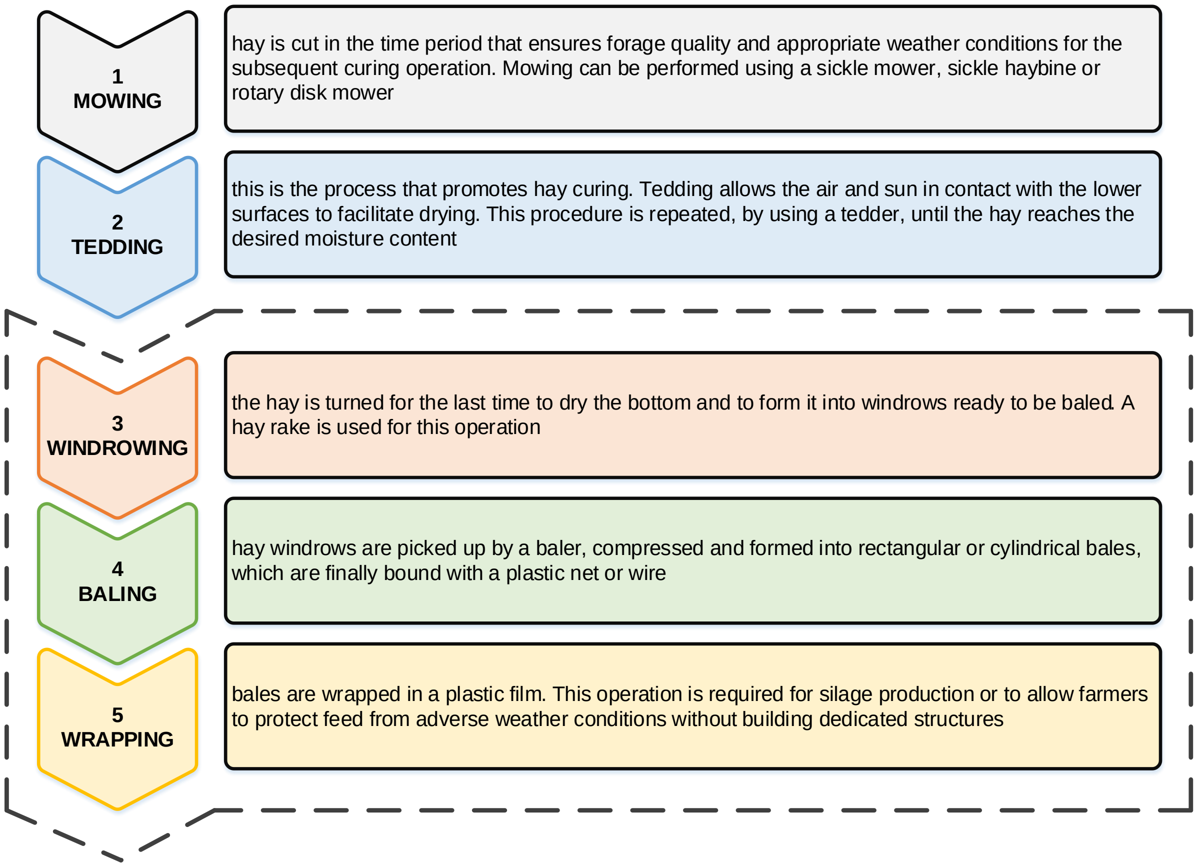
5.2.3 The haymaking process: traditional VS multi-functional system

Haymaking is the process of turning green, perishable forage into a product that can be safely stored and easily transported. Such a process aims to reduce the moisture content from cut forage by drying it through solar radiation and air convection energy. The process of drying, called "curing", involves reducing the water content of fresh forage, so that it can be stored without spoilage or, further nutrient loss. Depending on the moisture content, different kinds of forage are distinguished:

- *Green forage*: water percentage of 75-80%. It can be directly used for feeding or it can be cured and preserved as silage;
- *Silage* (wilted forage): moisture of 30-40%. The water content is sufficient to trigger anaerobic fermentation which preserves the nutritional quality without damaging the forage (fermented forage is also known as silage);
- *Dry forage*: the low water content (15-16%) allows long lasting storability in bales.

The haymaking process has five main steps: mowing, tedding, windrowing, baling and wrapping. Figure 5.2.2 details each phase. For each of the aforementioned steps, specific machinery/additional devices are necessary. The aim of this work is to improve the efficiency of phases 3, 4 and 5, which present a new system of hay making which can achieve the same results as the traditional hay making system of three machines with a single device (MFM).

The main advantages related to the new MFM are to complete the phases 3, 4 and 5 in only one passing across the field, with relevant savings in operation time and costs and environmental emissions.



hay is cut in the time period that ensures forage quality and appropriate weather conditions for the subsequent curing operation. Mowing can be performed using a sickle mower, sickle haybine or rotary disk mower

this is the process that promotes hay curing. Tedding allows the air and sun in contact with the lower surfaces to facilitate drying. This procedure is repeated, by using a tedder, until the hay reaches the desired moisture content

the hay is turned for the last time to dry the bottom and to form it into windrows ready to be baled. A hay rake is used for this operation

hay windrows are picked up by a baler, compressed and formed into rectangular or cylindrical bales, which are finally bound with a plastic net or wire

bales are wrapped in a plastic film. This operation is required for silage production or to allow farmers to protect feed from adverse weather conditions without building dedicated structures

Figure 5.2.2 - Haymaking process flow-chart

5.2.4 The haymaking devices: traditional VS multi-functional system

5.2.4.1 Traditional haymaking devices

In the traditional haymaking process, three standalone devices are used: a hay rake, a round baler and a bale wrapper. They are designed for raking, baling and wrapping, respectively. Their main characteristics and operating functions are presented in the following paragraphs.

5.2.4.1.1 Pick-up belt hay rake

The hay rake (see Figure 5.2.3) considered in this study, is a pick-up belt hay rake (PB-HR). It is a machine that does not drag the swath with traditional wheel rakes, but it raises the forage minimising the hay damage and preventing the collection of dirt and soil, which improves the product quality. The PB-HR comprises a support steel frame and two side wings with a total span of 8.2m. The wing configuration has a variable geometry depending on the desired windrow typology, e.g. one central windrow, two lateral windrows, two symmetrical swaths. The chassis is equipped with a wheeled cart that allows the rake to move both in the field and on the road. During the use phase, the PB-HR (weight of 2000kg) has to be towed by a tractor having a power of at least 70hp.

Figure 5.2.3 - Pick-up belt hay rake

5.2.4.1.2 Round baler

The round baler (RB) considered in this study is a variable chamber round baler (see Figure 5.2.4). It can produce bales of variable size with uniform and constant forage compression given a dedicated control unit. In general, the bale core is kept well ventilated to guarantee the best drying and preservation conditions. The RB contains rollers and belts. In the first phase, the forage enters the chamber. The chamber is gradually filled and when the bale reaches the desired size, the binding unit spins the bale with a polymeric net or twine while it is still in rotation. Finally, the opening of the rear part of the chamber enables the automatic bale unloading. The RB weighs 2,400kg and it needs to be drawn by a tractor of at least 100hp.

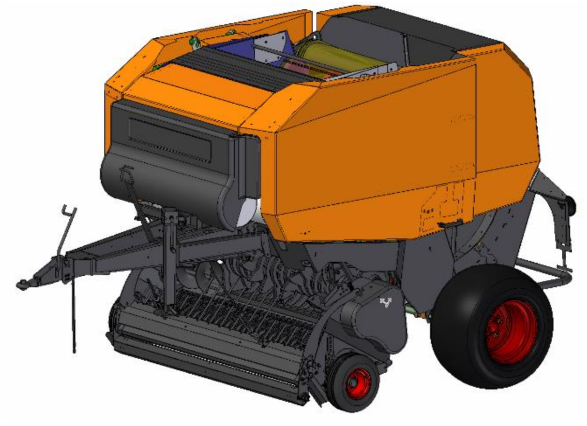


Figure 5.2.4 - Variable chamber round baler

5.2.4.1.3 Wrapper

The bale wrapper (BW) is the machine used to wrap the finished bale using a polyethylene film (see Figure 5.2.5). Typically, in the winding process, four to six layers of polymeric film are necessary to ensure complete protection of the inner silage. The bale wrapper receives the bale on a belt table rotating the bale around its axis. A group of arms spin orthogonally to the bale rotation direction and, keeping the film tense, wraps the bale. For the correct winding, the tension of the film has to be appropriately set, typically at 65-70% of the stretching elongation. This means that a meter of film becomes 1.65-1.70m around the bale. When wrapping is completed, the cutting system releases the bale, which is then discharged. The BW weighs 1,400kg and needs to be drawn by a power of at least 50hp.

Figure 5.2.5 - Bale wrapper

5.2.4.2 Multi-functional machine

For the production process of silage, bales a new MFM is designed to execute the operations of raking, baling and wrapping with a unique device integrating these three currently separate functional devices (see Figure 5.2.6 and Figure 5.2.7). The MFM front braces move close to the soil forming a central windrow. As the system advances, the baler pickup system collects and accumulates the windrow in the baling chamber. Once the bale is complete, the MFM stops for a time to bind the bale with net or twine. As soon as the bale is unloaded to the wrapping area, the baling chamber immediately re-starts the process again. Once the wrapper unit completes the bale filming, during the next stop, the completed bale is unloaded onto the ground. The MFM weighs 7,380kg and has to be towed by a tractor having power of at least 150hp.

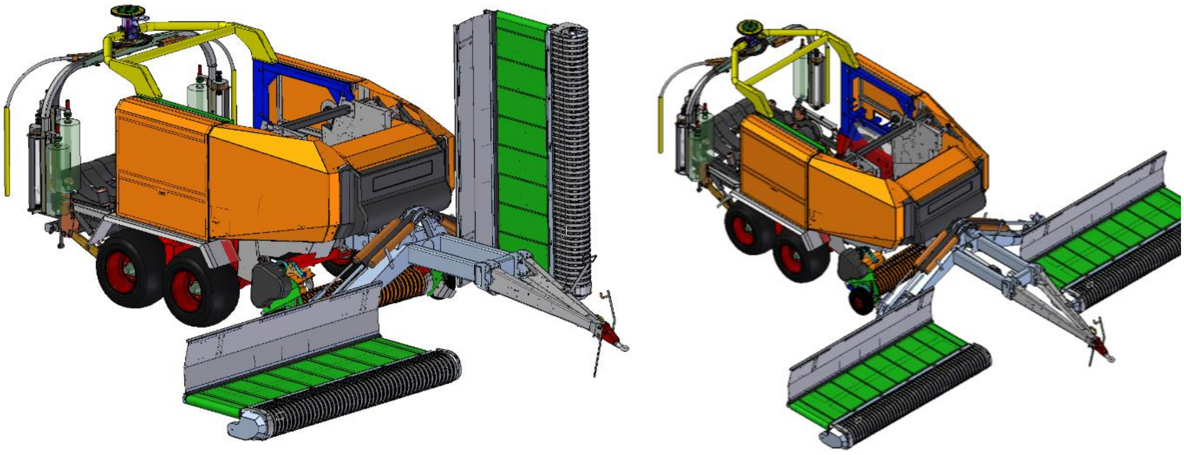


Figure 5.2.6 - Multi-functional machine (CAD rendering)

Figure 5.2.7 - Multi-functional machine (real prototype)

5.2.5 MFM design phase

The MFM design process starts from the three traditional separate devices available and engineered by the aforementioned Italian manufacturer. The design phase goal deals with the integration of these three machines into a single device to gain time, cost and environmental impact advantages. For standardisation purposes, the structures of the functional modules, i.e. the machine sub-assemblies directly responsible of the hay treatment, are not relevantly changed to reduce the design complexity and the related time consume. The three devices combined to create the MFM were chosen in order to minimise the re-design complexity for the combined system and potentially reduce the production time involved in production. The round baler and the bale wrapper modules are, only, slightly changed between the traditional device and the MFM, while the hay rake has to be significantly redesigned because of its position in the MFM and the different hay flow directed to the round baler. Most of the changes required in the prototype are in the MFM structural frame that is completely re-designed to optimise the machines configuration, reducing the material embodied energy and the overall system weight.

The design alternatives and choices taken consider both the manufacturer’s expertise and the know-how from the users familiar with the operating conditions e.g. the availability and typicality of the 150hp power tractor to tow the MFM in order to not overstate the required hay making investment costs.

The environmental assessment described in 5.3.6 is then adopted to validate and fully justify, technically, economically and environmentally, the performances of the system. The prototype in Figure 5.2.7 is used, then, to field-test the developed MFM.

5.2.6 Life Cycle Assessment

5.2.6.1 Goal and scope definition

The main objective of the proposed LCA is the environmental impact evaluation of the aforementioned agricultural machineries with the aim of comparing, from a sustainability point of view, two alternative haymaking systems. The first system is the traditional process, considering the use of three standalone machines (PB-HR+RB+BW), the second is an innovative process employing the MFM. The analysis leads to the identification of the life cycle stages and machine components that, directly and indirectly, generate the highest impact on the environment. In the following section, we review the boundaries and functional unit of the assessment and consider the research limitations presented.

5.2.6.1.1 Analysis hypotheses

Assumptions made:

- The machine speed in the field is assumed constant and equal to its average value;
- The bale binding is executed as follows: 50% with net and 50% with twine;
- In the machinery assembly operations, manual operations are considered only, while all consumptions due to assembly devices and phases are neglected;
- The average geographical distances between the supplier, the manufacturer and the final customer are estimated;
- The lifespan of each machine is assumed equal to 3,000h;
- The machine handling from the deposit to the field and return is neglected;
- The quality of the feed from both the innovative and the traditional processes is the same;
- The life cycles of the manufacturing plant and equipment utilised in the final assembly of the agricultural devices are not included in the boundary assessment.

5.2.6.1.2 System boundaries

In the LCA the following processes are considered: raw material extraction, manufacturing and assembly of the components, transportation of raw materials and the final products, the machinery use phase, waste treatment, disposal of machinery, wrapping film and engine and transmission oils, and material and component recycling and reuse. Maintenance activities are not included in the analysis.

5.2.6.1.3 Methodology

The life cycle impact assessment is carried out using ReCiPe 1.08 index (Endpoint method, worldwide scale normalisation, Hierarchical perspective), by Goedkoop et al. (2009), as the assessment methodology. This method focuses on the evaluation of the following midpoint indices: the damage to human health, measured in "DALY" (Disability Adjusted Life Years); the ecosystem quality, quantified in Species per year (Loss of species per year) and the resource surplus cost, evaluated in "USD surplus". Through the weighting and normalisation steps, ReCiPe calculates the so-called Endpoint Index (Pt) that measures the overall environmental impact of the analysed system. The use of a comprehensive assessment method is required: with ReCiPe greenhouse gas, sulfur (SOx) and nitrogen oxide (NOx) emissions, and particulate generation, resulting from fuel combustion are considered, in addition to effects on terrestrial acidification, ozone depletion, particulate concentration and climate change.

5.2.6.1.4 Functional unit

For this study, the functional unit is the amount of standard products producible during the entire lifespan of such machinery. As the system productivity is known, the environmental impact related to the production of a single bale can be calculated as follows. The standard unit of production is a bale of hay whose characteristics are presented in Table 5.2.1.

Diameter	**Width**	**Weight**	**Humidity**	**Volume**	**Main composition**
1200mm	1200mm	640kg	65%	1.36m^3	Lolium multiflorum; Triticale (Triticum); Dactylis glomerata; Alfalfa (Medicago sativa)

Table 5.2.1 - Standard bale characteristics

The machine lifespan is derived from the maintenance database of the manufacturer and it is equal to 3,000h/machine. To determine the total amount of bales produced during the machine life cycle, it is necessary to calculate the average time to complete a bale: T_{bale}.

$$T_{bale} = \frac{W}{Y \cdot L \cdot v} + T_{binding} \tag{1}$$

$$T_{binding} = \begin{cases} 15 \quad (net\ binding) \\ 30\ (twine\ binding) \end{cases} \tag{2}$$

Where:

- T_{bale} is the time to complete a bale [sec/bale];
- $T_{binding}$ is the time to compete the binding phase of the bale [sec/bale];
- W is the bale weight [kg];
- Y is the forage yield of the field, usually 0.4 [kg/m^2];
- L is the forage collection width of the hay rake, equal to 8.2 m;
- v is the average speed of the baler in the field, equal to 2.23 m/s.

Because of $T_{binding}$ depends on the net or twine usage, the time to complete a bale are, respectively T_{bale}=102.6 sec/bale and T_{bale}=117.7 sec/bale.

Considering an equal distribution of the net-bond (50%) and the twine-bond (50%) bales during the life cycle of each machine, the total amount of the produced bales N_{bales}, is:

$$N_{bales} = \frac{3000 * 0.5}{102.3} + \frac{3000 * 0.5}{117.7} = 98700 \; [bales/device] \tag{3}$$

5.2.6.2 Life cycle inventory (LCI)

Detailed data on component processing and energy consumption have been collected directly from the machinery manufacturer. Generic data from the literature together with professional databases have been used where primary data was missing, for example with raw material extraction and transformation data. Datasets of pollutant emissions and waste generation values were mined from the Ecoinvent v2.2 database (Ecoinvent databank version 2.2, 2010; Frischknecht and Rebitzer, 2005; Rebitzer et al., 2004). The four analysed devices are complex machines with several components. For example, the RB Bill of Material (BOM) includes more than 3,000 items. Each component has been classified within the different modules and sub-groups. Table 5.2.2 and Table 5.2.3 provide detailed data on the manufacturing processes included in the life cycle inventory of MFM.

Module	Sub-group	Material	Weight [kg]	Casting [kg]	Forging [kg]	Extrusion [kg]	Bending [m]	Cutting [m]	Welding [m]	Lamination [kg]	Injection Moulding [kg]	Zinc Coating [m^2]	Powder Coating [m^2]
Baling module	Binding module	P	0.02								0.02		
		S	55.22	54.05	0.42	0.75	20.42	31.79	4.82			0.05	0.05
	Connection with balancing table	S	117.51	48.9	4.07	64.54	4.05	21.96	5.42			0.05	
	Electrical system	P	0.18								0.18		
		PP	0.01								0.01		
		S	14.77	14.59		0.1	8.18	13.63	0.12		0.08	0.04	
	External carter	S	157.91	144.49	0.09	6.29	70.29	89.37	2.17	7.05			
	External frame - Baler	S	1175.47	751.03		424.44	66.35	266.9	86.32			0.03	0.03
	External frame - Wrapping	S	378.71	124.9	7.04	246.78	9.38	59.04	26.76				0
	Fixed module	N	1.45								1.45		
		P	0.05								0.05		
		R	0.1		0.1								
		S	784.75	489.53	95.87	177.63	75.32	203.46	53.14	21.73		4.88	4.83
	Hay-feeding module	N	0.25								0.25		
		S	415.95	334.86		81.09	41.29	194.67	23.58			1.8	0.05
	Movable module	N	1.58								1.58		
		S	649.47	561.2	27.11	59.17	43.96	137.04	24.37		2	0.07	0.01
	Net binding module	A	0.2	0.2									
		C	0.2			0.2							
		P	5.16	0.62		0.2					4.34		
		PP	0.01								0.01		
		S	88.58	37.85	1.33	47.5	19.17	45.7	2.99	1.9		1.79	1.03
	Pick up module	N	0.78								0.78		
		P	0.06								0.06		
		PP	5.6								5.6		
		R	7.6		7.6								
		S	338.92	201.11	7.55	107.33	65.94	197.29	15.65	15.69	7.24	1.4	0.87
	Protections	P	0.22								0.22		
		S	14.33	12.03		2.3	7.01	13.4	0.43			0.18	0.18
	Tyres module	P	0.8	0.8									
		R	64		64								
		S	609	225.06	98.88	9.26	19.41	42.54	15.64	275.8			
	Wire binding module	C	0.2			0.2							
		P	0.77	0.7							0.07		
		S	86.94	81.61	0.02	4.3	22.92	66.68	3.45	1		1.37	1
	Baling module Total		4976.77	3083.52	314.08	1232.06	473.67	1383.46	264.85	323.17	23.94	11.67	8.05

Table 5.2.2 - MFM bill of material and manufacturing process inventory - baling module

Module	Sub-group	Material	Weight [kg]	Casting [kg]	Forging [kg]	Extrusion [kg]	Bending [m]	Cutting [m]	Welding [m]	Lamination [kg]	Injection Moulding [kg]	Zinc Coating [m^2]	Powder Coating [m^2]
Pickup and Raking Module	Connection frame rake-baler	B	2.9			2.9							
		S	318.18	201.93		116.25	4.1	61.93	41				
	Pick up module	B	1.3			1.3							
		P	30.92	30.55							0.37		
		S	802.7	398.9	9.84	287.87	183.24	250.85	33.32	106.09			
	Shaft and front foot	P	4.35			4					0.35		
		S	115.77	58.96	1.89	8.6	6.53	16.66	7.06	46.32			
	Pickup and Raking Module Total		1276.12	690.34	11.73	420.93	193.87	329.43	81.38	152.41	0.72		
Wrapping module	Arms	A	51.4			51.4	0.22						
		N	0.47								0.47		
		P	2.14			2.05					0.09		
		S	104.64	60.25		30.6	4.85	42.83	8.11		13.79	0.45	0.45
	Balancing table	P	0.29	0.29									
		PP	16			16							
		S	189.3	87.2	12.79	102.4	7.84	19.21	10.77		-13.09	0.09	
	Engine support	S	46.77	13.01	0.62	18.14	0.58	6.69	3.76	15		0.01	
	Film cutter	P	0.4								0.4		
		S	54.9	36.93	0.13	17.84	7.1	43.18	9.55			0.2	0.2
	Oil distributor	P	0.19			0.14					0.04		
		PP	0.4								0.4		
		S	50.49	1.96		36	0.35	1.57	0.31	6.3	6.23	0.08	
	Table transmission	N	0.25								0.25		
		S	0.45	0.03	0.02	0.4	0.03	0.44	0.08				
	Wrapping module Total		518.08	199.67	13.56	274.98	20.97	113.92	32.57	21.3	8.58	0.82	0.65
Other	Cables transmission system	P	59.22			59.22							
	Small metal parts	A	0.01			0.01							
		B	3.47			3.47							
		C	0.12	0.12	0.12								
		S	496.8	261.27	292.05	112.36						39.89	
	Other Total		559.61	261.39	292.17	175.05						39.89	

Table 5.2.3 - MFM bill of material and manufacturing process inventory - pickup and raking module, wrapping module and other components.

5.2.6.2.1 Materials

The wide majority of components considered in the LCI can be summarised as follows: Steel (S), Copper (C), Bronze (B) Aluminium (A), Oil (O), Rubber (R), Polypropylene (PP), Nylon (N), and PVC (P). Their quantities are depicted in Figure 5.2.8 that summarises, from the mass point of view, all the machinery BOMs. Lubricating oil is included in the bill in order to show its relevance in terms of weight.

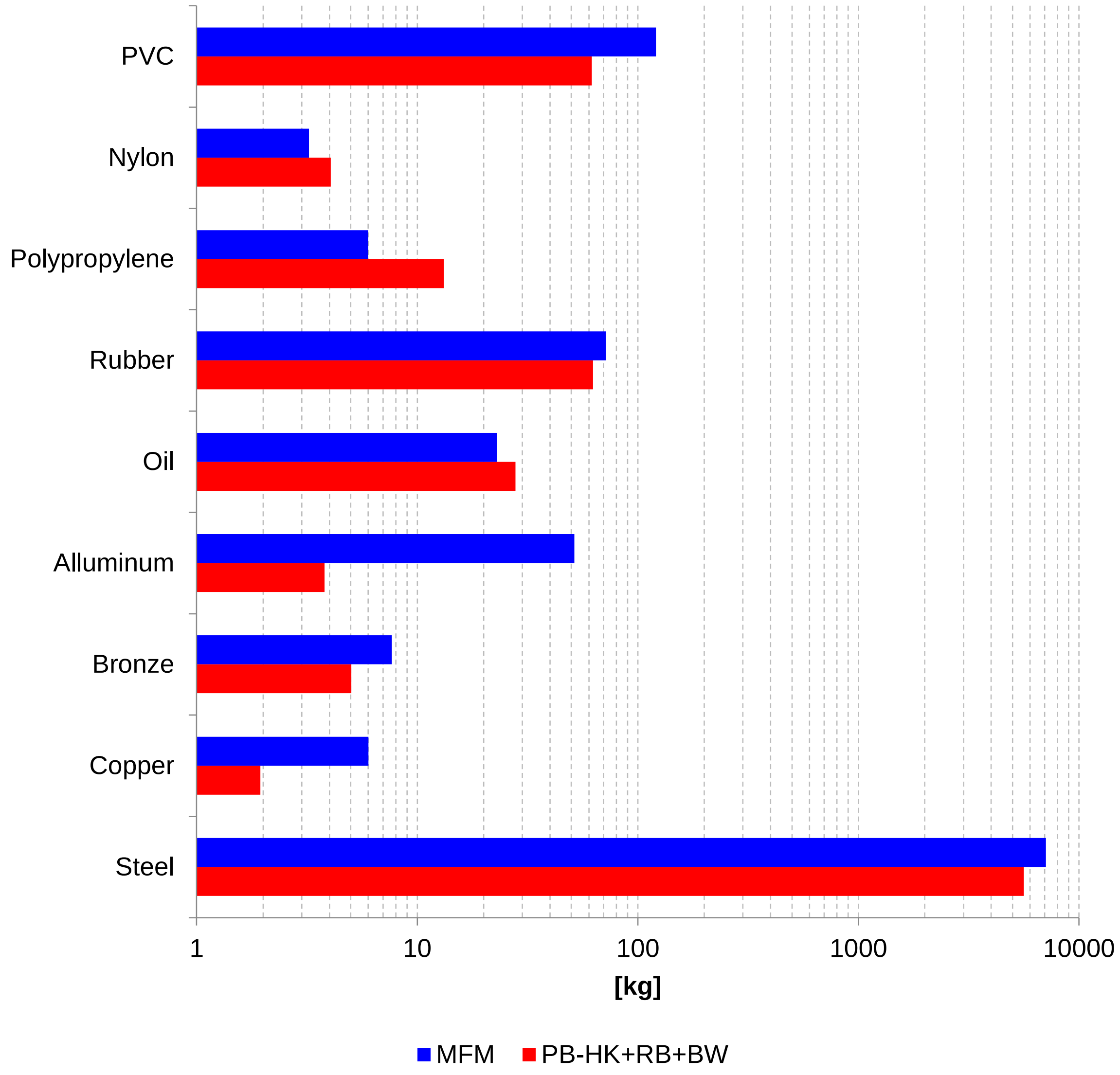


Figure 5.2.8 - List of materials belonging to the traditional (PB-HR+RB+BW) and innovative (MFM) hay making machinery

5.2.6.2.2 Manufacturing

Data on the extraction and transformation of the raw materials utilised in the analysis are considered and evaluated using the Ecoinvent v2.2 database. All processes required for the manufacturing and the assembly of each device is listed in Table 5.2.4.

Process	Material							
	S	A	C	B	N	R	PP	P
Casting	x	x	x	x				
Forging	x		x					
Extrusion	x	x	x	x		x	x	x
Bending	x	x						
Cutting	x	x						
Welding	x	x						
Lamination	x	x	x					
Injection Moulding					x		x	x
Zinc Coating	x							
Powder Coating	x	x						

Table 5.2.4 - Material/Process matrix

The energy consumption and the secondary materials used for manufacturing activities are then computed. Given the large majority of semi-finished products are transformed and assembled in Italy, the Italian electric energy mix (i.e. 68% from non-renewable fossil fuels, 14% hydroelectric, 4.5% other renewable sources, 13.5% imported) has been assumed in the calculation mix. Table 5.2.5 presents information on the energy consumption values assumed for the modelling of raw material transformation and the semi-finished processing required for the final assembly of the machinery devices themselves, including the extrusion of the polyethylene film and the production of polyethylene net and wire. For each process a reference unit in mass, surface or length is assumed. Value ranges are reported for those processes for which energy consumption depends on the material transformed. Generic data has been assumed for the metal casting and forging processes.

Process	Electric energy [MJ]	Thermal Energy [MJ]
Casting [kg]*	2.51-7.06	6.93-25.6
Forging [kg]*	4.3-9.02	5.8-15.7
Extrusion [kg]	2.38-5.3	0-4.76
Bending [m]	0.19-0.89	0-4.76
Cutting [m]	0.27-3.14	-
Welding [m]	0.09-0.27	-
Lamination [kg]	0.8-1.97	1.08-2.12
Injection Moulding [kg]	5.33	-
Zinc Coating [m2]	1.22	13.13
Powder Coating [m2]	4.68	7.3

Table 5.2.5 - Process/Energy consumption matrix [*] From Ecoinvent v2.2 database

5.2.6.2.3 Transport

The transportation of the raw materials from the suppliers to the factory for the manufacturing of the devices is estimated by assuming an average distance of 188km, while 1,500km is considered as the representative distance between the manufacturer and a typical final customer. For each delivery, the use of a truck with a compatible load capacity is assumed.

5.2.6.2.4 Use phase

In the use phase, fuel, lubricant oil and the polymeric wrapping materials, i.e. binding net or twine and wrapping film, are analysed. The diesel fuel used in the haymaking process, C_{diesel} [l/h], is estimated as a function of the tractor power, $P_{tractor}$ [hp], according to the following empirical equation (Grisso et al., 2004):

$$C_{diesel} = 0.167 \cdot P_{tractor} \tag{4}$$

Table 5.2.6 shows the estimated diesel fuel consumption per working hour for both the traditional standalone and combined systems (MFM).

Device	System	Tractor power [hp]	Diesel consumption [l/h]
PB-HR	Standalone	70	11.70
RB	Standalone	100	16.70
BW	Standalone	50	8.35
MFM	Combined	150	25.10

Table 5.2.6 - Estimated diesel consumption per working hour.

Required lubricant oil is summarised in Table 5.2.7 considering an average use schedule typical across the system lifespan. Data are collected from the original equipment manufacturer.

Device	System	Application	Replenishment interval [h]	Oil quantity per replenishment [kg]
PB-HR	Standalone	Transmission oil	300	2.3
		Hydraulic system	1500	6.0
RB	Standalone	Transmission oil	300	2.3
		Hydraulic system	1500	21.0
BW	Standalone	Transmission oil	300	2.3
		Hydraulic system	1500	6.0
MFM	Combined	Transmission oil	300	2.3
		Hydraulic system	1500	21.0

Table 5.2.7 - Estimated lubricant oil consumption during system lifespan.

For twine, net and film consumption used in baling a standard bale diameter of 1.2m is assumed.

Object	Material	Quantity [kg/bale]
Twine binding	HD Polypropylene	0.098
Net binding	HD Polyethylene	0.172
Film	LD Polyethylene	0.700

Table 5.2.8 - Twine, net and film consumption

Taking into account the reference machinery lifespan of 3,000h, each scenario produces 98,700 standard bales (see section 5.2.6.1.4). Table 5.2.9 and Table 5.2.10 show the comparison between the standalone (PB-HR+RB+BW) and the innovative (MFM) combined systems. Labour hours are included but bale-wrapping materials are excluded, as they are assumed identical in both systems.

Device	System	Labor [h]	Diesel [l]	Lubricant oil [kg]
PB-HR	Standalone	3000	35,070	35
RB	Standalone	3000	50,100	65
BW	Standalone	3000	25,050	35
MFM	Combined	3000	75,150	65

Table 5.2.9 - Resource requirement in the two scenarios.

System	Labor [h]	Diesel [l]	Lubricant oil [kg]
Standalone	9000	110,220	135
Combined	3000	75,150	65
Savings	6,000 (66.7%)	35,070 (31.8%)	70 (51.9%)

Table 5.2.10 - Resource requirement – savings.

Table 5.2.10 highlights that savings are obtained for all the three major resources used. A reduction in Labor of 66.7% is achieved with the MFM given its ability to integrate three work phases in a single step. Fuel cost reductions depend on the lower horsepower required by the tractor in the combined system configuration. Finally, a lower quantity of lubricant oil also results from the combined systems with a consumption saving close to 52%.

The lower consumption of fuel and lubricant oil generates a significant environmental benefit in terms of lower air emissions, which further result in a decrease in environmental impact of the combined system during the use phase. Table 5.2.11 provides detail of the CO_2, particulate, NO_x and SO_x emission savings associated with the reduced fuel and the lubricant oil use of the combined system. The presented data are derived from the Ecoinvent v.2.2 datasets.

Device	Diesel fuel	Lubricant oil

	CO2 [kg]	Particulate [g]	NOx [g]	SOx [g]	CO2 [kg]	Particulate [g]	NOx [g]	SOx [g]
PB-HR	93,370	49,603	233,426	160,480	41	23	245	69
RB	133,386	70,861	333,466	229,258	76	43	456	128
BW	66,693	35,431	166,733	114,629	41	23	245	69
MFM	200,079	106,292	500,198	343,886	76	43	456	128

Table 5.2.11 - Differential air emissions in the two system configurations.

Comparing the two scenarios, the combined system results in lower environmental impacts for all four air emission categories. The switch from the standalone to the combined system generates a global CO_2 emission reduction of 93.45tonnes, a particulate emission reduction of 49.65 kg, a NO_x emission reduction of 233.92 kg and a SO_x emission reduction of 160.62 kg across the machinery life cycle.

5.2.6.2.5 End-of-life

To identify a plausible end-of-life scenario for the disposal of the analysed machines, components and materials, the Italian disposal standard practices were considered. As there are no European or Italian regulations addressing appropriate agricultural machinery disposal methodologies/procedures, the haymaking devices themselves are considered as EoL vehicles. For each material class, the following disposal treatment is assumed:

- Metals: 99% recycling;
- Plastics: 10% recycling, 14.5% incineration;
- Oil: 100% regeneration;
- Rubber: 80% incineration with energy recovery.

Anything remaining materials are assumed to be non-recoverable parts and allocated to landfill.

5.2.7 Results and Life Cycle Impact Assessment (LCIA)

In this section, the life cycle implications of the standalone and MFM combined system are evaluated. The functional unit of 98,700 produced bales (as defined in section 5.2.6.1.4) is assumed in terms of life cycle production across three system LCA stages: manufacturing, use and EOL.

5.2.7.1 Standalone system

Figure 5.2.9, Figure 5.2.10 and Figure 5.2.11 propose the key results of the LCIA for the impact categories most affected (i.e. the effects of climate change on human health, the damage of particulate matter formation on human health, the impact of climate change on ecosystems, and fossil resource depletion) in the three main stages of the life cycle of the system. Detailed data, related to all the impact categories considered by ReCiPe method, are provided in Table 5.2.12.

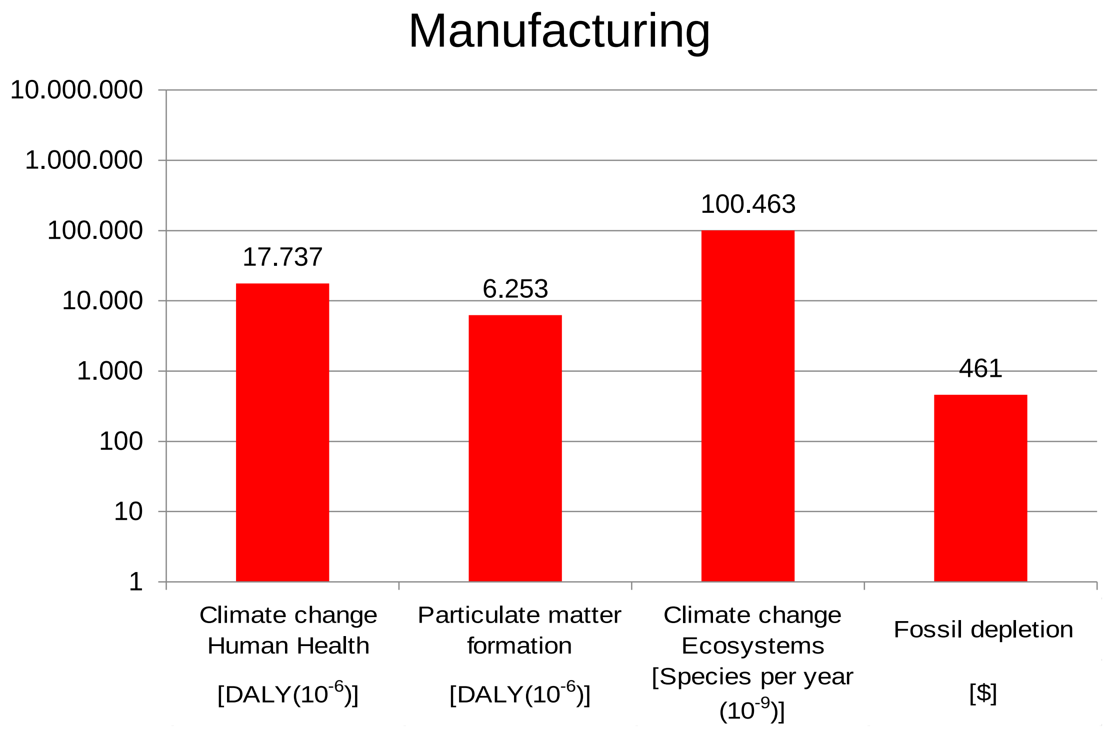


Figure 5.2.9 – Summary of LCIA on major impact categories (ReCiPe) - standalone system - manufacturing.

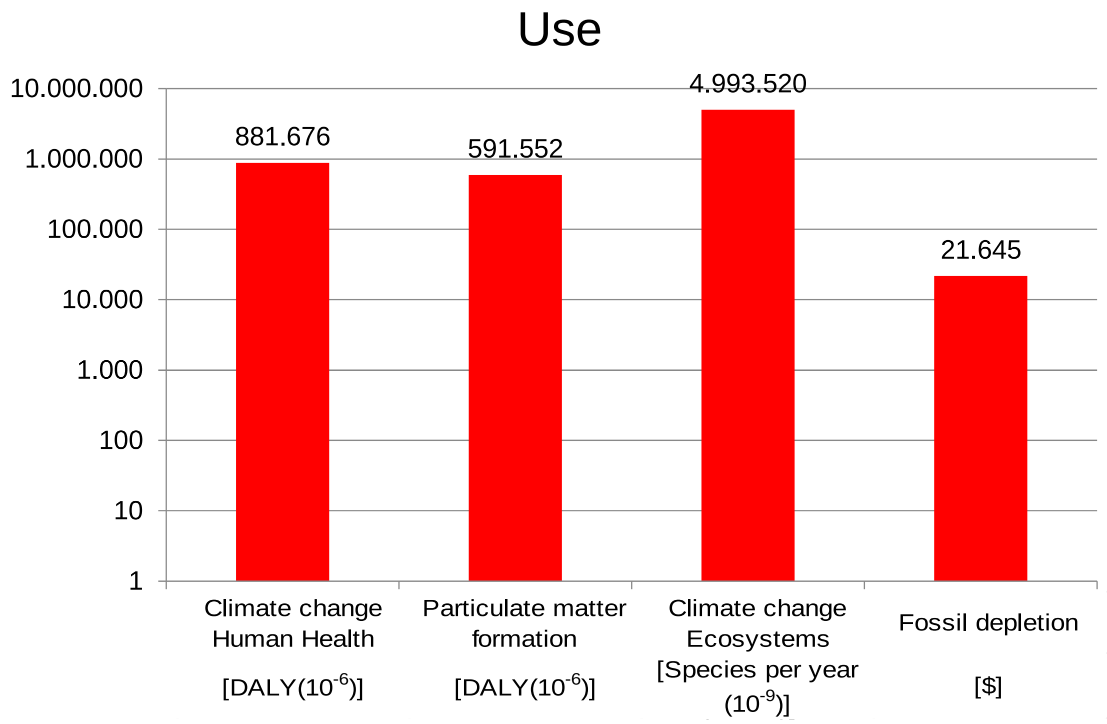


Figure 5.2.10 - Summary of LCIA on major impact categories (ReCiPe) - standalone system – use phase.

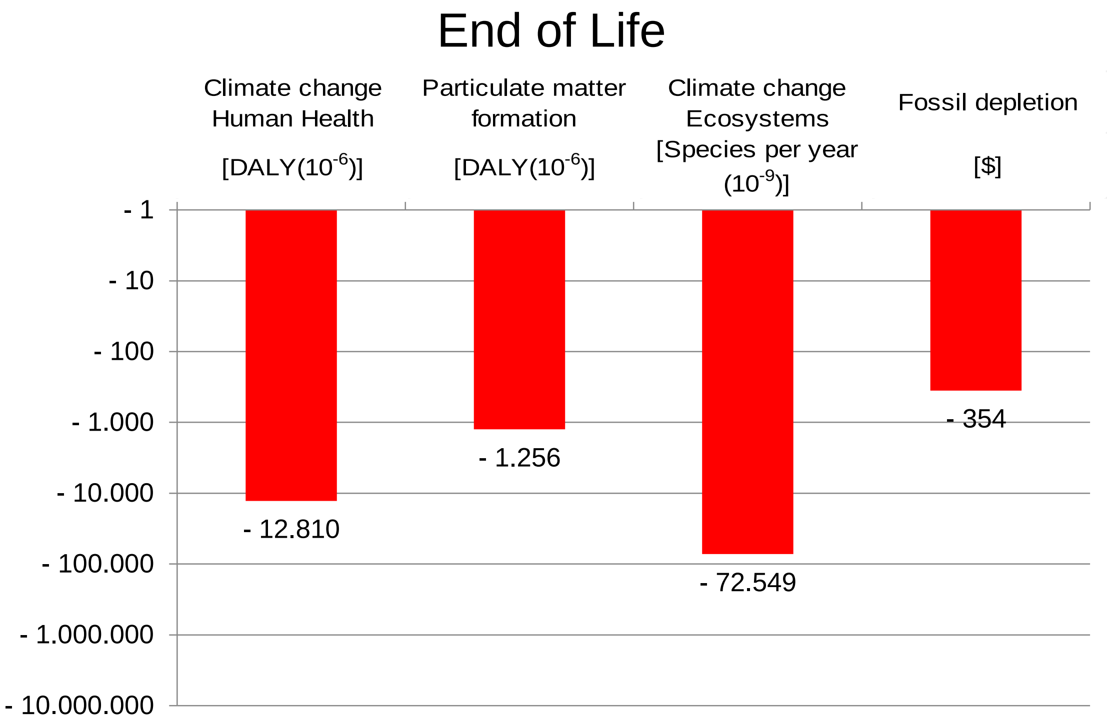


Figure 5.2.11 - Summary of LCIA on major impact categories (ReCiPe) - standalone system - EoL.

Impact category	Unit	Total	Manufacturing	Use	EOF
Climate change Human Health	DALY(10^{-6})	886,603.96	17,737.41	881,676.45	-12,809.91
Ozone depletion	DALY(10^{-6})	989.84	2.03	990.16	-2.35
Human toxicity	DALY(10^{-6})	11,350.92	3,324.62	7,662.69	363.62
Photochemical oxidant formation	DALY(10^{-6})	307.37	2.49	305.52	-0.63
Particulate matter formation	DALY(10^{-6})	596,548.50	6,252.94	591,551.75	-1,256.18
Ionising radiation	DALY(10^{-6})	635.65	22.81	612.83	0.01
Climate change Ecosystems	Species per year (10^{-9})	5,021,435.09	100,463.41	4,993,520.22	-72,548.54
Terrestrial acidification	Species per year (10^{-9})	28,311.39	438.82	27,987.34	-114.77
Freshwater eutrophication	Species per year (10^{-9})	140.41	10.76	136.42	-6.77
Terrestrial ecotoxicity	Species per year (10^{-9})	5,539.53	703.19	4,832.90	3.44
Freshwater ecotoxicity	Species per year (10^{-9})	150.14	2.27	147.80	0.07
Marine ecotoxicity	Species per year (10^{-9})	59.81	5.84	53.99	-0.02
Agricultural land occupation	Species per year (10^{-9})	310,439.93	2,047.62	308,379.96	12.35
Urban land occupation	Species per year (10^{-9})	39,482.16	9,409.64	30,068.00	4.52
Natural land transformation	Species per year (10^{-9})	267,942.88	9,621.15	258,350.26	-28.53
Metal depletion	$	137.04	19.07	118.87	-0.90
Fossil depletion	$	21,752.03	461.31	21,644.51	-353.79

Table 5.2.12 - LCIA on impact categories (ReCiPe) - standalone system - life cycle.

The use phase is the stage with the highest environmental burden. Its impact is over 95% of the total environmental impact value. This is largely attributed to diesel fuel use and bale wrapping. Diesel fuel use is associated with significant air emissions and the bale wrapping involves significant polyethylene consumption and the attendant environmental impacts. The EoL is also characterised by negative environmental impacts across several categories. Despite the energy consumption also associated with material recycling, the savings arising from a reduction in virgin raw resources still results in a positive environmental benefit.

5.2.7.2 Combined multi-functional system

Figure 5.2.12, Figure 5.2.13 and Figure 5.2.14 show the environmental impact values of the four major impact categories across the various life cycle stages of the MFM system.

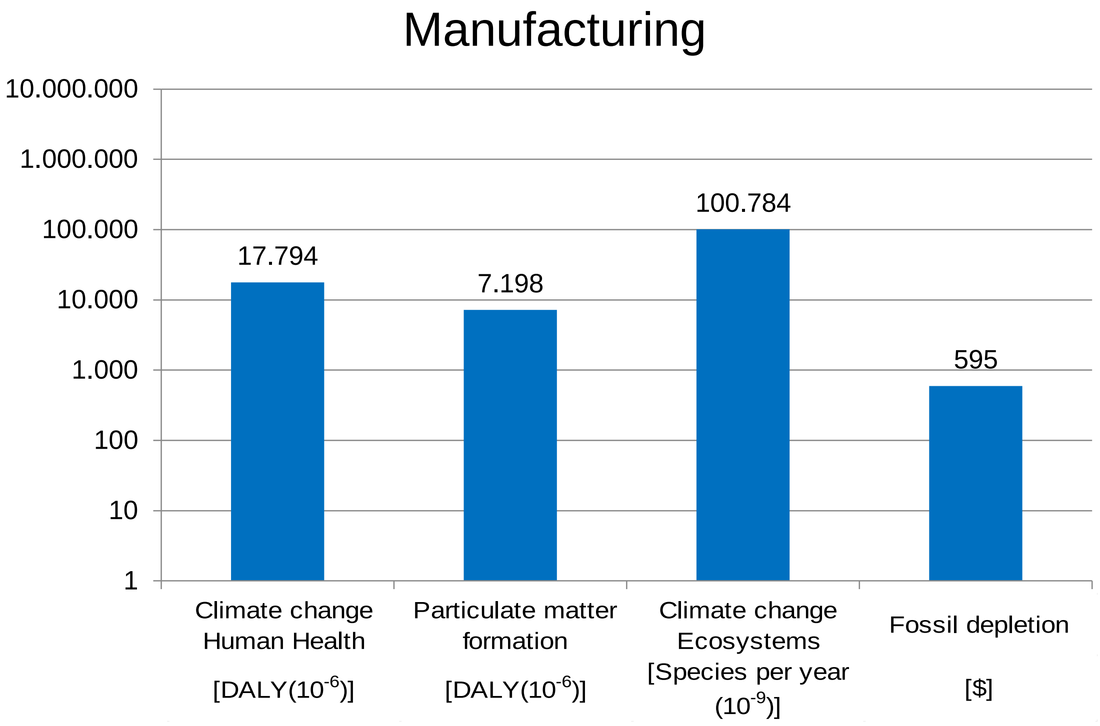


Figure 5.2.12 - Summary of LCIA on major impact categories (ReCiPe) - MFM system - manufacturing.

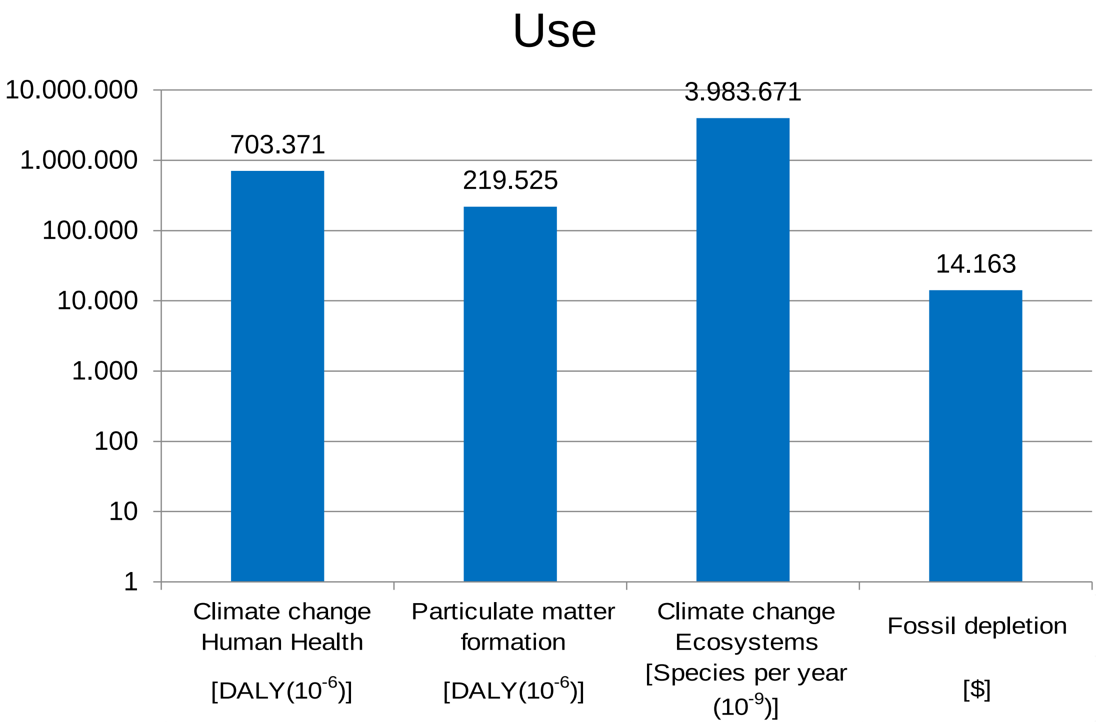


Figure 5.2.13 - Summary of LCIA on major impact categories (ReCiPe) - MFM system - use phase.

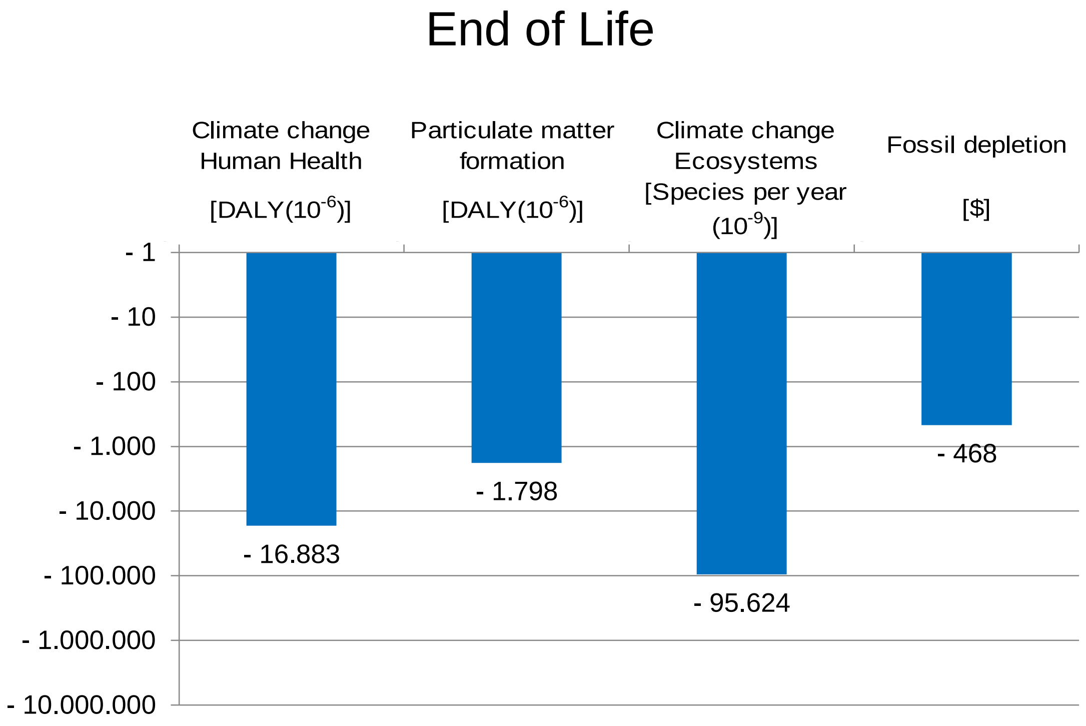


Figure 5.2.14 - Summary of LCIA on major impact categories (ReCiPe) - MFM system - EoL.

The use phase plays, again, a dominant role from an environmental impact point of view. Only 8% of the total impact is due to system manufacturing (the benefits introduced by recycling are discussed previously). The 92% of the impact relates directly to the towing process, synthetic oil consumption, bale ligature and wrapping. Detailed data, related to all the impact categories considered by ReCiPe method, are provided in Table 5.2.13.

Impact category	Unit	Total	Manufacturing	Use	EOF
Climate change Human Health	DALY(10^{-6})	704,281.46	17,793.73	703,371.11	-16,883.38
Ozone depletion	DALY(10^{-6})	874.43	2.24	875.56	-3.37
Human toxicity	DALY(10^{-6})	8,886.66	3,831.17	4,607.18	448.30
Photochemical oxidant formation	DALY(10^{-6})	139.29	2.99	137.20	-0.90
Particulate matter formation	DALY(10^{-6})	224,924.89	7,197.61	219,525.09	-1,797.82
Ionising radiation	DALY(10^{-6})	635.46	23.92	611.52	0.02
Climate change Ecosystems	Species per year (10^{-9})	3,988,831.31	100,784.39	3,983,670.51	-95,623.60
Terrestrial acidification	Species per year (10^{-9})	13,350.43	498.98	13,015.69	-164.24
Freshwater eutrophication	Species per year (10^{-9})	127.44	11.99	124.09	-8.64
Terrestrial ecotoxicity	Species per year (10^{-9})	2,313.44	822.48	1,487.20	3.75
Freshwater ecotoxicity	Species per year (10^{-9})	52.37	1.11	51.18	0.08
Marine ecotoxicity	Species per year (10^{-9})	22.22	6.93	15.34	-0.05
Agricultural land occupation	Species per year (10^{-9})	307,892.71	1,872.43	306,006.98	13.31
Urban land occupation	Species per year (10^{-9})	30,030.59	11,506.29	18,529.96	-5.66
Natural land transformation	Species per year (10^{-9})	35,985.67	14,549.04	21,430.03	6.60
Metal depletion	$	82.64	31.05	53.73	-2.14
Fossil depletion	$	14,289.76	594.69	14,163.15	-468.07

Table 5.2.13 - LCIA on impact categories (ReCiPe) - MFM system - life cycle.

5.2.8 System comparison

Whilst the MFM generates significant cost savings in labour, fuel and lubricant oil, it also has a number of environmental impact benefits. The MFM introduces results in lower environmental impacts across all categories than the traditional standalone machinery system. Figure 5.2.15 presents a percentage comparison between the two systems in terms of environmental impact.

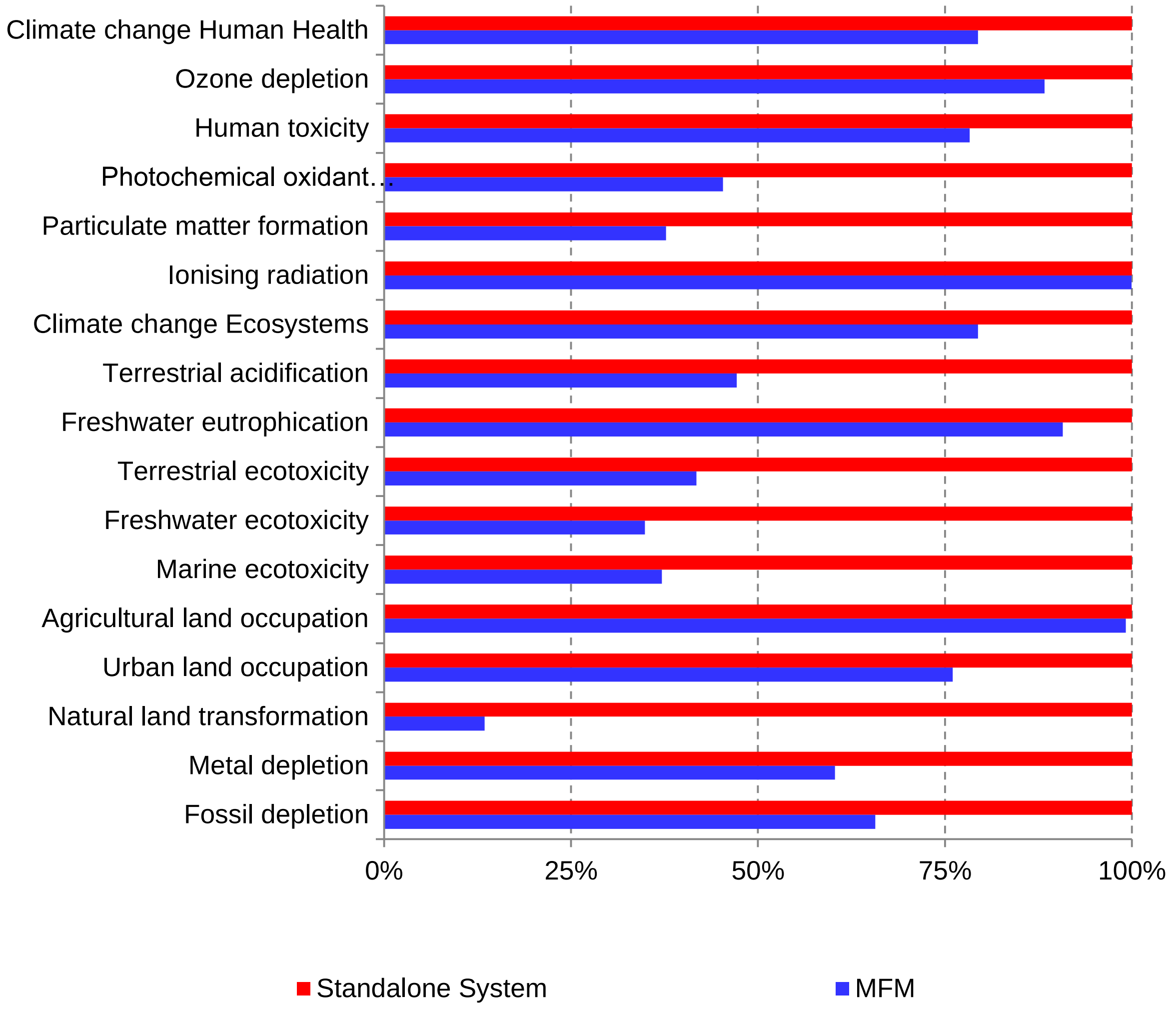


Figure 5.2.15 - LCIA on impact categories (ReCiPe) - Comparison between MFM and standalone system - life cycle

By using normalisation factors and weighting, as presented in the ReCiPe method, an aggregate comparison between the two systems is possible. Figure 5.2.16 shows the Endpoint Index per impact category for each system. The net environmental saving for the combined MFM system is of about 35%.

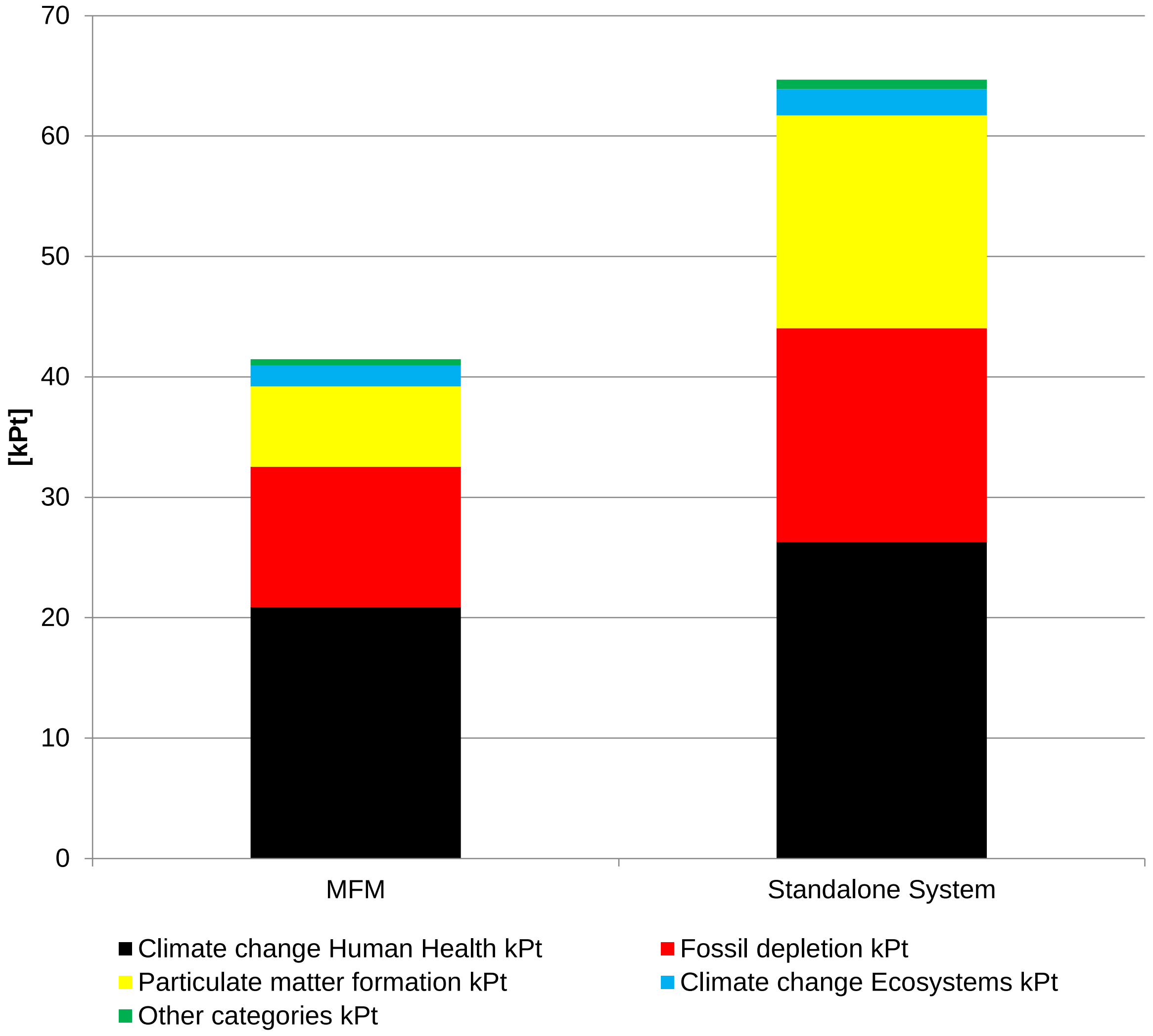


Figure 5.2.16 - LCIA – Comparison between standalone and MFM system – Endpoint Index evaluation (ReCiPe, Hierarchical version).

Reductions in ‘Climate change effects on human health’, ‘Fossil resource depletion’, ‘Particulate matter formation’ and ‘Climate change effects on the ecosystems’ are the four main environmental impacts with benefits arising from the adoption of the MFM.

With regards to the manufacturing phase the environmental impact of MFM is slightly greater than the sum of the impacts introduced separately by the three standalone machines: 1422.46 Pt for the combined system against 1255.95 Pt for the traditional resulting an increase of about 13%. Figure 5.2.17 shows the environmental impact on human health, ecosystem quality and resource depletion associated with the manufacturing of the four devices.

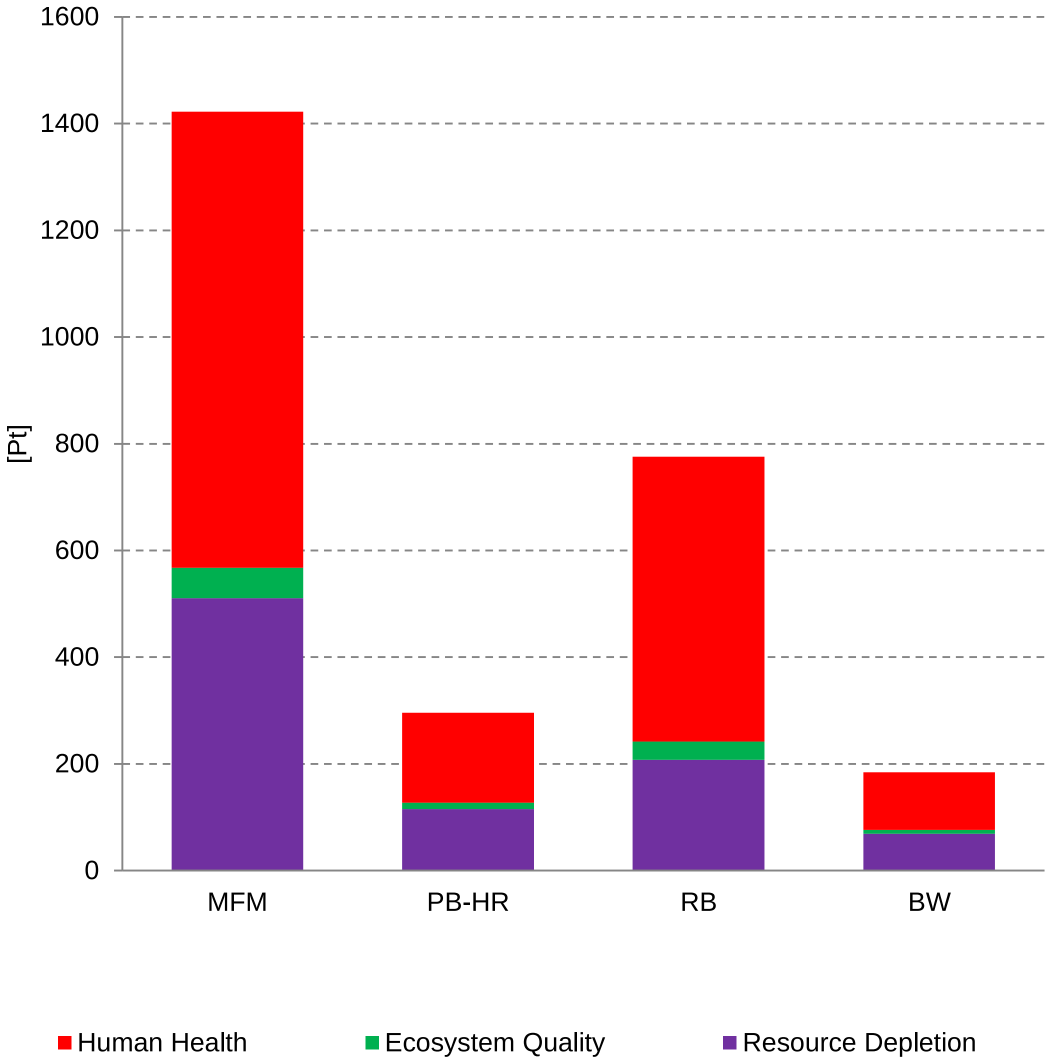


Figure 5.2.17 - Comparison on machine manufacturing –Endpoint Index (ReCiPe, Hierarchical version).

5.2.9 Discussion

According to (Grisso et al., 2004), animal feed production, particularly silage production, is one of the most significant areas of environmental impact in the life cycle of meat and dairy products. However, analysis to date has not involved detailed investigation of the silage production process. The findings of this study provide an in-depth analysis of a potential silage production process involving the combining of currently separate hay making systems into a single step. Raking, baling and wrapping system that results in reductions in operating time and costs and environmental impact. A life cycle assessment of the various separate devices involved in both the current traditional system and the combined MFM system demonstrates that the use stage is the most relevant in terms of environmental impact, accounting for 95% (traditional) and 92% (MFM) of the life cycle of both systems respectively. Analysis of the manufacturing stage (Figure 5.2.9 and Figure 5.2.12) highlights its relatively smaller contribution to overall environmental impact, when compared to the use stage and confirms estimations reported by Meisterling et al. (2009) who similarly calculated that machinery manufacturing contributes only 4% of the environmental impact in wheat harvesting. In addition, with reference to the manufacturing phase, MFM does not result in any advantage in terms of abatement of environmental impact (Figure 5.2.17, Table 5.2.12 and Table 5.2.13). This suggests that hay production hotspot in the analysis is in the use phase. MFM involves physical savings in lubricating oil and fuel consumption (Table 5.2.10) which result in a 35% reduction in the environmental burden associated with silage production. In particular, the savings in fuel combustion in the tractor drawing process reduces carbon dioxide emissions by 32%. The selection of ReCiPe as an impact assessment methodology allows a wider view of the advantages of MFM and allows the conversion of material and energy consumption, waste generation and pollutant emissions for different categories and areas of protection (i.e. human health, ecosystem quality, resource depletion). Given the strong sensitivity of results to carbon dioxide emissions, an estimation of the carbon footprint alone would have been a sufficient demonstration of the benefits resulting from the combined MFM system. However, the additional benefits associated with reductions in particulate matter and fossil fuel depletion would not have been appreciated, and it would result in an underestimation of the environmental benefits associated with the MFM system.

5.2.10 Conclusion

In this study, an innovative Multi-Functional Machinery (MFM) system for haymaking process is presented. The environmental impacts for different environmental impacts created during its production life cycle are analysed and estimated using Life Cycle Assessment (LCA) methodology. From a sustainability point of view, the MFM is compared with the equivalent traditional standalone machinery system for haymaking. The LCA result demonstrates the advantages associated with the use of the MFM combined system over the standalone system. These benefits are quantified using the ReCiPe 1.08 method (Endpoint version, Hierarchical perspective), which estimates that the MFM environmental burden is about 35% lower than that created by the traditional system. The MFM Endpoint Index is 0.42 Pt per standard bale and 0.66 Pt for the traditional system. This environmental benefit is largely attributed to the use phase. Whilst the manufacture of the MFM machinery system results in a slightly higher environmental impact than the traditional standalone system, but does introduce significant savings in terms of resource consumption with significant reductions in fuel (31.8%) and oil (51.9%) consumption in particular., like fuel and oil. The MFM also involves significant savings in terms of the haymaking process duration and consequently a reduction in labour hours and costs (net reduction of 6,000h equal to 66.7%). The existing limits of the MFM include its overall system weight, which is higher than for the traditional standalone system, potential manoeuvrability difficulties which have yet to be tested in small and irregular fields and the road shipment of the MFM system from the farm to the field, which may add further untested complexity to its operation.

Ongoing further research could also be focused on the substitution of the polymeric stretched film used in the bale wrapping with biodegradable bio-film, verifying its stretching and covering properties. The future aim is to decrease the environmental emission derived from the use of polymeric materials.

5.2.11 References

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5.3 COMPARATIVE LCA OF REFRIGERATION UNITS: A WALK-IN SYSTEM

5.3.1 Introduction

According to the IPCC 2013, the atmosphere and oceans are warming because of greenhouse gas (GHG) emissions from anthropic activities. In this context, an extremely important pressure is played by economic activities that are significant emitters like those associated with the refrigeration process. In OECD countries, refrigeration accounts for about 15% of electric energy consumption (Aprea et al., 2012) and results in significant GHG emissions. In Europe, the commercial refrigeration sub-sector is the third largest refrigerant consumer with 17% (Aprea et al., 2012) and in the UK, retail food refrigeration is responsible for 3% of total electrical energy consumption and 1% of total GHG emissions (Sogut et al., 2012). Due to the adoption of greenhouse effect refrigerants, like hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), their accidental leakage into the atmosphere, together with their electric energy consumption in a refrigeration cycle doubles their contribution to global warming. Given this, (Tassou et al., 2011) distinguished two separate GHG strategies for refrigeration: firstly mitigating the direct effects by developing and promoting refrigerant fluids that are harmless in terms of greenhouse effect and ozone depletion, and secondly, improving the efficiency of the vapour compression refrigeration cycle by modifying or implementing more efficient systems. International regulations and research are spread across these two emission areas.

Since the enactment of the Montreal Protocol of 1987, governments have been trying to mitigate the impact of refrigeration by defining gradual restrictions on the use of ozone depleting and global warming gases. The latest European legislative actions relate to the manufacture and use of refrigeration systems (i.e. European Directive 40/2006; European Regulation 842/2006) and define a clear strategy: the use of refrigerants with non-zero ODP (Ozone Depletion Potential) and high GWP (Global Warming Potential) should be gradually restricted and Original Equipment Manufacturers (OEMs) must adapt their products to the use of refrigerants with zero ODP and minimal GWP. Growing concern from the publication of the fourth Assessment report of the IPCC 2007 and the issuing of the European Directive 29/2009 (also known as “20/20/20 climate and energy package”) further accelerated this sustainability program. The EU Proposal for regulation 2012/0305 and the succeeding European Legislative Resolution on Fluorinated gases 2014 define, for stationary equipment, freezers and refrigerator for commercial use, the timeframes for the decommissioning of HFCs with a GWP greater than 2500, by 2020, and 150, by 2022. For domestic refrigerators the restriction is even more stringent: GWP lower than 150 by 2015. However, according to the proposal, “the prohibition shall not apply to equipment for which it has been established in ecodesign requirements adopted under European Directive 125/2009, 2009 that due to higher energy efficiency during its operation, its lifecycle CO_2 equivalent emissions would be lower than that from equivalent equipment which meets relevant ecodesign requirements and does not contain hydrofluorocarbons.”. In fact, the replacement of Fluorinated gases with almost-zero

GWP refrigerants must be considered as a vital but not sufficient solution for reducing the environmental damage created by the adoption of refrigeration devices. Refrigerant retrofitting must therefore respect these performance requisites, and entail energy savings and generate a real environmental benefit.

As with international regulations and directives, research contributions can also be classified, depending on whether the focus is on the mitigation of either direct or indirect emissions, as follows:

1. Studies assessing in response to the ban or restrictions on CFCs, HCFCs and HFCs, the capability and effectiveness of their replacement by natural refrigerants (e.g. carbon dioxide, ammonia), hydrocarbons (e.g. butane, isobutane) or new generation hydrofluoroolefins (HFO) e.g.Aprea et al. (2012), Bovea et al. (2007), Calm (2002), Dalkilic and Wongwises (2010), Hwang et al. (2007), Mani and Selladurai (2008), Mohanraj et al. (2009), Sogut et al. (2012), Wu et al. (2013);
2. Studies focusing on the evaluation and increment of efficiency refrigeration units operating with traditional refrigerants such as HCFCs and HFCs e.g. Bolaji (2010), Davies and Caretta (2004), Han et al. (2007), Wu et al. (2009), Yanagitani and Kawahara (2000).

Since the former group considers the use of innovative plant architecture and refrigerants that, in most cases, involve significant plant modifications and do not guarantee competitive system efficiencies (Bovea et al., 2007; Girotto et al., 2004). These approaches can be classified as long-term strategies that consider the replacement of HFCs and HCFCs possible and desirable but subordinated to further technical improvements. On the other hand, the latter group focuses on short- and medium-term strategies, that consider decreasing indirect GHG emissions by reviewing plant-refrigerant configurations based on common components and commercial refrigerants that, given the forthcoming international restrictions, will be banned in a few years (Bovea et al., 2007; Girotto et al., 2004; European Legislative Resolution on Fluorinated gases, 2014). This study focuses on research in this latter group.

From a research point of view the total replacement of GHG's in refrigeration systems can and must be pursued. However, an important shift like the abandonment of HCFCs and HFCs as refrigerants needs intermediate and transitional steps. If the retrofitting of HFCs by alternative and more efficient HFCs involving no or minimal plant modifications gives significant and demonstrable environmental benefits, this action should be pursued, in particular because it takes into account industry needs and involves a faster and more feasible intervention on global warming mitigation. One of the aims of the research in this study is to demonstrate, through the presentation of an experimental based case study, that this direction can have important GHG management benefits.

This study presents an assessment of the Carbon Footprint (CF) created by two commercial walk-in cold room refrigeration systems throughout their life cycle under different use configurations and operational HFC refrigerants. The second section presents a survey of environmental impact assessment methodologies applied to refrigeration systems. In the third section the results of the testing of refrigerant retrofitting in two walk-in cold room systems is presented. In the fourth and fifth sections the application of the CFA methodology and the results from two separate walk-in cold room refrigeration systems are reported and discussed. The Final discussions focus on the methodology used in the study and conclusions on the research results.

5.3.2 The environmental impact of refrigeration systems

The environmental impact associated with refrigeration systems can be evaluated by using different methodologies and measured with different indices. Relevant works related to the environmental impact evaluation of refrigeration systems are reported in this section and classified according to the adopted methodology. Discussion is also provided on the methodology adopted in this study and its innovative features are explained.

5.3.2.1 GWP

Global Warming Potential is defined as ”the climatic warming potential of a greenhouse gas relative to that of carbon dioxide and is calculated in terms of the 100-year warming potential of one kilogram of a gas relative to one kilogram of CO_2” (European Regulation 842/2006, 2006). The GWP of a gas is measured in mass of equivalent carbon dioxide (CO_{2e}).

5.3.2.2 Total Equivalent Warming Impact

The Total Equivalent Warming Impact (TEWI) index (Fischer, 1993) considers both direct and indirect emissions related to a refrigeration system. The former represents the quantity of refrigerant leaked from the equipment during its use phase and maintenance, the latter represents the amount of GHG gases released because of the production of the energy consumed by the refrigeration plant. The TEWI index is based on the GWP index of GHG and is calculated as the sum of direct and indirect emissions related to a refrigeration unit, but limited only to its use phase. The TEWI index can be successfully used as a term of comparison between different machine designs or different refrigerant retrofitting options. (Fischer, 1993) utilised the TEWI index in order to compare the environmental benefits created by the substitution of R-12 with R401A and R-290 in a vapour compression refrigeration unit. Davies and Caretta (2004) presented a technical design for large direct expansion systems suitable for supermarket use and showed the TEWI associated with different refrigerants (i.e. R404A, R-744, R-717) in order to demonstrate the potential substitution benefits. Aprea et al. (2012) compared a commercial R-134a refrigeration plant and a prototypal R-744 system working in a trans-critical cycle based on the TEWI index resulting from the analysis of the two systems operating in different configurations and scenarios.

5.3.2.3 Life Cycle Global Warming Impact and Life Cycle Climate Performance

Life Cycle Global Warming Impact (LCWI) extends the concept of TEWI on the basis of the assumption that indirect emissions resulting from manufacturing, delivery and recycling of refrigerants contribute to the environmental burden and must be included in the impact assessment (Papasavva and Moomaw, 1997). Life Cycle Climate Performance (LCCP), is comparable to LCWI, and extends the concept of TEWI, including the consideration of the warming impact associated with the energy consumed to manufacture both the refrigerant and the raw materials used for the manufacturing of the refrigerant, and the direct warming impact of any fugitive greenhouse gases emitted during the refrigerant manufacture (Papasavva and Moomaw, 1997). LCCP was adopted by (Little, 2002) to compare the effects caused by the use of R-290, R404A and R410A in a walk-in refrigeration system. The authors proposed different technical solutions in order to adapt the plant to the use of each gas. The compressor, condenser and suction line are redesigned for each refrigerant. Results demonstrated that R410A has less or equivalent impact as compared to R-290 when safety, environmental impact, cost and performance are evaluated. However, according to the methodology adopted by the authors the life cycle of the refrigeration unit/body was not considered in analysis boundaries, such that comments on a further device redesign were also missing. Therefore, despite the definition of LCCP, equipment manufacturing and disposal have often not been considered within the system boundaries. In some studies, these phases have been modelled only through energy flow accounting.

5.3.2.4 Life Cycle Assessment

The evolution of the methodologies for the assessment of refrigeration systems has involved a gradual but continuous growth in the number of considered activities, particularly in the widening of the system boundaries. This evolution culminated in the development of the most comprehensive of impact assessment methodologies, i.e. Life Cycle Assessment (LCA). As environmental impact assessment methodology, LCA has been proposed as a supporting tool for the ecodesign process (Bovea and Pérez-Belis, 2012; Finnveden and Moberg, 2005; Keoleian, 1993). Nielsen and Wenzel (2002) proposed a framework for the integration of product LCA within the ecodesign process where the product environmental profile resulting from LCA application involves design improvement proposals that are then applied in cascade, systematically, from conceptual to detailed product development. Johnson et al. (1998) proposed one of the first LCA applied to a refrigeration system. They analysed the life cycle of a set of automobile air conditioning systems and estimated global warming impact and volatile organic compound emissions resulting from the use of R-134a and a hydrocarbon blend. The authors did not consider the life cycle of the refrigeration unit, so the study was limited to the analysis of the refrigerant life cycle. Yanagitani and Kawahara (2000) analysed two air conditioner units for residential use. In this case, solutions with R410A and R-22 were compared on the basis of the impact on global warming, energy consumption, water pollution, acidification and ozone layer depletion. Although the adoption of R410A involved modification of the plant designed for R-22, the impact associated with this plant redesign was not considered. Ciantar and Hadfield (2000) examined refrigerator manufacturing and disposal for the first time, considering the refrigeration system from a cradle-to-grave perspective. However, the analysis was strongly focused on the manufacturing of refrigeration unit components, for which a detailed inventory was presented, while the use phase of the system was modelled with broad operational assumptions.

5.3.2.5 Carbon Footprint Assessment

The need for simplifying the data hungry LCA methodology has encouraged many streamlined methodologies (Rebitzer et al., 2004). Carbon Footprint Assessment (CFA) defines the measure of the total amount of equivalent carbon dioxide emissions directly and indirectly created by anthropic processes (Rebitzer et al., 2004). CFA can consider the whole life cycle (as can LCA) but estimates the environmental burden of a single damage category i.e. global warming (as TEWI, LCWI and LCCP do).

An extended survey on the state-of-art of carbon footprinting was proposed in (Wiedmann and Minx, 2008). CFA can be considered a streamlined version of LCA (Weidema et al., 2008) where the inventory level of detail and system boundary extension remain untouched, while the environmental damage assessment is limited to GHG emission, and related climate change potential estimation. A thorough review of the application of CFA is given by (Weidema et al., 2008) who presented a model for the estimation of the CF of a food transport refrigeration system. In this case study the performance of R404A, R-744 and R410A were compared across various scenarios: ambient temperature, refrigeration temperature, lifetime and refrigerator drive modality were assumed as the parameters influencing the impact of the system and then individually analysed in order to estimate result sensitivity.

5.3.3 Methodology selection

The selection of CF as an environmental performance index is supported by the consideration that the compared refrigerants have nil ODP, while their GWP and the indirect GHG emission are the real discriminating factors whose impact is comprehensively measured with the CF index. The frequent use in literature of TEWI, LCWI and LCCP suggests that global warming is the category of main interest, and represents the discriminating value for the selection of the most suitable refrigerant within those with nil ODP (Bovea et al., 2007). However, (Bovea et al., 2007) discussed the importance of the inclusion of the life cycle of the actual refrigeration unit within the analysis boundaries and demonstrated that the completeness of TEWI, LCWI and LCCP, which only have a refrigerant life cycle perspective, is therefore limited. On this basis, the authors have considered CFA as the most suitable methodology for the environmental impact assessment of the proposed refrigeration systems. Figure 5.3.1 shows the system boundaries of the proposed CFA. The refrigeration unit and refrigerant are included in the analysis providing a cradle to grave assessment.

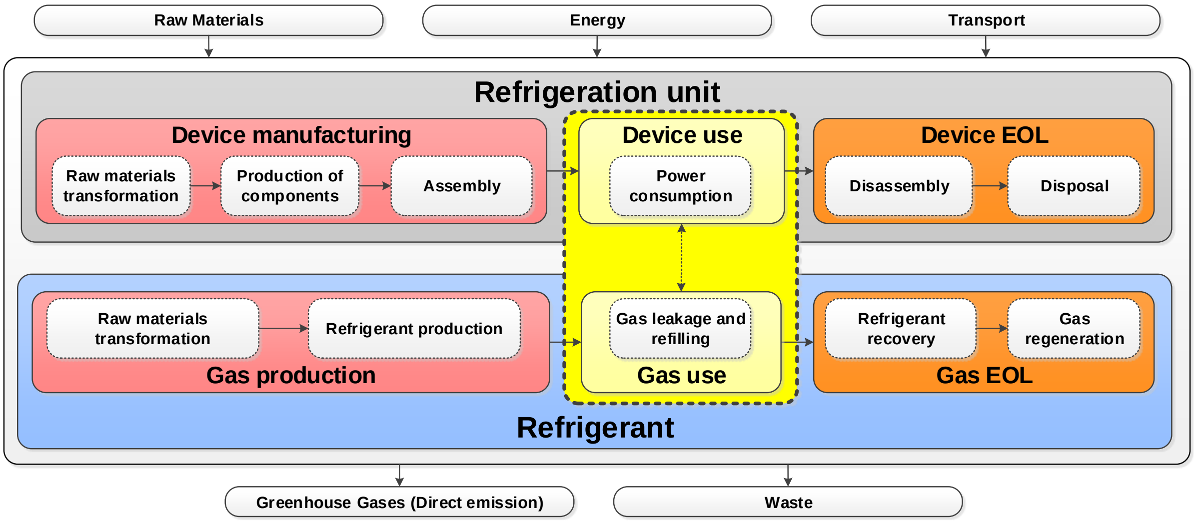


Figure 5.3.1 - System Boundaries of the proposed CFA

As demonstrated by the majority of literature, several parameters affect the behaviour of a refrigeration system. The ambient temperature (T_{ext}), room setpoint temperature, heat transfer coefficient of the room, refrigerant leakage rate and refrigerant type are the main parameters considered having significant influence on refrigeration system behaviour. The refrigerant leakage rate and refrigerant type both influence the direct emission contribution. The heat transfer coefficient of the room influences the cooling energy that the refrigeration system must provide in order to keep the setpoint temperature stable and depends on the thermal insulation of the refrigeration room. Ambient and setpoint temperatures and refrigerant type affect the system Coefficient of Performance (COP) and, in turn, the consumption of electric energy, which is supposed to be the main cause of indirect emissions from the refrigerating units operations. The abovementioned relationships make the analysis of a generic system not representative of the possible conditions and configurations. Therefore, in this study the system under analysis has been tested across different scenarios and, for each scenario, the COP value of the system has been measured.

5.3.4 Equipment description and performance measurement

5.3.4.1 Technical specs and plant scheme

In this study, two commercial refrigeration systems suitable for small to medium size cold rooms were analysed: a refrigerating unit for medium temperature ranges [-5÷5] °C, henceforward referred to as “MTR”, and a unit for low temperatures [-25÷15] °C, referred to as “LTR”, both provided by an Italian original equipment manufacturer (OEM) working in the refrigeration and air-cooling industry. Both MTR and LTR have been originally designed by the OEM for R404A. The main technical details of the systems are listed in Table 5.3.1.

Technical parameter	**MTR**	**LTR**
Working temperature range [°C]	-5÷5°C	-25÷-15°C
Total weight [kg]	56	64
Refrigerant (currently used)	R404A	
Compressor type	Hermetic	
Compressor nominal power [kW]	0.56	1.3
Nominal current consumption [A]	4.9	5.1
Max current consumption [A]	8.3	10.9
Total weight [kg]	56	64
Expansion type	Capillary tube	
Condenser type	Micro-channels	
Condenser flow rate [m^3/h]	600	
Evaporator type	Finned heat exchanger	
Evaporator flow rate [m^3/h]	600	
De-frost system	Hot fluid (bypass)	

Table 5.3.1 - Technical data of MTR and LTR devices

The two devices were tested in an experimental campaign. During the tests, refrigerant type, room setpoint temperature, condensing inlet air temperature, and room thermal load were changed in order to analyse different use scenarios and system configurations. Refrigerant pressure, refrigerant temperature, and air temperature were monitored and measured. In order to proceed with the measurements a testing apparatus with sensors and data acquisition system were built. The apparatus have been used for the measurements on the two devices, mounted on the same chamber, and tested one at a time. The chamber is externally and internally made of stainless steel. The external dimensions are 1800x1800x2200mm while the internal dimensions are 1600x1600x2000mm defining an internal volume of 5.12 m^3. A 100mm layer of rigid expanded polyurethane provides the insulation.

The simplified plant diagram, including the cold room, is shown in Figure 5.3.2. MTR and LTR operations consist of a classic vapour compression refrigeration cycle in which the fluid expansion is obtained with a capillary tube. Sub-cooling of the condenser outlet flow is provided by transferring heat to the evaporator outlet flow inside the capillary tube. In order to avoid the reduction of thermal exchange between the evaporator and the thermostatic chamber, the system also includes a bypass tube to defrost the evaporator coils.

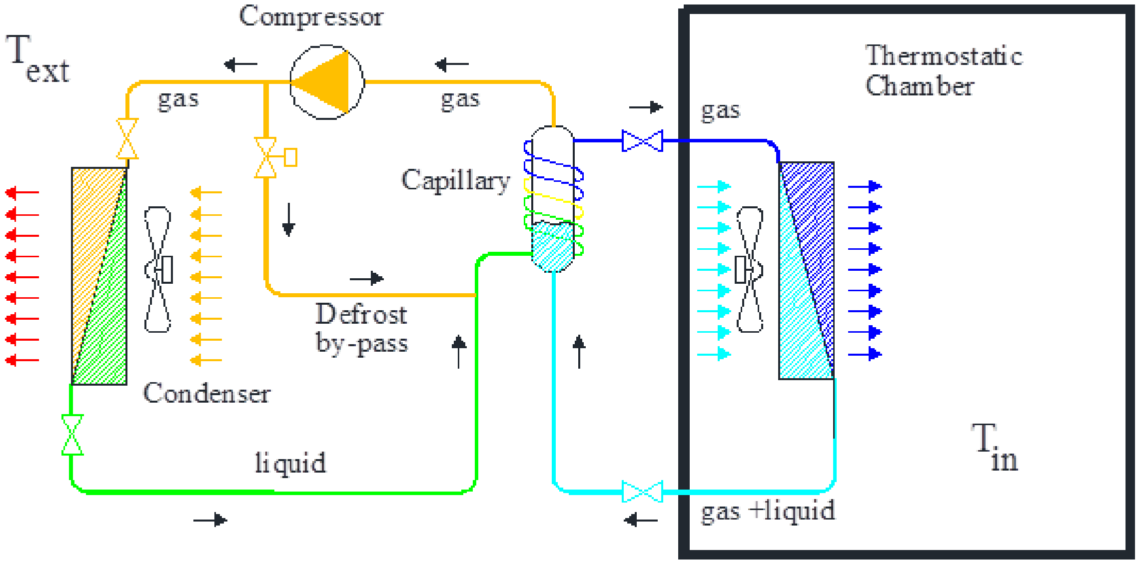


Figure 5.3.2 - MTR and LTR exemplifying plant diagram

5.3.5 Laboratory tests

The purpose of the experimental analysis is the evaluation of the system performance in different conditions. These conditions are defined by the value of different parameters, as explained in section 5.3.3. External air temperature (3 intervals), room setpoint temperature (3 values) and refrigerant type (3 gases) are the parameters that have been modified for both the MT and LT systems, resulting in the creation of 54 potential use scenarios. The analysis of the theoretical refrigeration cycle suggested R407F and R410A as possible retrofits for R404A, which was being used by the OEM for both the MTR and LTR systems. Table 5.3.2 shows the R404A, R410A and R407F chemical composition, ODP and GWP values.

Refrigerant	ODP*	GWP*	Chemical composition			
	[kg R-22$_e$]	[kg CO$_{2e}$]	R143A	R125	R134A	R32
R404a	0	3922	52%	44%	4%	-
R410a	0	2088	-	50%	-	50%
R407f	0	1825	-	30%	40%	30%

Table 5.3.2 - Refrigerant chemical composition and environmental characterisation

The refrigerant replacement involved no plant modifications, except for the substitution of the reciprocating compressor with a rotary compressor for the testing of the R410A.

5.3.6 Performance measurement

The refrigeration power (Q_f) and the coefficient of performance (COP) define the range of application and the efficiency of the refrigeration system. Q_f represents the amount of heat that the refrigeration system can remove from the chamber through the refrigerant evaporation; it is defined in (1):

$$Q_f = Q_{load} + Q_{walls} = I_{load} * V_{load} + k_{room} \cdot \Delta T \qquad (1)$$

With

$$\Delta T = T_{ext} - T_{in} \qquad (2)$$

Where Q_{load} is the representative thermal load inside the room controlled by setting the load electric current (I_{load}) and voltage (V_{load}), Q_{walls} is the power dissipated through the walls and estimated by the measurement of the room heat transfer coefficient (k_{room}) and the difference (ΔT) between the internal (T_{in}) and external air temperature (T_{ext}). From a preliminary experimental analysis, conducted with a T_{in} value set to 50°C, a k_{room} value of 8.2 W/°C was estimated, which has been assumed to be linear and representative of the room insulation index.

COP is here defined as the ratio between the refrigeration power and the systemic electric power supply.

$$COP = Q_f / P_s \qquad (3)$$

Where P_s is the total system power supply, calculated by the product between the circulating current, I_s, and the grid voltage, V_{supply}.

$$P_s = I_s \cdot V_{supply} \qquad (4)$$

According to (3) and (4), the COP value, in this study, is assumed comprehensive of the whole energy power supplied to the system and not only to that absorbed by the compressor, as usually reported in the literature. Therefore, the electric consumption values that follow are all-inclusive of fan and control unit operations. The experimental campaign resulted in the definition of a set of COP values for each analysed scenario. COP values for the systems equipped with MTR and LTR are shown in Figure 5.3.3 and Figure 5.3.4, respectively.

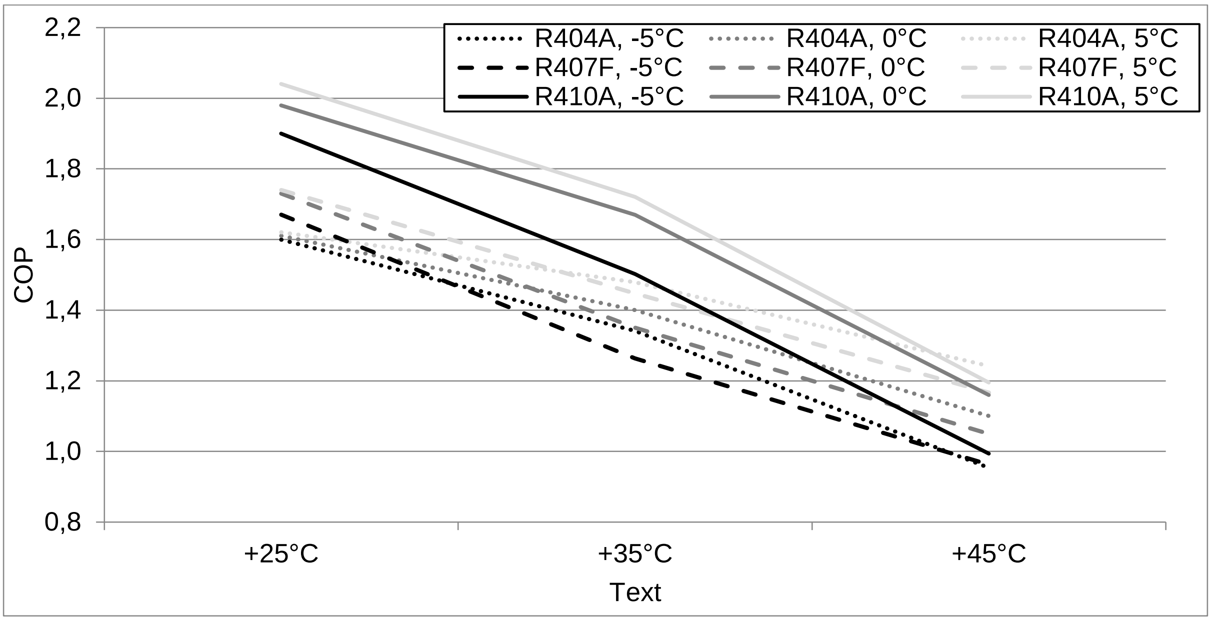


Figure 5.3.3 - COP values of MTR for different refrigerants, external temperature and setpoint temperatures

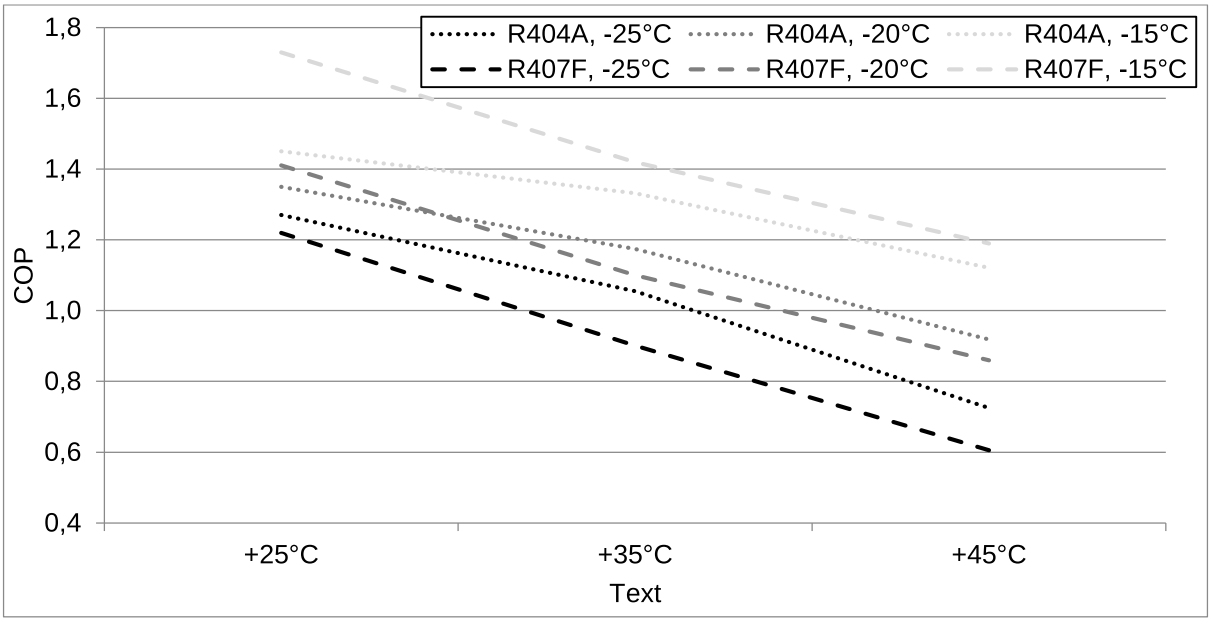


Figure 5.3.4 - COP values of LTR for different refrigerants, external temperature and setpoint temperatures

For medium setpoint temperatures, R404A and R407F have similar COP values and trends. R407F has better performance for T_{ext} lower than 35°C, while R404A involves a lower sensitivity to high external temperatures and entails good performance for T_{ext} greater than 45°C. However, as a rule, for medium setpoint temperatures R410A is the refrigerant that promises the best performance, in particular for an ambient temperature close to 25°C.

However, the adoption of R410A in the LTR did not succeed, as it was not possible to reach the room setpoint temperature. Therefore, R410A is considered unsuitable for low setpoint temperatures in the assumed operating conditions. For every analysed scenario with room temperature lower than -15°C, R407F produced performances higher than R404A, in particular for external temperatures close to -15°C. This rule is subverted only for a setpoint temperature lower than -20°C and only for external temperatures not greater than 30°C. In general, R407F provides efficiency advantages ahead of R404A, but which decline with any decrease in setpoint temperature.

The performance analysis demonstrates that COP values are highly sensitive to the value of external and internal room temperatures, as also demonstrated by (1), (2) and (3), and the refrigerant type. The COP values recorded during the laboratory tests have been used as input parameters in the analysis of the environmental impact of the presented refrigeration systems. However, since walk-in refrigeration rooms are usually installed in closed air-conditioned environments, with air temperatures rarely exceeding 30 °C , therefore the COP values recorded for T_{ext}=25 °C are assumed representative of the efficiency of the analysed walk-in systems. However, different refrigerant options and different setpoint temperature values are certainly potential variations for multi-scenario analysis.

5.3.7 CFA of two refrigeration systems for walk-in cold rooms

5.3.7.1 Goal and scope definition

The goal of the study is the evaluation of the environmental impact caused by two walk-in cold room refrigeration systems throughout their life cycle. Two versions of the system are evaluated: one adopting the MTR device, for MT ranges; the other adopting the LTR device, for LT applications. The analysis is aimed at the identification of the environmental profile of the equipment, the assessment of the environmental impacts caused by certain walk-in cold room use configurations and the estimation of the environmental benefits associated with the replacement of R404A.

5.3.7.1.1 Functional Unit

The functional unit expresses and identifies the operational unit of the analysis. The functional unit chosen in this study corresponds to the whole life cycle, from the cradle to the grave, of both refrigeration equipment and refrigerant. The equipment is represented by the MTR and LTR devices; the refrigerant is R404A, R407F or R410A. This functional unit is the basis from which comparisons between alternative design solutions presented in this study are made, and represents the starting point for potential future comparative analyses.

5.3.7.1.2 System boundaries

The system boundaries considered in this analysis are represented and ordered in Figure 5.3.1. For each one of the sub-systems (refrigeration unit and gas) three main life cycle phases are highlighted:

manufacturing, use phase and EoL. The use-phases of device and refrigerant are conjointly considered. The assessment of the life cycle of the walk-in chamber is beyond the scope of this analysis, while its heat exchange coefficient is a parameter considered in the evaluation of system energy consumption.

5.3.7.1.3 Data category and source

The inventory analysis (LCI) was conducted by the collection of information from different sources. The OEM provided information on the composition of the refrigeration units, the characteristics of their components and the geographic position of certain suppliers and subcontractors. All processes carried out upstream of the activities performed by the OEM, as well as the EOF treatment of equipment and refrigerant, were reconstructed through the support of literature data. Table 5.3.3 shows categories and sources of the data used within the LCI phase. “Specific data” refers to the data strictly related to the specific case study and collected from the direct observation of the manufacturing processes carried out within the OEM plant. “Generic data” are the data retrieved from literature, or scientific publications, academic papers, relevant LCA studies, and the LCA professional database Ecoinvent v2.2. A detailed presentation of Ecoinvent is proposed by (Frischknecht and Rebitzer, 2005).

Phase	Process	Data category	Data Source
Device manufacturing	Raw material transformation	Generic	Ecoinvent + Literature
	Manufacturing of components	Specific	Ecoinvent + OEM
	Assembly	Specific	OEM
Refrigerant production	Raw material transformation	Generic	Ecoinvent + Literature
	Refrigerant production	Generic	Ecoinvent + Literature
Refrigeration system use phase	Energy consumption	Specific	Laboratory Tests
	Performance	Specific	Laboratory Tests
	Gas leakage rate	Generic	Literature
Device EOF	Disassembly	Generic	Literature
	Disposal	Generic	Ecoinvent + Literature
Refrigerant EOF	Recovery	Generic	Literature
	Reclamation	Generic	Ecoinvent + Literature

Table 5.3.3 - Data category and source

5.3.7.1.4 Assumptions

The analysis is based on a set of simplifying hypotheses. The equipment is supposed to have a lifespan of 10 years (Frischknecht and Rebitzer, 2005), during which the system works continuously for 8760 hours a year. The duration of the experimental campaign was too short to have reliable data on the refrigerant leakage rate. Therefore, the leakage rate value is considered less reliable (Aprea et al., 2012; Mudgal et al., 2011) and its effects are estimated through a sensitivity analysis. It is assumed that that the devices are installed in a European OECD country.

5.3.7.2 Life Cycle Inventory

5.3.7.2.1 Refrigeration unit manufacturing

Both MTR and LTR are mainly composed of the following main parts: a hermetic reciprocating compressor, a copper-aluminium finned evaporator, an aluminium micro-channel condenser, two fans powered by electric motors, an electronic control unit, copper piping, valves, and a steel/plastic support frame. Figure 5.3.5 reports the bills of material (BOM) for MTR and LTR.

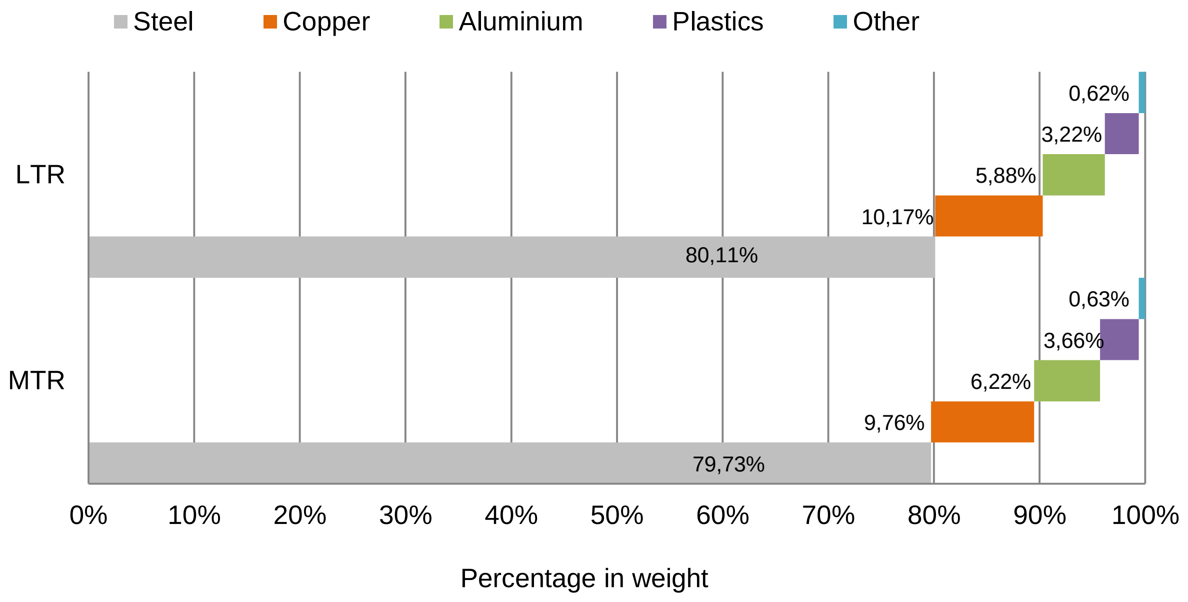


Figure 5.3.5 - MTR and LTR Bill of Materials

The main transformation activities accounted in the manufacturing of the devices are metalworking processes. Table 5.3.4 summarises the inventory of manufacturing operations of MTR main components.

The refrigeration units' support frame is created by cutting, bending, punching and drilling zinc coated steel sheets. The piping is created by curving, tapering and brazing welding copper pipes. Plastic components are obtained by injection moulding or thermoforming. The manufacturing inventory data for the hermetic compressor was extrapolated from (Aprea et al., 2012; Calm, 2002; Johnson et al., 1998). The manufacturing processes for some complex elements (e.g. sensors, electronic components) were simplified with the estimation of the electric energy consumed during their production. The consumption of electric energy, thermal energy and raw metals are the most relevant inputs of the analysed system. Specific data on material and component supplier have been collected in order to estimate the contribution of transportation to the environmental impact. The manufacturing phase includes the transportation of each device and its refrigerant charge from the OEM to the final customer: the use of a 24-ton truck and an average distance of 500 km between the two nodes are assumed.

Group	Casting/ Forging [g]	Termoforming/ Injection Moulding [g]	Cut/ bending/ Deep Drawing [g]	Wire Drawing/ Extrusion/ Lamination [g]	Welding/ Soldering [mm]	Powder Coating/ Zinc Coating/ Cataphoresis/ Anodizing [m^2]	Other Machining [g]
Compressor	23700						*
Compressor Frame	635		635	635		0.08	
Condenser	1019		53		940	2.35	966
Condenser Fan	1341	141	186	630	80	0.12	158
Condenser Frame	2519		2520	2520		0.72	
Control Unit	224	788	14	14		0.01	**
Evaporator	2998		3600		1100	1.07	1198
Evaporator Fan	1341	141	186	630	80	0.08	158
Evaporator Frame	3904	369	3905	3905		2.51	
External Frame	13271	219	14319	15089		5.74	
Piping	2516	324	2816	1816	1680		
Total	53467	1980	28234	25238	3880	13	2480

Table 5.3.4 - MTR manufacturing inventory (summary)
[*] from Biswas and Rosano (2011)
[**] from Ecoinvent

5.3.7.2.2 Refrigerant manufacturing

No specific data on the manufacturing process of R404A, R407F and R410A are available in literature. Both (Biswas and Rosano, 2011), and McCulloch and Lindley (2003) reported information about the production phases of R-134a and estimate the related CF. Also Heck (2007) reported an extended inventory, based on Frischknecht (1999), and CF about R-134A manufacturing. Little (2002) estimated the CF differential value between the production of R134A and other HFCs, e.g. R-143a, R-152a, R-125, R32, some of which are components of R04A, R407F and R410A (see Table 5.3.2). Data from Heck (2007), which has been considered by the authors more prudent in regards to the abatement of GHG emissions during refrigerant production than those reported by Campbell and McCulloch (1998), McCulloch and Lindley (2003) and Little (2002), have been elaborated by the authors in order to define the CF of the manufacturing of a unit quantity of R404A, R407F and R410A.

5.3.7.2.3 Use phase

During the use phase, the main process is the use of the refrigeration unit for the preservation of the setpoint temperature within the room. The refrigeration process entails the consumption of low voltage electric energy with the activities of the ventilation system and compressor. The energy consumption of the latter is influenced by the COP value and Q_f requested by the room. The environmental impact given by the power consumption of the system depends on the electric energy mix of the region in which the system is assumed to operate. Table 5.3.5 shows the percentage contributions of renewable and non-renewable energy sources for the production of electric energy in European OECD countries (IEA, 2012). According to the assumptions, the CO_{2e} emission factor for the electric energy consumption is set to 91.94 g/MJ.

Source	**Coal/peat**	**Crude oil**	**Natural gas**	**Nuclear**	**Hydroelectric**	**Biofuel/Waste**	**Other**
Amount	19.49%	37.97%	24.15%	9.97%	2.19%	4.89%	1.34%

Table 5.3.5 - OECD electric mix – source (IEA, 2012)

During the use phase, a second activity is given by the replenishment of the amount of refrigerant leaked from the unit. Bovea et al. (2007) considered direct expansion systems with an annual gas leakage rate of 10%, while Tassou et al. (2011) assumed 15%. Like Aprea et al. (2012) we considered a discrete variation range of [5 ÷ 15%] in order to evaluate different scenarios.

5.3.7.2.4 Refrigeration unit EoL

The EoL of a refrigerating system includes a first phase of remediation, through which the residual refrigerant is recovered. After the remediation, the refrigerator and the refrigerant are treated separately. The refrigerating unit is assumed to be disposed of in accordance with the following procedures: manual disassembly, hulk shredding, material separation, recycling of metals, incineration or disposal in landfill for the residue. An energy consumption of 144 J/kg for hulk shredding and material separation is considered. Steel, aluminium and copper are recycled at a rate of 37%, 32% and 22% in weight, respectively. Plastics and residue are incinerated for 20%, with landfill disposal accounting for 80%.

5.3.7.2.5 Refrigerant EoL

We assume that only 70% of the recovered gas can be regenerated by filtering and distillation, because in the 30% of cases the degradation of fluid characteristics does not allow its reuse. It is also hypothesised that 1% of fluid is emitted in atmosphere because of the reclamation procedure, 1% is composed of impurities. For one kg of processed refrigerant 0.41 MJ of electric energy and 0.2 MJ of thermal energy are consumed for filtering and distillation, and 686 grams of refrigerant are regenerated and can be reused.

5.3.8 Results

5.3.8.1 Life Cycle Impact Assessment

GHG emissions have been calculated from the LCI data, and then accumulated in a single index obtained using IPCC (2007) characterisation factors and measured in mass of CO_{2e} as explained in section 5.3.2.1. Results are presented as follows: CF of refrigerant manufacturing, EOF and leakage (5.3.8.1.1); CF of manufacturing and EOF of refrigeration units (5.3.8.1.2); CF of the refrigeration system life cycle, ordered by MT and LT applications, in different scenarios (5.3.8.2).

5.3.8.1.1 Refrigerant life cycle

This section presents the CF of the refrigerant life cycle in different possible scenarios. Gas production, EOF treatment, and leakage during the use-phase are the life cycle processes included in the assessment. Table 5.3.6 reports, for each suitable combination refrigerant-device and for each leakage rate hypothesis, the quantities of refrigerant produced and supplied for the initial charge, and the amount leaked and consequently replaced during the system life cycle. The refrigerant charge corresponds to the optimal quantity, measured during the test phase, which guarantees the highest COP value. The last column presents the estimated total refrigerant CF created in a 10-year period, which corresponds with the assumed refrigeration unit lifespan. The total refrigerant CF is calculated as follow:

$$\text{Total Refrigerant CF} = \text{Direct emission} + \text{Refr. Manufacturing} + \text{Refr. EoL} \tag{5}$$

$$\text{Direct emission} = \text{GWP} * \text{Refr. charge} * \text{Annual leakage rate} \tag{6}$$

System	Refrigerant	Annual leakage rate	Refr. charge [kg]	Refr. leakage [kg]	Direct emission [kg CO_{2e}]	Refr. manuf. [kg CO_{2e}]	Refr. EOF [kg CO_{2e}]	Total refrigerant CF [kg CO_{2e}]
MTR	R404A	5%	0.38	0.19	735	91	-41	785
		10%	0.38	0.38	1471	122	-41	1551
		15%	0.38	0.56	2206	152	-41	2317
	R407F	5%	0.4	0.2	365	71	-32	404
		10%	0.4	0.4	730	95	-32	793
		15%	0.4	0.6	1095	118	-32	1181
	R410A	5%	0.47	0.24	491	87	-39	538
		10%	0.47	0.47	981	116	-39	1058
		15%	0.47	0.71	1472	145	-39	1578
LTR	R404A	5%	0.35	0.18	686	85	-39	733
		10%	0.35	0.35	1373	113	-39	1448
		15%	0.35	0.53	2059	142	-39	2162
	R407F	5%	0.35	0.18	319	62	-28	353
		10%	0.35	0.35	639	83	-28	693
		15%	0.35	0.53	958	103	-28	1034

Table 5.3.6 - Refrigerant inventory details and emissions

For each scenario, the contribution of the refrigerant leakage to global warming is estimated to be 90-95%, much higher than that introduced by manufacturing and disposal. The increase in leakage rate involves two main effects: firstly, an increment of direct emissions, and secondly, the rise of indirect emissions caused by the production of additional refrigerant required for the replacement of refrigerant losses. Results show that the latter effect is about 5 to 10 times less than the former. The impacts created by manufacturing and EOF have low sensitivity to the actual refrigerant type. On the other hand, the direct emissions have a strong sensitivity to refrigerant type and leakage rate. Refrigerant remediation, recovery and reclamation after the refrigeration unit EOF involves a negative impact that means an impact avoided due to the avoiding of the production of an equivalent amount of new virgin gas. In addition, independently from its reuse, gas recovery from the plant prevents a direct impact even greater than that obtained due to the gas leakage during the use phase.

5.3.8.1.2 Refrigeration unit life cycle

In this section, the CFs of manufacturing, delivery and EOF treatment of MTR and LTR are presented. The contribution of the use phase is not considered in this stage, but included in the comprehensive system LCIA in section 5.3.8.2.

Results are ordered by MTR and LTR devices, or rather by MT and LT applications respectively, then ordered by device configuration, as a function of refrigerant adopted, and finally by life cycle stage. Table 5.3.7 shows the amount of CO_{2e} associated with manufacturing, packaging and delivery, and EOF treatment. For each scenario, the environmental load is similar since, as specified in 5.3.7.2.1, the BOMs of MTR and LTR are almost equivalent. Minimal difference is appreciable between the MTR system configured for R410A and that configured for the two other gases considered, as the only technical difference is given by the assembly of a different compressor (see 5.3.5).

System	**MT**			**LT**	
Device	**MTR**			**LTR**	
Refrigerant	**R-404A**	**R-407F**	**R-410A**	**R-404A**	**R-407F**
Manufacturing of plant [kg CO2eq]	231.58	231.58	227.27	267.49	267.49
Delivery and Packaging	9.19	9.19	9.19	10.46	10.46
EOF of plant [kg CO2eq]	13.69	13.69	12.97	15.29	15.29
Total	254.46	254.46	249.43	267.49	267.49

Table 5.3.7 - Manufacturing, delivery and EOF of MTR and LTR

Since the manufacturing phase has greater relevance than the distribution and EoL of the refrigeration units, its impact is analysed in detail. MTR and LTR components are grouped by sub-assemblies. Figure 5.3.6 shows the contribution of each sub-assembly to the total impact associated with the refrigerating unit manufacture. For MTR an average value between the configuration that support R410A and that supporting R407F and R404A is assumed as representative of the MTR implement.

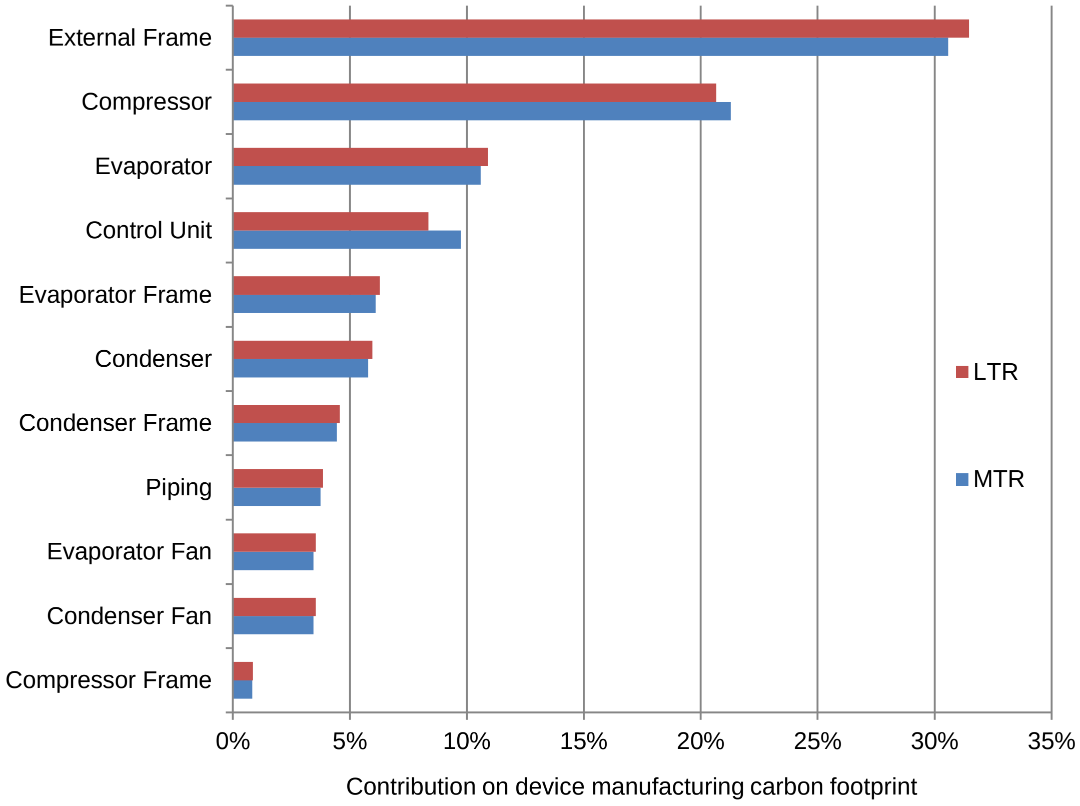
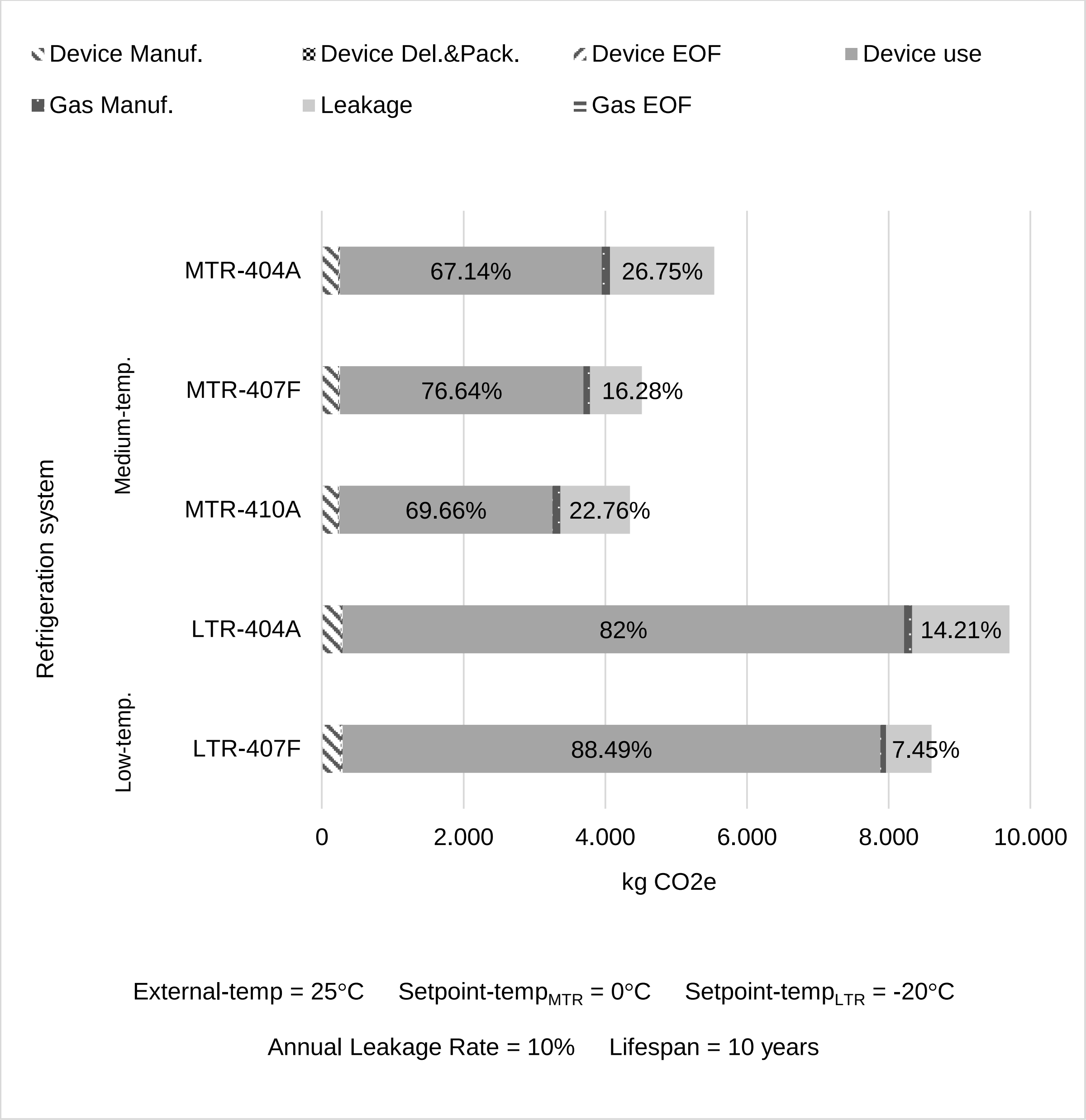


Figure 5.3.6 - CF contribution of device sub-groups to total device manufacturing impact

As expected, the results for MTR and LTR present minimal differences. The steel-aluminium frame, compressor and heat exchangers represent the large majority of the CF embedded in the two devices. Despite the minimal weight, the control unit contributes 8-10% of the manufacturing impact, mainly because of the energy consumption introduced during the manufacturing of its electric and electronic components. The system adjustment operated to get the MTR suitable for the use of R410A, i.e. the replacement of the reciprocating compressor with a rotary one, introduces a minimal change. The rotary compressor is lighter than that used for R404A and R407F; therefore it involves a small saving in manufacturing emissions (8%). Since compressor manufacturing represents about 22% of total plant manufacturing, compressor replacement for R410A adoption implies a 1.8% reduction of device manufacturing total impact. This demonstrates that the adaptation of the system to R410A does not involve any appreciable effect on device manufacturing CF.

5.3.8.2 System life cycle and multi scenario analysis

For a comprehensive CFA of the analysed refrigeration systems, an aggregate evaluation of refrigerant and refrigeration unit life cycles is proposed. The analysis system boundaries are those presented in Figure 5.3.1 and described in 5.3.7.1.2. Use phase of refrigeration unit, i.e. electric energy consumption, is now considered in the CF estimation. Figure 5.3.7 shows the CO_{2e} contributions of the system life phases for each suitable combination device-refrigerant. Setpoint temperature values are assumed as follows: 0°C for MT systems, -20°C for LT. An average value of 10% of refrigerant leakage rate is assumed for each scenario, as well as a 10-year lifespan and an external temperature of 25°C (see 5.3.6). Figure 5.3.7 shows also the absolute value of the contribution of each life stage to the overall CF. For use-phase and refrigerant leakage, the percentage weight to the overall life cycle is also reported.



External-temp = 25°C Setpoint-temp$_{MTR}$ = 0°C Setpoint-temp$_{LTR}$ = -20°C

Annual Leakage Rate = 10% Lifespan = 10 years

Figure 5.3.7 - CF in different scenarios – comparison between life cycle stages

As expected, LT systems introduce a greater global impact than the MT ones. Given the above listed assumptions, the adoption of R410A results in the lower global impact within the MT system configurations. While, for LT applications, the use of R407F is the best environmental decision. Refrigeration unit and refrigerant manufacturing, distribution and EOF processes, all together, contribute 4-8% to the total CF. It follows that, in general, direct impact and indirect effects of energy consumption represent the large majority of system life cycle CF: from 92 to 96%. In every scenario, the direct impact is smaller than the indirect one, for which the energy consumption, introduced by refrigeration unit use, represents the main factor: from [70÷77%] for MT, to [82÷88%] for LT systems. However, the direct effect of refrigerant leakage also has a relevant impact on the overall footprint: from [7÷14%] of LT systems to [16÷27%] of MT systems. In addition, it is interesting to notice that there are cases in which a refrigerant with a higher GWP introduces also a higher direct and indirect impact, e.g. the case of R404A in MTR if compared with the other analysed solutions. In addition,, there are cases in which a gas with a higher GWP creates a lower global impact, because of a higher energy efficiency, e.g. the case of R410A compared with R407F for MT applications, where the first entails a 10-year period of carbon savings of 4%, even if its GWP is 8% higher than the warming potential of the latter.

In order to have a wider perspective of the results, the number of scenarios is now increased. Figure 5.3.8 and Figure 5.3.9 show the overall life cycle CFA for the presented LT and MT system, respectively. The aim of the analysis is the evaluation of the sensitivity of systemic environmental impacts from setpoint temperature, refrigerant leakage rate and refrigerant selection, which represent the main parameters of the multi-scenario analysis. For this analysis, external temperature and system lifespan are assumed constant.

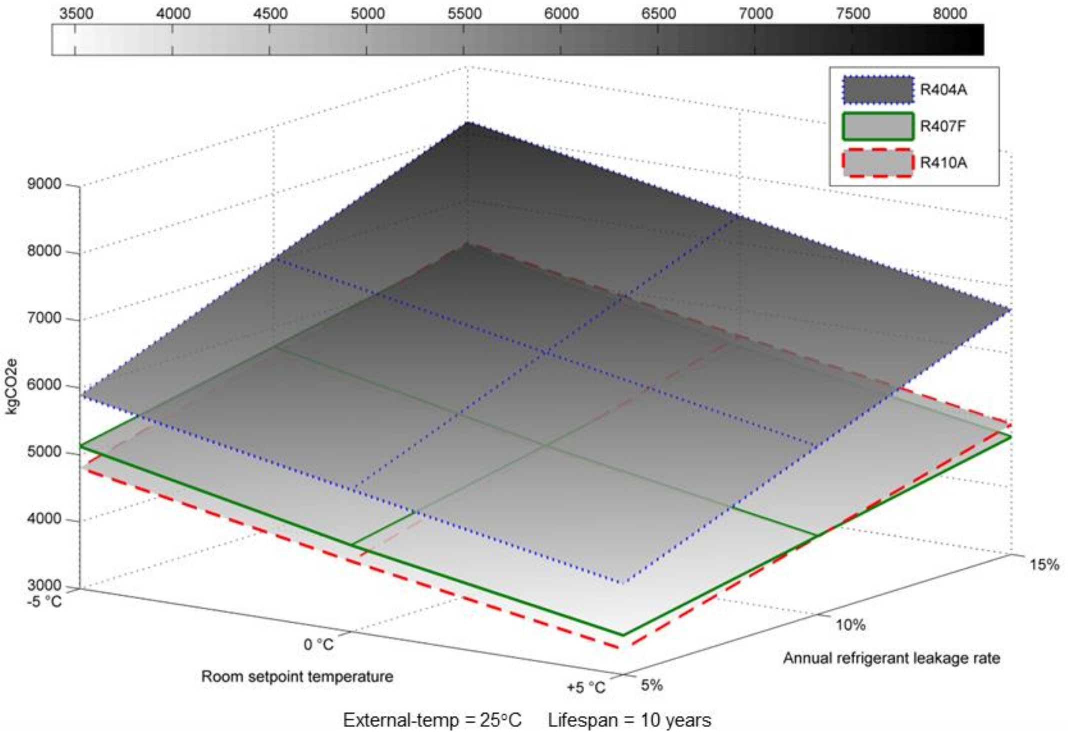


Figure 5.3.8 - CF of MTR life cycle in multi-scenario analysis

Figure 5.3.8 presents the value of CF, measured in mass of CO_{2e}, emitted in a 10-year period, associated with the MT system life cycle and calculated to the variation of refrigerant (R404A, R407F, R410A), setpoint temperature [-5÷5°C] and annual leakage rate [5÷15%]. CF values are ordered as a function of the adopted refrigerant across three surfaces. Results show the existence of almost linear relationships between the emissions value and the values of setpoint temperature and the leakage rate.

As expected, for each gas the minimum emission value corresponds with the minimum setpoint temperature and maximum leakage rate. This result highlights the importance of energy consumption, and therefore, the systems energy efficiency in influencing the overall emissions impact. The most interesting aspect is the evaluation of the effects caused by the refrigerant choice. Figure 5.3.7 shows how, given a setpoint temperature of 0°C and a leakage rate of 10%, R410A determines the best environmental performance for the MT system. However, as shown in Figure 5.3.8, with an increase of leakage rate R410A loses advantage against R407F, such that, starting with [10÷13%] of leakage rates and depending on the setpoint temperature, R407F results the best solution. R404A, instead, shows for each scenario the worst environmental performance.

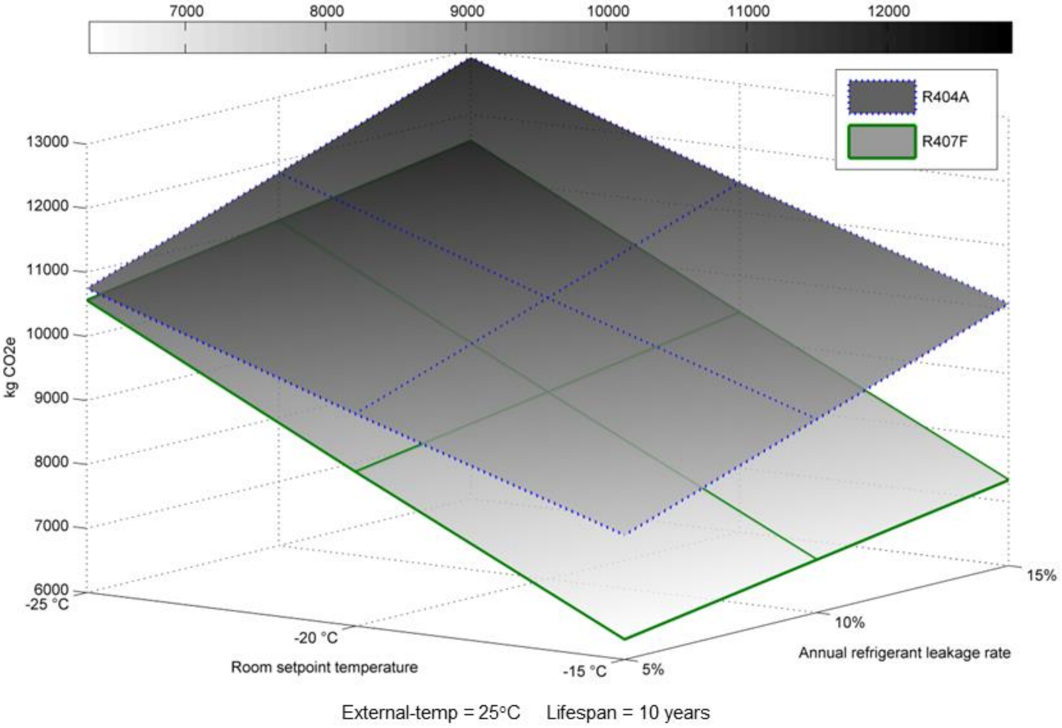


Figure 5.3.9 - CF of LTR life cycle in multi-scenario analysis

Figure 5.3.9 presents the value of CF, measured in mass of CO_{2e}, emitted in a 10-year period, associated with the LT system life cycle. Setpoint temperature is assumed to have a LT range [-25÷-15°C] and the set of system configurations is here limited to those adopting R404A and R407F, since R410A is not suitable. The values of leakage rate, external air temperature and lifespan correspond to those assumed for the analysis of the MT system presented in Figure 5.3.8. Results show that, for each analysed scenario, R407F is preferable to R404A. The greater advantage is appreciable for high leakage rate and moderately low temperatures. In these cases, the choice of R404A is a suboptimal solution: the retrofit with R407F involves the double benefit of having better technical performance and lower GWP such that a CF saving of up to 27% is possible. This benefit decreases with a decrease in setpoint temperature and leakage rate, until the benefits are almost nullified with a leakage rate of 5% and setpoint temperature of -25°C, where the advantage in emission reduction is reduced to 2%.

5.3.9 Discussion

The discussion section is organised as follows. The first part is dedicated to discussion on the analysis methodology. The second part reports final considerations of the analysis technical results.

5.3.9.1 Discussion on methodology

With regard to the adopted methodology, some considerations on how the choice of system boundaries, data accuracy, and environmental impact index influenced the study results must be reported. When compared with studies in which refrigeration systems are analysed and compared by calculating TEWI (see 5.3.2.2) or LCWI (see 5.3.2.3), this study gives much more attention to the modelling of the manufacturing and EOF treatment phases of both devices and refrigerants. The most relevant life cycle process, i.e. the refrigeration device use phase, has been modelled through the support of test laboratory and accurate performance index measurements. The second most significant activity in terms of emissions, i.e. refrigerant leakage from device piping, has been modelled in a multi-scenario analysis, in order to minimise result uncertainty. This makes this analysis particularly accurate, such that the right magnitude of each stage of the system life cycle can be finally evaluated. In this study, the environmental impact evaluation has been limited to the life cycle CFA, which entails only GHG emissions, direct and indirect, and the greenhouse effect has been considered representative of the system environmental damage. Even if CFA can be considered a streamlined LCA Rebitzer et al. (2004), the CO_{2e} evaluation is a popular choice in literature, e.g. in Aprea et al. (2012), Davies and Caretta (2004); Fischer (1993), Hwang et al. (2007), Papasavva and Moomaw (1997). On the contrary some authors, e.g. Bovea et al. (2007), Ciantar and Hadfield (2000), Johnson et al. (1998), Yanagitani and Kawahara (2000) extended, in their refrigeration system analyses, the concept of environmental impact considering a wider panel of categories, such as ozone depletion potential, acidification potential, water pollution, eutrophication potential and photochemical oxidation. In this study, the analysed refrigerants have nil ODP and the manufacturing phase, which is marked for its abiotic resource depletion potential, is not a discriminant in design choice. However, energy consumption and HFC leakage, that are life cycle hotspots, are accurately and thoroughly characterised by GHG emission assessment in this analysis. Therefore, this study demonstrates that, given the abovementioned preliminary conditions to the study, CF is an effective and comprehensive method in which it is possible to evaluate alternatives and assist key design decisions. In this respect, even if the presented analysis is related to a particular application (i.e. walk-in cold room refrigeration), this study provides an indication of the priorities in the ecodesign of refrigeration systems and the improvement of the energy efficiency. This analysis helps to explain the trade-off problem noted by the European Legislative Proposal 2012/0305 (2012) and the succeeding European Legislative Resolution on Fluorinated gases (2014), which highlights why regrigerant GWP is a relevant design driver, but is secondary to the final system CF, which is primarily influenced, as this study demonstrates, by the system (device and refrigerant) efficiency.

5.3.9.2 Discussion on study results

With reference to the technical results of the analysis, the following considerations can be made. The environmental impact of refrigeration systems is mainly influenced by system energy efficiency and, in turn, by the indirect impact caused by energy production. System energy efficiency being equal, the environmental impact can be minimised through energy source selection, such as selecting renewable energy sources for refrigeration system power supply. However, considering that the world average energy mix is still largely based on fossil fuel combustion (IEA 2013), this option cannot be considered effective in the short and medium period. Given this, further technical improvements are needed in the abatement of refrigerant leakage by minimising vibrations, monitoring piping wearing and corrosion, which can all improve significantly piping tightness. As shown in Figure 5.3.7, an annual leakage rate of 10% can represent up to 27% of the life cycle CF for a refrigeration system. Halving this rate can reduce the life cycle CF up to 21%, as shown in Figure 5.3.8 for R404A. For both MT and LT systems, the replacement of operating refrigerant can provide relevant environmental benefits. In the analysed LT system the retrofit of R404A, currently adopted, with R 407F can result in an average increase of 0.36% of COP value, and in a CO2e emission average reduction of 14%. For the MT system, the retrofit of R404A with R410A results in the COP average increase of 15% and in an emission average decrease of 23%. Further consideration can be made in the adoption of R407F in the MT system in which, for high leakage rates and setpoint temperature, as this gas has slightly higher environmental performances than R410A (Figure 5.3.7). One of the most interesting results is that, as demonstrated by laboratory test, the abovementioned improvements can be obtained by refrigerant retrofitting that involves minimal or no modifications to the refrigeration plants. In general, this study demonstrates that significant technical improvements can be adopted by OEMs with minimal effort. Although the results presented here are quite specific for small-medium-size walk-in refrigeration rooms, the application of this methodology can be repeated on other refrigeration systems, and represents a starting point for further comparisons with similar equipment.

5.3.10 Conclusion

This study presents the results of the environmental impact analysis of two commercial refrigeration systems for walk-in application under different conditions. The first objective of this study is the review of current state-of-the-art of methodologies for environmental impact assessment. The CF assessment of the life cycle of the system composed of refrigerant and refrigeration units has been evaluated as the most suitable methodology within the possible options. The sensitivity of a CF of refrigeration systems involving a set of different operating parameters including system energy efficiency and refrigeration power is reviewed. Then, the role of the room heat exchange coefficient, refrigerant type, setpoint temperature and external air temperatures on the system performances are assessed including system power consumption This data, together with the data inventory related to the life cycle of refrigerants and refrigeration devices, are incorporated with the LCA methodology, in order to model a set of possible life cycle scenarios. Different configurations of refrigerant-device are evaluated by assessing the CF of single subsystems (i.e. refrigerant life cycle and device life cycle), single life stages and then aggregated in an overall evaluation. A multi-scenario analysis completes the evaluation. The sensitivity of the environmental impact of the two systems from the previously listed parameters is demonstrated and quantified. The refrigerant type that introduces the best environmental performance is then identified for each case. Results show that the sustainability of a refrigeration system utilising a fluorinated gas is first of all determined by its energy efficiency, second by the direct impact of gas leakage, and finally, to a lesser extent, by the manufacturing and disposal of both the refrigerator and refrigerant. This study is not just limited to the demonstration of design benefits of an energy efficient system, but also defines the gap that exists between the phases of manufacture and use from an environmental point of view. The energy efficiency of the system refrigerator-refrigerant must be investigated in order to reduce the CF involved in refrigeration production and use. This study also demonstrates that it is possible to make significant improvements in refrigeration system sustainability without making any significant changes to the system design. Although the European directives declare the undeniable intention to dismiss HFCs, a careful selection of fluorinated gases may, in the medium term, lead to the simplest solution for refrigeration manufacturers.

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6 DESIGN AND PLANNING OF GREEN SUPPLY CHAINS

According to the classification adopted and described in Chapter 3, Chapter 6 presents the research on the area of Green Operations, in particular in the design and planning of Closed-Loop Supply Chain networks according to the principles of Green Supply Chain Management.

The cases of the closed-loop supply chain of containers for fresh food distribution (section 6.1) and the automotive closed-loop supply chain (section 6.2) are assumed as representative of the various industrial sectors on which the research on decision-support tools for supply chain design and planning can be useful. A combination of methodologies is here presented. Life Cycle Assessment and Life Cycle Costing are adopted as support to strategic and tactical decisions in fresh food distribution system. A Mixed Integer Linear Programming model is used as support for the design and planning of a network for end-of-life vehicles recovery, remanufacturing of parts and their reuse, with the purpose of minimising vehicle life cycle cost, i.e. costs bearing on Original Equipment Manufacturers and customers.

6.1 ECONOMIC AND ENVIRONMENTAL ASSESSMENT IN MULTI-PACKAGING FRESH FOOD SUPPLY CHAIN

6.1.1 Introduction

During the past decade, one of the most popular and universal issues raised has been that of sustainable development, ensuring that following generations will be able to experience the same standards of living and opportunities for growth that are currently enjoyed. Both public organisations and private firms are under increasing pressure to assess their current processes in order to identify and mitigate real or potential waste sources throughout their supply chains. Packaging plays an integral role in protecting, distributing and labelling products. However, its ubiquity and importance makes packaging one of the most relevant sources of waste. The greater the reliance on packaging during forward chain processes, the larger its impact on end-of-life treatments and procedures.

Traditional packaging solutions have environmental impacts that are not sustainable in the long term. These impacts include consumption of non-renewable resources, Greenhouse Gas (GHG) emissions resulting from manufacturing, transportation and usage, and production of solid waste, which highlights the relevance of end-of-life packaging management and disposal. Industry and researchers have identified the design and application of more sustainable packaging solutions as one of the most crucial challenges; many studies focus on package shape and material to enable ergonomic, effective and efficient handling and shipping operations and to reduce the overall costs of working cycle activities and end-of-life treatments.

In recent years, much of the debate and activity around packaging and its environmental impacts has focused upon the grocery and food retail sector. Packaging preserves the chemical, physical and nutritional conditions of foods as well as facilitates purchasing, warehousing and transportation activities throughout “the farm to the fork chain” (Verghese and Lewis, 2007). Beneficial changes are occurring; for example the use of Reusable Plastic Containers (RPC) is gaining traction within the grocery and food retail sector; and researchers such as (Verghese and Lewis, 2007) and (Verghese and Lewis, 2007) document such implementations, demonstrating adoptions of RPC systems can provide significant economic and environmental benefits for all stakeholders. It should be noted that the grocery and food retail sector is characterised by high and consistent material flows, accurate demand forecasts and delivery points that are both few and known, such as distribution centres (DC) devoted to cross docking and consolidation.

The evolution of food purchasing and consumption behaviours has inevitably increased the production of waste and garbage from fresh food packaging. In particular, growing demand for restaurant, catered and take-away meals has resulted in an alarming increase in waste due to the disposal of primary and secondary packages. The food catering chain (FCC) primarily relies on single-use packaging and has not experienced the adoption of RPCs, which are widely adopted in grocery and food retail sectors. The food catering chain is characterised by low sales volumes per customer and a large variety of partners responsible for packing, storage and distribution activities throughout the chain. Furthermore, the points of demand, such as restaurants, canteens and bars, are more diverse and scattered. The complexity of such systems and network constraints makes the development and management of a reverse flow of reusable packaging solutions inherently more difficult, but this is a challenge that begs for further study so an appropriate solution can be designed.

The first goal of this study is to introduce an original and general conceptual framework for the integrated design of a food packaging and food distribution network for providing a sustainable and efficient ecodesign solution. The proposed framework has been applied to the assessment of economic and environmental impacts of an RPC system in a real case study of a fresh food catering chain. This analysis focuses on organic fresh fruits and vegetables and considers organisation and logistics issues.

The major targets of this study follow:

- Integration of the economic and the environmental analyses on food packaging for distribution of fresh food products;
- Analysis and comparison of different packaging types found in the FCC;
- Analysis of the food catering distribution network, as characterised by a small number of both customers and farmers and by short distances;
- Integration of both packaging and distribution network issues in a Design for Environment (DfE) analysis and approach.

The reminder of this study is organised as follows. Section 6.1.2 presents a literature review that considers recent studies on sustainability in packaging design and selection. Section 6.1.3 illustrates the conceptual framework for designing the food package and the food distribution network from economic and environmental perspectives. Section 6.1.4 introduces the analysed scenario, a fruit and vegetable catering chain and describes the characteristics and features of single-use packaging and RPC systems. Section 6.1.5 reports the environmental impact assessment via LCA methodology, comparing the current and proposed packaging systems solutions. The economic return is computed through a differential cost analysis of packaging, storage and transportation processes provided within Section 6.1.6. Section 6.1.7 presents the results from a sensitivity analysis on the package system as integrated with the distribution system. Finally, Section 6.1.8 discusses conclusions and further research.

6.1.2 LCA and Fresh Food Supply Chain in literature

The growing interest in sustainable development is clear from the literature of the last years related to different application fields. Carter and Easton (2011) remark on the need for more sustainability analysis within supply chain management (SCM). They present a review of the literature on sustainable supply chain management (SSCM) and demonstrate the necessity for an integrated approach to SCM analysis that embeds environmental, social and economic performance evaluations. Many researchers view the food supply chain as particularly ripe for study and improvement. Apaiah et al. (2005) present a study focused on measuring the environmental loads and impacts within a generic FSC. By analysing energy demands, Apaiah et al. (2006) consider the environmental impacts of FSCs. Several studies focus specifically on the integration of food and SSCM; Green (2010) present a paper on the integration of sustainability and risk approaches within the food industry. Zanoni and Zavanella (2012) compare chilling and freezing as food processing treatments from both an environmental and a quality point of view. Some authors adopt LCA methodology for the evaluation of environmental impacts of food products and processes; Chaabane et al. (2012) apply LCA principles, considering material features and characteristics in a framework for sustainable supply chain design. Virtanen et al. (2011) use LCA to measure the carbon footprint of the meat, grain and dairy chains. Roy et al. (2009) present a review of LCA studies on agriculture and industrial food products and underline the necessity of an integrated approach to LCA analysis and other environmental care approaches towards improving food sustainability and security and reducing human health risk. Andersson et al. (1998) present a case study related to the screening life cycle assessment of tomato ketchup.

Given that packaging is an integral necessity in modern society, responsible for protecting, distributing and labelling products and processes in industry and in supply chains, it also plays a critical role in SCM sustainability (Bovea et al., 2006). Not surprisingly, the environmental impact of packaging is frequently studied within the literature. Some authors use the LCA methodology for the analysis of package systems; (Bovea et al., 2006) argue that environmental innovation in industrial packaging systems requires an integrated supply chain approach to ensure the reduction of environmental impacts and costs. The authors analyse the industrial package waste reduction through the life cycle assessment methodology. (Bovea et al., 2006) conduct a LCA analysis of a plastic packaging recycling system, aiming to quantify the real advantage in plastic container recycling, both from environmental and economic perspectives. Ross and Evans (2003) present a LCA analysis evaluating the effects of reuse and recycling strategies for plastic packages on reducing flows to landfills. Tsiliyannis (2005a) measures the environmental performance of packaging products, assuming at least one reuse per year. His contribution highlights the importance of assessing alternative packaging systems considering a combination of reuse and recycle strategies.

Other contributions investigate the reverse logistics associated with packaging returns, with particular attention to the choice of recovery policies. Tsiliyannis (2005b) introduces a new rate index for environmental monitoring of combined reuse/recycle packaging systems; he compares different reuse and recycling systems, quantifying how increasing the reuse and recycling rate improves the environmental performance. Recently, Das and Chowdhury (2012) propose a mixed-integer linear programming framework and model for the design and management of a reverse network for package recovery and collection. Wen et al. (2010) present a game theory approach for managing a distribution network of recycling packaging products and test the effect that government regulations on recycle policy may have.

The next group of contributions shows that the sustainability of the whole FSC may be addressed through the proper management of packaging waste and the adoption of reuse and recycling practices. The study of food packaging materials is strategic for the planning and management of the end-of-life treatments and activities. Reuse, recycling, and remanufacturing are the keys to sustainability, allowing for packaging that still preserves the chemical, physical and nutritional condition of food. Siracusa et al. (2008) present an overview of biodegradable polymer packages for food application; the authors underline the necessity for research on bio-based polymers, in order to combine environmental impact with integrity proprieties. González-García et al. (2011) blend LCA methodology with a DfE approach in defining a sustainable wood box for wine bottle storage.

The literature includes many studies of alternative package systems, with particular attention to sustainability achieved from the use of different materials. Zabaniotou and Kassidi (2003) present an application of LCA in comparing egg cartons fabricated from recycled paper versus polystyrene. Lee and Xu (2004) analyse the environmental impact of a conventional wooden pallet in contrast to that of a fully recyclable plastic bulk packaging system, as both are used to transport empty yogurt containers. Several authors investigate packaging reuse, in particular for vegetable and fruit package materials. Levi et al. (2011) conduct a comparative LCA upon the disposable and reusable packaging for the distribution of Italian fruit and vegetables. This study compares from environmental perspective two different packaging and distribution systems used in large retailers: single-use corrugated boxes and RPCs. Singh et al. (2006) present a similar study focused on the North American market. The authors analyse the greenhouse gas emissions and the production of solid waste due to the adoption of either RPCs or display-ready corrugated containers used for packaging fresh fruit and vegetables. Chonhenchob and Singh (2003, 2005) and Chonhenchob et al. (2008) compare use of corrugated boxes and RPCs for different types of fruit, respectively mango, papaya and pineapples. Franklin Associates (2004) document life cycle inventories (LCI) of two types of RPC for fresh products. Albrecht et al. (2007) study the sustainability of packaging systems for fruit and vegetable transport in Europe, in which single-use wooden and cardboard boxes are compared to multi-use plastic ones. Capuz Rizo (2005) presents a comparison of the environmental and economic characteristics of RPCs and corrugated boxes in the long-distance transport of fruits and vegetables.

This overview of the literature demonstrates that environmental issues in SCM and, in particular, FSC are increasingly crucial topics for sustainability. The environmental effects of RPC systems in food retail chains are emphasised by recent literature that considers packaging and logistic networks. The economic convenience of multi-use and single-use packaging system in food retail chain is considered. However, none of these studies focuses on the joint analysis of environmental and economic benefits from the implementation of an RPC packaging system in an important and growing subset of the FSC, the network associated with producing and delivering prepared foods, the FCC. This study attempts to bridge the gap, and the conceptual framework illustrated in next section supports an integrated DfE of both the food packaging system and the related distribution network.

6.1.3 A conceptual framework for designing food packaging and food distribution network according to Green Supply Chain Management principles

This section presents a conceptual framework for designing food packaging solutions and FSC networks according to the Green Supply Chain Management principles.

The integrated design of a packaging system and supply chain network represents a new challenge for competitiveness. In recent years, enterprises have completely reconfigured their supply chains to improve customer service levels and address higher demand variability. In the food industry, the customer service level of the supply chain is affected by the quality and safety of products and requirements of system flexibility strengthen the bridge between the producers, the logistics providers, the packagers and the final consumers. Furthermore, the increasing attention on environmental impacts due to human behaviour makes sustainability a concrete objective for practitioners and researchers alike. Therefore, quality, efficiency and sustainability become the principle drivers for the integrated design of food packaging systems and supply networks (Manzini and Accorsi, 2013).

Figure 6.1.1 illustrates and organises the principle concepts, analytic approaches and outputs identified in this study. The observed processes concern the typical stages of food supply chains; each step considers a specific set of issues and concerns dealing with the dimensions of Green Supply Chain management: the design, the management and control of materials flow, processing and logistic networks and operations.

The food supply step (see Figure 6.1.1) as denoted encompasses the farming processes, the consolidation of raw food commodities and their transportation to the manufacturing facilities. The food processing step consists on the process of food transformation into finished goods. The food packing and food distribution steps include the assembling and distribution activities devoted to the conservation of food products and their distribution (i.e. storage, handling and shipping) to the final consumer.

As illustrated in Figure 6.1.1, FSCs develop close relationships between packaging and products chains. Food products require physical, chemical and biological protection, as well as informational labels for nutrition and expiration. All of these requirements are met through packaging, a crucial component of FSCs, which must follow the food product from its processing and manufacturing until its purchase by consumers. In other words, the primary chain (the product chain in Figure 6.1.1) involves the steps of food supply, the food processing, the food packing and the distribution to the final consumers while the secondary chain (the packaging chain) meets the primary chain at the packing step until the product consumption.

While the food product life cycle ends with consumption, the package life cycle continues generating material flows to be properly handled and addressed.

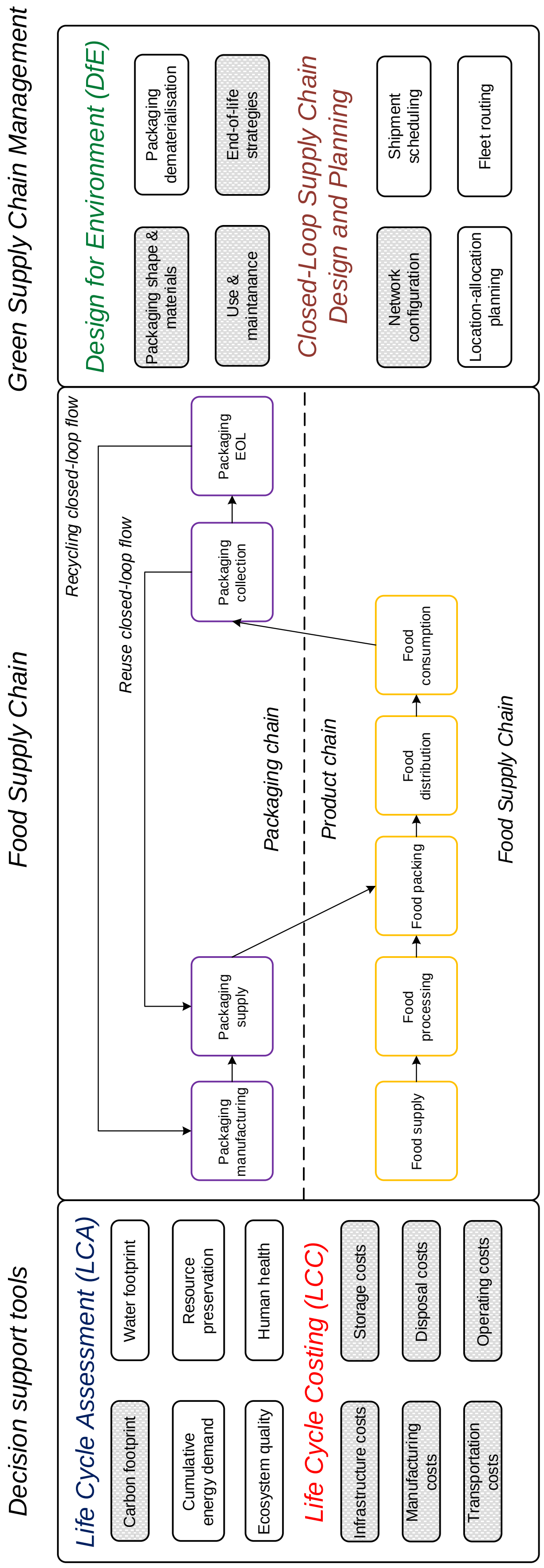

Figure 6.1.1 - Conceptual framework for Green Supply Chain Management in food industry

The illustrated framework highlights two potential closed-loop flows of package depending on the adopted end-of-life strategies. The reuse closed-loop flow (see Figure 6.1.1) considers the collection of reusable packages that return for packing process, whilst the recycling closed-loop flow involves the recycling process of a fraction and the return of the recycled secondary materials for packaging manufacturing. One of the contributions of this study is the comparison of these closed-loop alternatives for the packaging chain from both an economic and environmental perspective.

The illustrated analytic approach consists, firstly, on the adoption of LCA and life cycle costing (LCC) tools for the evaluation of both the environmental and economic costs and on defining key performance indicators (KPIs) for each step within the observed supply chain. Possible environmental KPIs (i.e. impact assessment methods) for assessing environmental impacts include the Carbon Footprint, the Water Footprint, the Cumulative Energy Demand, and others damage categories such as Resource Preservation, Ecosystem Quality and Human Health (see Chapter 4). The LCC tools attempt to identify and quantify the economic benefits or costs attributable to the network infrastructure, manufacturing, transportation, storage, disposal, and general operating drivers.

The proposed conceptual framework next incorporates the KPIs resulting from the application of LCA and LCC tools as the main drivers for the DfE approach. A wide set of aspects and issues can be considered for DfE suggestions and improvements. Some of these mainly concern packaging implications related to package design (i.e. shape and materials) and engineering, packaging dematerialisation, packaging use and maintenance strategies.

Indeed, distribution processes involve the application of Design for Environment (DfE) approach, such as for the design and definition of the proper packaging systems to safeguard product quality and enable effective handling operations. The package is not an added value for final consumers, and trade-offs often must be made between handling performance, product preservation, cost, and waste.

At the same time, designing a food distribution systems involves the application of a Supply Chain Network Design principles for the configuration of the logistic network, the strategic location-allocation planning of facilities and material flows, the scheduling of shipments, and the management of fleet routing.

Finally, the management, collection and treatment of waste are captured by the last steps of the packaging chain (see Figure 6.1.1): the packaging end-of-life. The planning of the waste collecting and recovery network encompasses the definition of the specific end-of-life strategies and treatments (e.g. reuse, recycling, landfill) to adopt. The selection of materials properties and dis-assembling procedures of products and packages affects mostly these end-of-life scenarios. The resultant environmental and economic assessments ideally would lead to opportunity for further ecodesign, planning and management of both chain networks and materials flows and processing.

In the following section, this illustrated framework is applied to a real case study of an Italian fresh food catering chain, focusing on the distribution and end-of-life steps within the supply chain. For the specific case study, with reference to the conceptual pattern illustrated in Figure 6.1.1, we consider a subset (i.e. coloured in grey) of economic and environmental KPIs. The resulting environmental and economic assessments are adopted to power an assortment of what-if multi-scenario analyses involving package design, package usage and maintenance strategies, network configuration and end-of-life scenarios for the overall assessment of reusable plastic containers in fresh food catering supply chain.

6.1.4 Case study

Evolution in peoples' food consumption habits has led to increasing waste from food catering packaging. During the last few decades, Europeans have increasingly chosen to eat out or buy take-away foods. More than 1.4 million enterprises were active in the restaurants, bars and catering sector in the EU-27 in 2006 (Manzini and Accorsi, 2013). Restaurants, bars and catering enterprises generated 298.6 € billion of turnover in the EU-27 in 2006, resulting in 116.5€ billion of added value; these indicators represent around two thirds of the accommodation and food services totals (Manzini and Accorsi, 2013). The number of food and beverage manufacturing, wholesaling, retailing and service providing enterprises has peaked in the southern member states – in particular, Italy and Spain. For example, in 2006 Spain had, on average, one local unit (single restaurant, bar or café) providing food and beverage services for every 157 inhabitants.

This growth in volume has naturally led to increasing amounts of package waste, exacerbated as the food catering chain service does not currently employ reusable packaging systems. The four main barriers preventing the adoption of this more environmentally sound solutions are as follows:

1. the low managed volume per single customer order;
2. the lack of a centralised logistic network given the huge amount of customer orders to fulfil;
3. the particular profile of customer demand, which requires less than unit picks/loads;
4. the wide and complex multi-agent supply system.

The case study under analysis deals with the fruit and vegetable packaging and distribution systems of an Italian catering supply chain, with particular attention to the organic segment of the fruit and vegetable market, which is characterised by a short supply chain with a small number of vendors, namely local farmers. A catering supply chain network within the Emilia-Romagna region is considered, with reference to a distribution centre (DC) located in Bologna, a pooling centre located in Ferrara, sixteen organic farmers and a set of potential clients spread within the region. Differential capital and operative costs and environmental impacts resulting from different packaging systems and distribution network configurations are considered in order to assess the effectiveness of the previously illustrated integrated ecodesign framework.

6.1.4.1 Distribution network configuration

The analysed catering supply network (AS-IS configuration) is summarised and illustrated in Figure 6.1.2(a). The DC receives products and empty packages from vendors and suppliers and is responsible for the storage, picking, loading and shipping processes. Carriers are responsible for transportation activities throughout the network.

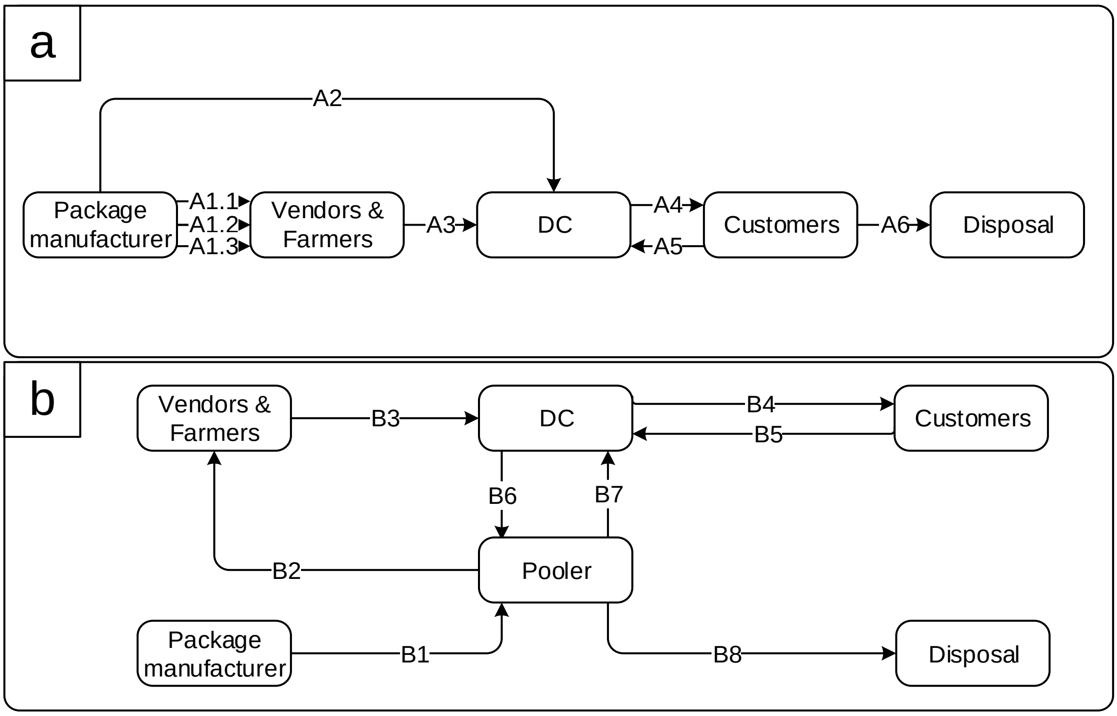

Figure 6.1.2 – Current (a) and future (b) catering supply chain networks

The alternative and new packaging system (TO-BE configuration) requires involving a new agent, the pooler along with the introduction of a reusable packaging system. In particular, the pooler is responsible for supplying RPCs, washing and engaging in other recovery treatments, and managing the packaging cycle. The pooler matches the forward-reverse catering chain cycles by supplying empty packages to the DC and vendors after recovery treatments. The TO-BE configuration of the catering chain is illustrated in Figure 6.1.2. The main features of the transportation processes for both packaging systems (i.e. single-use system and reusable system) are reported in Figure 6.1.1 with particular attention to distance, frequency and truck type.

Route	Description	Distance [km]	Frequency [trips/year]	Package condition	Truck type
A1.1	Supply of wooden boxes from manufacturer	100	26	Empty	Heavy
A1.2	Supply of one-way plastic crates from producer	100	26	Empty	Light
A1.3	Supply of Cardboard boxes from manufacturer to farmers	50	26	Empty	Heavy
A2	Supply of Cardboard boxes from manufacturer to DC	50	26	Empty	Light
A3	Transport of products on one-way packages to DC	100	52	Filled	Heavy
A4	Transport of products on one-way packages to Customers	100	120	Filled	Heavy
A5	Transport of packages to end-of-life treatment facility	100	52	Empty	Heavy

B1	Supply of new RPCs from manufacturer	700	1	Folded	Light
B2	Transport of RPCs from pooler to vendors and farmers	100	52	Folded	Light
B3	Transport of products on full RPCs	100	52	Folded	Light
B4	Supply of products on RPCs	100	120	Filled	Heavy
B5	Backhaul of empty RPCs	100	120	Filled	Heavy
B6	Transport of RPCs to pooler for washing and redistribution	35	52	Folded	Light
B7	Supply of clean RPCs to DC	35	52	Folded	Light
B8	Transport of RPCs to end-of-life treatment facility	100	1	Folded	Light

Table 6.1.1 - Single-use and RPC network routes

6.1.4.2 Packaging and vehicles specification

The most popular materials for fresh food secondary packaging are cardboard for its cheapness and plastic for its strength and resistance to humidity (Manzini and Accorsi, 2013). The packaging formats typical to the catering fruit and vegetable chain are wooden boxes, plastic crates and cardboard boxes. Cardboard packaging is utilised to contain costs and for marketing opportunities (e.g. displaying promotions). Plastic crates are widely and frequently used because of their resistance to water and stress, and the most common material is Polypropylene Polymer (PP). Finally, wood packages are favoured for their low cost and inherent strength.

The proposed multi-use RPC system uses PP materials to guarantee complete recyclability in end-of-life treatments. Shape, size, and closing ability of RPC packages match ergonomics and space efficiency needs to comply with inbound and outbound handling operations. This case study considers three specific single-use packaging solutions, wooden boxes, plastic crates, paper cardboard boxes, and the multi-use reusable RPCs, as briefly described and illustrated in Table 6.1.2.

	Wooden boxes	Plastic crate	Paper Cardboard	RPC
Weight [kg]	0.9	0.9	0.785	2
External dimensions [mm]	600x400x240	600x400x240	600x400x240	600x400x240
Load weight capacity [kg]	15	15	15	15
Boxes per pallet (filled)	36	36	36	36
Boxes per pallet (folded)	-	-	-	213

Table 6.1.2 - Packaging systems analysed

The standardisation of package size and weight is necessary for making the packaging alternatives comparable. The required number of packages for the proper management of the catering chain network is quantified as the ratio of the annual product flow to the net load capacity of each package.

The overall flow of organic products demanded by the catering chain under study is about 1200 tonnes per year. The typical less-than-unit picking process to fulfill restaurants and canteens orders compels the pooler to supply even empty RPCs to the DC. In this term, a surplus of 8% empty RPCs would be necessary.

Table 6.1.3 shows the annual packaging flow for both the single-use and the RPC networks. Use percentage data are collected from the specific case study: cardboard boxes are the most popular packaging in current use, followed closely by wood boxes, with plastic crates comprising only 15% of the total single-use packages. RPCs are reused for multiple cycles until they become inoperable, but their lifespan is not certain and depends on package quality, maintenance operations and use conditions. In this study, three different hypotheses on RPC lifespan are considered, as shown in Table 6.1.3.

Network	**One-way**				**RPC**		
Package	Wooden box	Plastic crate	Cardboard box	Total one-way	RPC lifespan 30	RPC lifespan 50	RPC lifespan 70
Use % for full loads from vendors to DC	40.6%	15.1%	44.3%	100%	100%	100%	100%
Number of packages for delivery from vendors to DC	32,451	12,075	35,474	80,000	2,667	1,600	1,143
Use % for fractioned loads from DC to customers	-	-	1	1	1	1	1
Number of packages for fractioned delivery from DC to customers	-	-	6,400	6,400	214	128	92
Total yearly amount of packages	32,451	12,075	41,874	86,400	2,881	1,728	1,235

Table 6.1.3 - Network packaging requirements

Two types of vehicles are taken into account: the “light” truck (with a maximum load tolerate capacity of 7.5 tonnes and 15 pallets) and “heavy” truck (with a maximum load capacity of 28 tonnes and 30 pallets). The former involves a lower unit transportation cost (i.e. cost per kilometer) than the latter.

6.1.5 Environmental Assessment

The environmental performances of the proposed multi-use packaging system can be evaluated by applying LCA methodology. This methodology supports the decision making process of design and management of the supply chain system. This process is made of strategic (e.g. the determination of the supply and distribution system configuration) and tactical (e.g. the management of flows of product packages within the system) decisions.

6.1.5.1 Goal and scope definition

This step includes the following activities:

- identification of the environmental impacts generated by single-use packages flowing throughout the FCC and its processes (i.e. manufacturing, transport, end-of-life treatments);
- evaluation of the environmental impacts due to the use of RPCs and the dedicated supply and distribution network;
- identification of the critical parameters (e.g. washing frequency and lifespan) that mostly affect the environmental impact of the RPC packaging system, through the application of sensitivity analysis;
- what-if multi scenario analysis of the packaging system from the sustainability perspective, by varying package end-of-life scenarios and RPC lifespan.

The functional unit (FU) of this study is represented by the transportation of 1200 tonnes of fruits and vegetables throughout the FCC. The functional flow consists of the quantity of packages necessary for the product delivery, as reported in Table 6.1.3, where the previously defined single-use and multi-use systems are distinguished.

In LCA methodology, the system boundaries define the set of processes related to the packaging life cycle to be taken into account. To this purpose, Figure 6.1.4 shows system inputs (i.e. materials and energy) and outputs (i.e. waste and pollutants) for both single-use and multi-use packaging systems and network configurations.

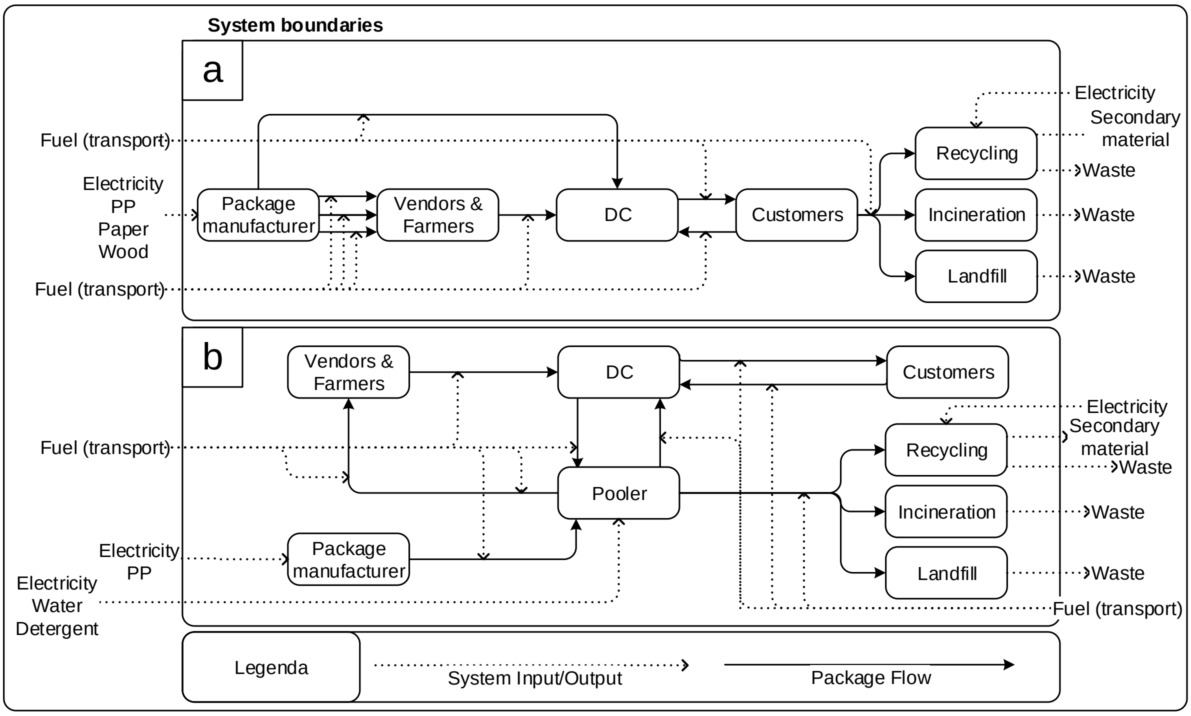

Figure 6.1.3 - LCA system boundaries

The single-use network involves the manufacturing processes for corrugated cardboard boxes, plastic crates, wooden boxes and the transportation activities from package suppliers to vendors and farmers, from vendors and farmers to the DC, from the DC to customers and finally from the latter to the disposal centre. Regarding the end-of-life treatments, three different scenarios are considered: sanitary landfill, municipal incineration and recycling.

For the RPC packaging system configuration, the considered life cycle steps follow:

1. the RPC manufacturing process;
2. the transportation activities from package suppliers to the pooler and from the pooler to the disposal centre;
3. the transportation activities between the pooler, farmers, DC and customers with a frequency depending on the package lifespan;
4. the RPC washing treatment;
5. the end-of-life scenarios (i.e. landfill, incineration and recycling).

Processes that do not differ greatly between the two packaging systems or that result in negligible environmental impact are not analysed. In particular, the processes ignored include: farming and harvesting, product packing, handling activities (e.g. truck loading/unloading, RPC opening/folding, pallet consolidation) and picking activities.

6.1.5.1.1 Impact assessment method selection

The choice of the impact assessment method is one of the main hotspots of the LCA approach. It determines the results of the analysis and supports their comparison with other studies and benchmarks. In particular, the literature adopts different impact assessment methods to address particular instances. Table 6.1.4 summarises the applied impact assessment method for ten LCA studies dealing with food packaging that are presented in the literature review section.

The table illustrates that the LCA literature in this area does not agreed upon a single best practice for assessment; there is no evidence of univocally use of a particular impact assessment method (e.g. single and multi-issue or mid and end-point). However, these reported studies do have in common the evaluation of the carbon footprint, which is sometimes integrated into more articulated indices.

The carbon footprint (CF) is adopted as a metric for assessing the environmental impact of both packaging systems under analysis. The IPCC 2007 GWP 100 year-period is selected as the particular impact assessment method. Although the CF provides a limited view of the overall environmental impacts, whereas other methods consider many impact categories (e.g. human health, resource preservation, ecosystem quality), the estimation of the equivalent carbon dioxide (CO2eq) is applied widely in the literature and, thus, is useful for comparison with other studies. Furthermore, the use of different metrics of environmental impact (in particular multi-issue methods such as Eco-indicator) might lead to an incoherent interpretation of obtained results. Indeed, the application of multiple impact assessment methods to the analysis requires an extended discussion on the obtained results about the consistency of each method; and this is far from the scope of this current research.

Authors and date	Paper title	Impact assessment method
Eurostat - European Business (2009)	Life cycle assessment of a plastic packaging recycling system	consumption of natural resources; air pollution (GHG emissions included); water pollution; quantities of solid waste generated.
Packaging Italian Institute (2010)	Application of Life Cycle Assessment to improve the Environmental Performance of a ceramic tile packaging system	Eco-indicator 95; Eco-indicator 99; EPS 2000 (Environmental priority system);
Chaabane et al. (2012)	Design of sustainable supply chains under the emission trading scheme	Carbon Footprint
Singh et al. (2006)	Life Cycle Inventory and Analysis of Re-usable Plastic Containers and Display-ready Corrugated Containers Used for Packaging Fresh Fruits and Vegetables	Energy consumption , solid waste production and Carbon Footprint
Virtanen et al. (2011)	Carbon footprint of food – An approach from national level and from a food portion	Carbon Footprint
Zabaniotou and Kassidi (2003)	Life cycle assessment applied to egg packaging made from polystyrene and recycled paper	Eco-Indicator 95
Albrecht et al. (2007)	The sustainability of packaging systems for fruit and vegetable transport in Europe based on life cycle analysis	CML 2001
Ross and Evans (2003)	The environmental effect of reusing and recycling a plastic-based packaging system	Carbon Footprint; environmental effects of photochemical oxidants
Lee and Xu (2004)	A Simplified Life Cycle Assessment of Re-usable and Single-use Bulk Transit Packaging	EPS 2000 Default Method
Levi et al. (2011)	A comparative life cycle assessment of disposable and reusable packaging for the distribution of Italian fruit and vegetables	EPD index
González-García et al. (2011)	Combined application of LCA and ecodesign for the sustainable production of wood boxes for wine bottles storage	CML 2000

Table 6.1.4 - Literature review of the adopted Impact Assessment Method

6.1.5.1.2 Data sources and quality

This study draws from a variety of preliminary data sources. Some information is taken directly from this specific case study (i.e. packing materials and vehicle types). Other data are collected from literature studies (i.e. single-use package and RPC production processes, packaging dimensions, tare, weight and net weight capacity, RPC washing process, recycling rate, recycling process efficiency and related energy consumption). A benchmarking activity has been conducted concerning data collected from literature studies. In the case of missing or unreliable data some hypotheses have been made and different scenarios are evaluated (e.g. RPC lifespan, RPC washing rate, packaging end-of-life treatment allocation). The Ecoinvent databank v2.2 (2010) is used as source for assessing the inputs and outputs of each process.

6.1.5.2 Life Cycle Inventory

In this step, the Ecoinvent databank v2.2 (2010) is used to select the relevant processes and steps encompassed in the life cycle inventory, according to the available input data. For each packaging system a specific analysis of the manufacturing, use-phase and end-of-life processes has been conducted and is illustrated below.

6.1.5.2.1 Manufacturing

6.1.5.2.1.1 Corrugated cardboard box manufacturing

Corrugated cardboard for food delivery, according to Levi et al. (2011) is mainly composed of kraft paper (60% by weight) and semi-chemical paper (40% by weight) although up to 3% of scrap paper is assumed. For the final fabrication of boxes an additional scrap of 1% in weight is used and energy consumption averages 0.1kWh per kilogram of package produced. Packaging manufacturing processes are properly modified according to the materials and package components, per the Ecoinvent databank v2.2 (2010).

6.1.5.2.1.2 Wooden box production

The manufacturing of wooden boxes entails three steps: wood production, veneer production and box assembly (Albrecht et al., 2007). Plywood is produced either by wood sawing or peeling. We consider the latter process because it introduces a lower scrap rate. A quantity of 2.65kg of hardwood is expected for the final production of one kilogram of plywood, while 30g of staples and 1kWh of electric energy are required for the final assembly of one wooden box. Similar wooden boxes manufacturing processes are found in the (Albrecht et al., 2007) and have been modified to fit the standardised packages presented in Table 6.1.2.

6.1.5.2.1.3 RPC and single-use plastic crate manufacturing

(Albrecht et al., 2007) also report that single-use plastic crates and RPCs are composed of both polythene (PE) and PP. This study, considers only PP as constituent material. If an amount of 2.8% of scrap is added during the production phase, 0.925kg of polypropylene granulate can be expected to yield one kilogram of product. RPC manufacturing processes are found in the (Albrecht et al., 2007) and modified appropriately.

6.1.5.3 Use-phase

During the use-phase, both packaging systems are subjected to transportation and delivery processes, but RPC alone incurs washing treatments. As previously discussed in 6.1.4.1 two transportation vehicles are assumed: light and heavy trucks. The required number of shipments and cycles among logistic nodes is determined from the shipping policy, the shipped product flows and the best fitting load capacity of vehicles. In this study, only the differential impacts and costs of transport of packages are evaluated. Even though both networks manage the same FU, the different weight and load capacities of two packaging systems affect the number of trips as well as the selection of the most suitable vehicle type, according to capacity.

6.1.5.3.1 Single-use packaging use-phase

Table 6.3.5 shows the annual package flows. Accounting for the tare weight, the number of dispatched packages, and the distance between the network nodes, the annual quantity of shipped package mass per distance is quantified for each route.

6.1.5.3.2 RPC use-phase

In the RPC system configuration, a set of routes depends on the lifespan of the package (i.e. routes B1 and B6 in Table 6.1.1). For instance, if the RPC lifespan were 50 cycles, the number of packages required to deliver 1200 tonnes of products with fully loaded containers (i.e. 15 kilograms of goods per box) would be 1600. An additional 128 boxes would be required to guarantee the DC fulfils 6400 less-than-unit orders. Table 6.1.5 reports the expected quantity of RPCs handled throughout the catering supply and distribution chain.

Route	Distance [km]	Lorry type	Adopted package	Travelling packages per year	[Tonne*km]
A1.1	100	Heavy	Wooden box	32,451	2,920
A1.2	100	Light	Plastic crate	12,075	1,086
A1.3	50	Heavy	Cardboard box	35,474	1,392
A2	50	Light	Cardboard box	6,400	251
A3	100	Heavy	All one-way pack.	80,000	6,792
A4	100	Heavy	All one-way pack.	86,400	7,294
A5	100	Heavy	All one-way pack.	86,400	7,294
B1	700	Light	RPC Folded	1,728	2,419
B2	100	Light	RPC Folded	80,000	16,000
B3	100	Light	RPC Folded	80,000	16,000
B4	100	Heavy	RPC Filled	86,400	17,280
B5	100	Heavy	RPC Filled	86,400	17,280
B6	35	Light	RPC Folded	86,400	6,048
B7	35	Light	RPC Folded	6,400	448
B8	100	Light	RPC Folded	1,728	345

Table 6.1.5 - LCI transport phase

6.1.5.3.3 End-of-Life

The disposal phase represents a crucial step for the whole life cycle evaluation, especially for single-use packaging systems, due to the amount of waste generated every year. A sensitivity analysis compares the environmental impacts of three different disposal scenarios: disposal scenario I, which considers a 100% of municipal incineration without energy recovery; disposal scenario L, whereas the total amount of waste is landfilled; disposal scenario R, where package waste is allocated to incineration, landfill and recycling in the proportions of 25%, 25%, and 50% respectively. Ecoinvent databank v2.2 (2010) provides detailed data on incineration and landfill processes, while recycling treatments are not included. Therefore, a recycling process is assumed for each package type.

6.1.5.3.3.1 Corrugated cardboard box recycling

According to Levi et al. (2011), the recycling of one tonne of corrugated cardboard requires 7m^3 of water, 600kg of steam and 700kWh of electric energy. The resultant output is 950kg of test liner paper.

6.1.5.3.3.2 Wooden box recycling

Wooden boxes are a multi-material package because of the presence of wood veneers and steel staples. For each kind of material, a different recycling process is assumed. Recycling 1 tonne of plywood consumes 100 kWh of electric energy and generates 800kg of wood wool and 200kg of wood chips. We assume that all the staples can be recycled, consuming 100kWh per tonne of processed steel.

6.1.5.3.3.3 One-way plastic crate and RPC recycling

Because of the similarity in materials (i.e. 100% of PP), the two packages are subjected to the same recycling process. 80% of PP packages can be recycled, generating 800kg of secondary granulate per each tonne of recycled crates. This secondary granulate can be used instead of virgin granulate in some applications, so plastic package recycling reduces the required production of primary polypropylene granulate. According to Levi et al. (2011), each tonne of treated waste consumes on average 600kWh of electric energy.

6.1.5.4 Life Cycle Impact Assessment (LCIA) and Interpretation

The environmental impact associated with the life cycle phases of package can now be evaluated. The methodology computes the CF for each inventory process. Manufacturing processes, distribution, washing procedures and final end-of-life treatments are analysed for both single-use and RPC package systems and the results compared. This section considers the assessment of the CF for the following life cycle steps.

6.1.5.4.1 Manufacturing

In the previous phase of LCA methodology, accurate data on package manufacturing activities are collected and converted in inventory processes. The environmental impacts given by the production of one kilogram of package are here listed in terms of kilograms of emitted CO2eq. Thus, corrugated cardboard box production generates 1.18kg CO2eq; wooden box production generates 0.43kg CO2eq and plastic crate or RPC production generates the most, at 3.4 CO2eq. As Table 6.1.3 shows the annual amount of required packages and packaging sizes and features, the CF resulting from the manufacturing of both packaging (single-use and reusable) can be calculated and is reported in Table 6.1.6.

6.1.5.4.2 Use-phase

For both single-use and RPC systems, use-phase is characterised mainly by transportation. Table 6.1.6 reports the overall amount of CO2eq produced by distribution processes. Two vehicle types are taken into account, considering different vehicle weight and load capacity (i.e. carried tare). The environmental impact given by the transport phase within the RPC distribution network is indirectly influenced by the package lifespan: the higher the number of cycles per package, the lower the quantity of reusable boxes manufactured, and the lower the flows for routes B1 and B2, as shown in Figure 6.1.2.

Comparing the distribution phases of the two alternative networks, the environmental impact introduced by the RPC system appears relevant and is not strictly affected by the reusable package lifespan. This result is caused by the greater amount of required shipments as well as by the high use of lighter vehicles (i.e. for delivery of empty RPCs). Washing is an exclusive phase of the RPC network, resulting in estimated emissions of about 0.024kg of CO2eq per package. The washing procedure is not mandatory for the pooler; its frequency depends on the quality-of-service.

6.1.5.4.3 Disposal

As expressed in Section 6.1.5.3.3, the allocation of package disposal treatments is affected by uncertainty and geographic specificity. Three different disposal scenarios that consider different treatment allocations are assumed. The CF related to the disposal phase for each package systems is reported in Table 6.1.6. In disposal scenario I 100% of waste is disposed through municipal incineration, but no energy recovery is included. In this case, disposal of wooden boxes introduces a minimal contribution of CO2eq whereas plastic packages have high impact. However, when PP packages are landfilled (i.e. disposal scenario L), emissions are lower due to slow process of releasing of pollutants. Finally, in disposal scenario R, where a significant percentage of recycling is assumed for each package type, a negative impact is estimated for all package types.

6.1.5.4.4 Life cycle

Table 6.1.6 shows the calculated CO2eq emissions during the life cycle steps for each package type. The last section of the table presents the annual life cycle impact as the sum of the previous contributions. Because of the high sensitivity of the results from the selected end-of-life treatment, a life cycle assessment is reported for each of the above presented disposal scenario (e.g. disposal scenario L is utilised for life cycle L). The left side of the table refers to the single-use distribution network, with the impacts from each of the three single-use packages displayed, given their prevalence in the system. The sum of these comprises the total one-way impact. The right side illustrates two significant RPC life cycle scenarios. The “RPC (30-100%)” scenario assumes a lifespan of 30 cycles and a washing rate of 100% whereas the “RPC (70-50%)” scenario considers a 70-cycle lifespan and a washing frequency of 50%. These scenarios represent the highest and the lowest life cycle environmental impact values for RPCs, respectively.

Figure 6.1.5 illustrates and summarises the results of the proposed CF analyses and assessment. For example the "Cardboard I" stacked bar represents the life cycle of a cardboard boxes when the disposal scenario is incineration. It should again be noted that magnitude of the emissions for each single-use packaging type are also affected by how many such packages are used. Table 6.1.3 previously showed that cardboard, plastic and wood comprise 45%, 15% and 40% of the single-use packages, respectively. Thus, it is clear that a single use plastic container would result in greater emissions overall than a like cardboard container, and that a wood container would have the lowest CF.

Network		**One-way network [kg CO2eq/year]**				**RPC network [kg CO2eq/year]**	
Package		**Cardboard box**	**Plastic crate**	**Wooden box**	**Total one-way**	**RPC 30-100%**	**RPC 70-50%**
Manufacturing		38,832	36,931	12,526	88,289	19,574	8,389
Use-phase	Transport	2,191	1,049	1,932	5,172	18,186	16,954
	Washing	-	-	-	-	2,066	1,033
Disposal	I	824	28,318	358	29,500	15,009	6,432
	L	39,582	1,081	1,851	42,514	573	246
	R	-7,523	-13,731	-2,839	-24,093	-7,278	-3,119
Life cycle	I	41,849	66,296	14,815	122,960	54,835	32,808
	L	80,607	39,060	16,308	135,975	40,399	26,622
	R	33,501	24,249	11,618	69,368	32,548	23,257

Table 6.1.6 - LCIA results

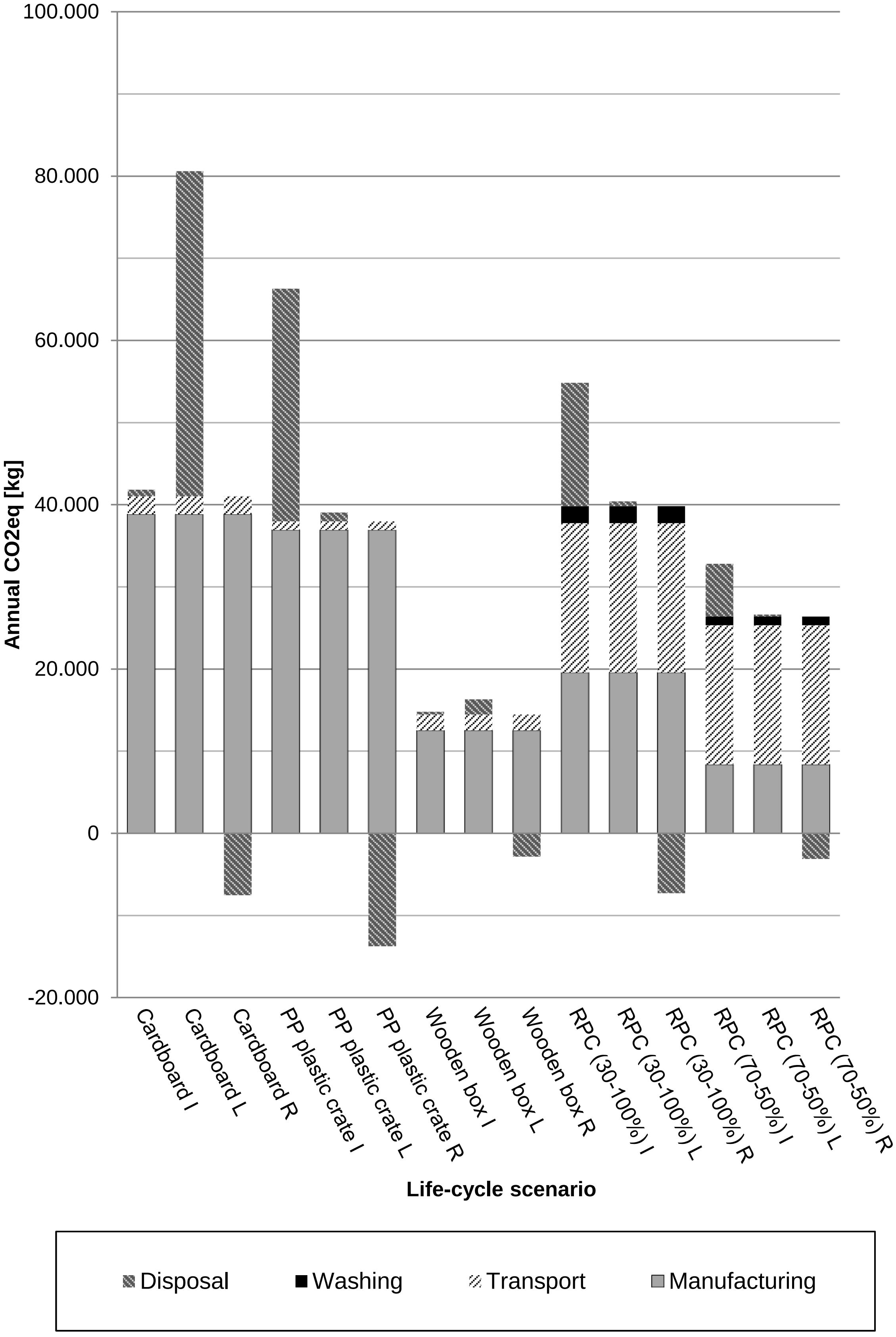

Figure 6.1.4 - Package life cycle impact assessment

Figure 6.1.5 also illustrates that the manufacturing and disposal phases have the greatest impact in the overall life cycle for all single-use package types, whereas transportation is the most relevant process of the RPC life cycle. Washing treatment does not significantly affect results.

Figure 6.1.6 reduces the consideration of single-use packages to the composite usage in contrast to RPC usage. Figure 6.1.6 also depicts three life cycle scenarios: Scenario I, Scenario L and Scenario R in which for every packaging type disposal scenario I, disposal scenario L and disposal scenario R is assumed, respectively.

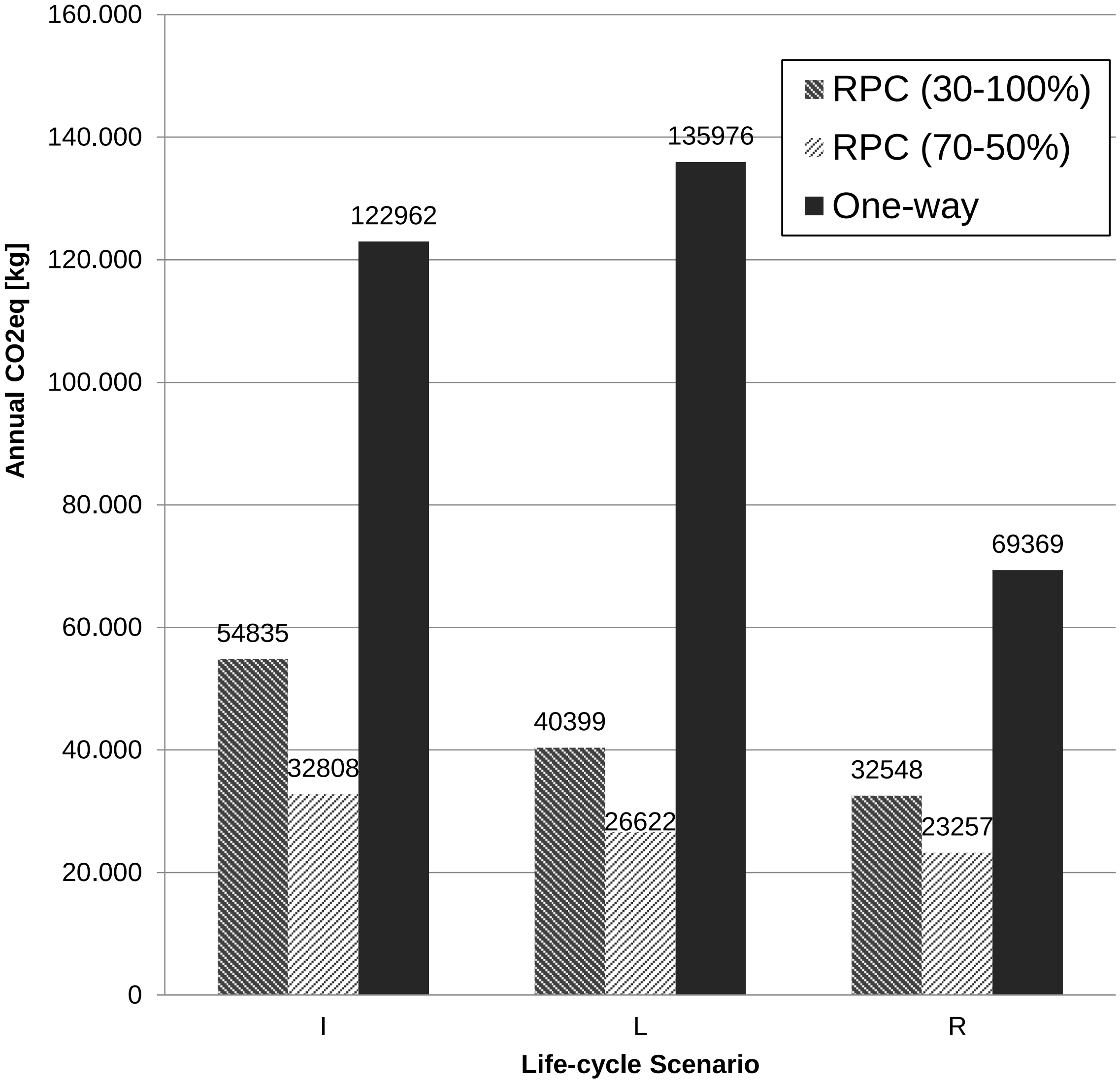

Figure 6.1.5 - Single-use and RPC network life cycle impact assessment

No matter which RPC configuration is assumed, the RPC packaging system results in a lower environmental impact, at least as measured by the CF, than the single-use system. The differential for this environmental impact depends both on the considered disposal scenarios (i.e. incineration or landfill) and package lifespan. For instance, the CF measured of landfill disposal for single-use packages is five times greater than for reusable packages. The adoption of Scenario R and the related recycling of relevant portion of packaging waste potentially reduce such difference. A comprehensive multi-scenario analysis is presented in section 6.1.7, where the relation between network geographical extension and the environmental impact of the two alternative packaging systems is also analysed.

6.1.6 Economic analysis

In this section, an economic analysis of the proposed system configurations is presented. The economic effects of packaging system definition and supply network configuration involve three main actors: (1) vendors and farmers, (2) the DC and (3) customers. The results illustrated in this section are presented as differential costs between the current single-use network configuration (AS-IS) and the RPC based distribution systems (TO-BE).

The introduction of the RPC packaging system causes the following network rearrangement:

- in addition to the purchasing of packages, RPC users experience a service cost in each package delivery cycle;
- for each node of the network (e.g. the DC or the generic customer), higher labor costs are provided due to the additional activities of opening and closing the RPC unit before and after consignment;
- to maintain RPC traceability, packaging informative registration is required at each delivery step;
- costs related to traceability mistakes and packaging losses are expected;
- greater transportation costs are expected.

6.1.6.1 Cost elements

6.1.6.1.1 Packaging Purchasing costs

In the multi-use RPC-based system, products and packages are stored in the warehousing system and shipped from vendors/farmers to the DC and from the DC to the customers as a result of the product picking and package fractioning. The packaging pooler offers two supply alternatives: (1) total purchasing of RPC packages and (2) leasing. The former is the option considered in this analysis.

As demonstrated in section 6.1.4.2, the amount of packages used annually depends on packaging lifespan. A service unit cost is associated to each packaging cycle rotation and step (e.g. washing, packaging tracing, third-party damage insurance). In both single-use and RPC networks, the contribution of transport cost from manufacturer to buyer is included in the final purchasing cost.

6.1.6.1.2 Transport costs

In the RPC-based network, greater transportation costs are expected when compared to the one-way transportation costs inherent to single-use packaging. Even though RPC folding allows the use of smaller and more densely packed vehicles, packages travel along wider networks. Hence, in the RPC network the total covered distance is greater than in one-way system. In this analysis, only differential transport contributors are taken into account. Waste delivery from the customer to the end-of-life treatment centre is excluded because its related cost is included in packaging purchasing cost.

6.1.6.1.3 Labour/handling costs

RPC folding, opening and checking activities require an additional manual labour cost. Even though these procedures require only a few seconds per container, the annual amount of packages flowing through the system every year (about 86,400 package/year) results in a relevant time cost. Furthermore, before and after every delivery truck loading and unloading procedures are required. The closable feature of RPCs allows saving time and space for handling and loading operations.

6.1.6.1.4 Management costs

In the RPC network, shipment traceability needs requires management of vast amounts of data. An informative registration procedure is associated to each RPC transfer step. Furthermore, fixed annual administration costs are incurred. We assume an operator should be completely dedicated to monitoring RPC customer stocks.

6.1.6.1.5 Other costs

During the RPC registration phase, track and trace errors and costs are incurred. In addition, packaging losses from stealing, misplacement and breakage are calculated for each network node. In particular, significant losses at customers are expected. In single-use packaging systems, however, a disposal municipal fee is charged to customers for packaging waste management.

6.1.6.1.6 Earnings

DC operators are responsible for a preliminary package cleaning step, before shipping back the crates to the pooler. This process improves RPC hygienic conditions and avoids further washing procedures. The pooler promotes this practice by rewarding a DC with a monetary compensation.

6.1.6.2 Economic Assessment

Table 6.1.7 summarises the most significant cost drivers experienced by the three principle actors of the catering chain, the vendors, DC and customers. The differential costs between the single-use and the RPC packaging systems refer to the annual operations necessary to process the FU of products throughout the supply chain. This analysis assumes a RPC lifespan of 50 cycles.

This economic assessment highlights the benefits of vendors and farmers for adopting the RPC system. The most evident advantage consists on savings in packaging purchasing. Conversely, DC and customers experience higher costs for traceability transportation and handling activities and due to the expected losses, respectively. The adoption of a RPC system would result in a global cost increase of about 69,300€ a year for this particular volume of food analysed, translating to a cost increase of 0.058€/kg for the delivered goods.

Vendors and farmers		DC		Customers	
Cost element	Differential costs [€/year]	Cost element	Differential costs [€/year]	Cost element	Differential costs [€/year]
One-way pack. purchasing	-71,039	One-way pack. purchasing	-5,930	RPC folding	2,400
RPC purchasing	8,800	RPC purchasing	704	RPC reg. (from DC)	4,700
RPC service cost	21,600	RPC service cost	1,728	RPC reg. (to DC)	4,700
RPC opening	2,222	RPC opening	178	Waste collection	-9,600
RPC weighting	8,000	RPC pallet transfer	406	Disposal fee	-5,300
Truck unloading	-1,231	RPC checking	6,912	Losses	18,000
Transp. Pooler-vendors	8,362	Truck unloading	-98		
RPC registration (to DC)	4,352	Transport customers-DC	20,532		
Track and trace errors	1,000	Transport DC-Pooler	2,927		
Losses	3,000	Transport Pooler-DC	2,927		
		RPC reg.(to customer)	4,700		
		RPC reg.(from customer)	4,700		
		RPC reg.(from vendors)	4,352		
		RPC reg.(from pooler)	348		
		Administration	28,900		
		Return from pooler	-7,000		
		Losses	3,000		
Total cost	-14,934		69,286		14,900

Table 6.1.7 - Economic convenience assessment of RPC packaging system

6.1.7 Multi-scenario analysis

One of the aims of this study is to conduct a multi-scenario evaluation of environmental and economic impacts due to the adoption of the RPC packaging system in lieu of a single-use system in a regional food catering network. The previously illustrated LCA analysis demonstrates the dependence of the obtained performance by varying key parameters (e.g. RPC lifespan, end-of-life scenario, RPC washing rate). The environmental impacts related to the distribution network are also affected by node distances: the wider the network, the higher the environmental costs. The economic convenience of an RPC system depends on the purchasing costs, RPC lifespan and node distances. Although packaging washing rates and waste treatment influence the environmental sustainability of the overall catering network, their economic impact is not directly evaluated. The former affects the pooler service costs, which are not included in this economic assessment. For the latter, according to the current waste management system, this study ignores the interdependence between waste treatment choice and municipal disposal fee. The analysis considers a single washing frequency of 100% and one disposal scenario, (i.e. disposal scenario R).

Consequently, only RPC lifespans and network node distances have been selected as the drivers for the following sensitivity analysis. We consider lifespan levels: 30, 50 and 70 use cycles. In order to evaluate the effects due to different node distances, we introduce a corrective factor (i.e. x1, x2, etc.) multiplying the starting distance values assumed in Table 6.1.1. The purpose of this step of analysis is the evaluation of the impact of the network dimensions on the environmental and economic benefits generated (or not generated) by the introduction of an RPC packaging system.

Table 6.1.8 presents the results of the multi-scenario analysis. For each combination of RPC lifespan and network configuration it reports the following expected performance as the sum of different packaging type contributions:

- the annual environmental impact of the RPC distribution network and the one-way packaging distribution network;
- the annual differential distribution costs experienced by vendors and farmers, DC, customers and the whole network.

Parameters			**Annual packaging life cycle impact CO2eq [tonne/year]**					**Annual differential cost [€/year]**			
Scenario	RPC lifespan	Distance multiplicative factor	RPCs	Cardboard boxes	Plastic crates	Wooden boxes	One-way packages	Vendors and Farmers	DC	Customers	Total network
1	70	x1	24.29	33.5	24.25	11.62	69.37	-17,449	71,393	14,998	68,941
2	50	x1	26.77	33.5	24.25	11.62	69.37	-14,935	71,594	14,998	71,657
3	30	x1	32.55	33.5	24.25	11.62	69.37	-9,068	72,063	14,998	77,993
4	70	x2	40.32	34.65	24.61	12.58	71.84	-11,906	90,973	14,998	94,065
5	50	x2	42.8	34.65	24.61	12.58	71.84	-9,392	91,174	14,998	96,780
6	30	x2	48.58	34.65	24.61	12.58	71.84	-3,525	91,644	14,998	103,116
7	70	x3	56.35	35.81	24.97	13.55	74.32	-8,682	104,389	14,998	110,704
8	50	x3	58.83	35.81	24.97	13.55	74.32	-6,168	104,590	14,998	113,420
9	30	x3	64.61	35.81	24.97	13.55	74.32	-301	105,059	14,998	119,756
10	70	x4	72.38	36.96	25.33	14.52	76.8	-3,264	116,528	14,998	128,262
11	50	x4	74.85	36.96	25.33	14.52	76.8	-749	116,729	14,998	130,977
12	30	x4	80.64	36.96	25.33	14.52	76.8	5,117	117,198	14,998	137,313
13	70	x5	88.41	38.11	25.68	15.48	79.28	1,203	126,997	14,998	143,198
14	50	x5	90.88	38.11	25.68	15.48	79.28	3,718	127,198	14,998	145,913
15	30	x5	96.67	38.11	25.68	15.48	79.28	9,584	127,668	14,998	152,249

Table 6.1.8 - Economic and environmental impact multi-scenario analysis

6.1.7.1 Multi-scenario analysis and RPC network environmental impact

Figure 6.1.7 shows the annual emissions in term of CO2eq generated by the alternative packaging systems.

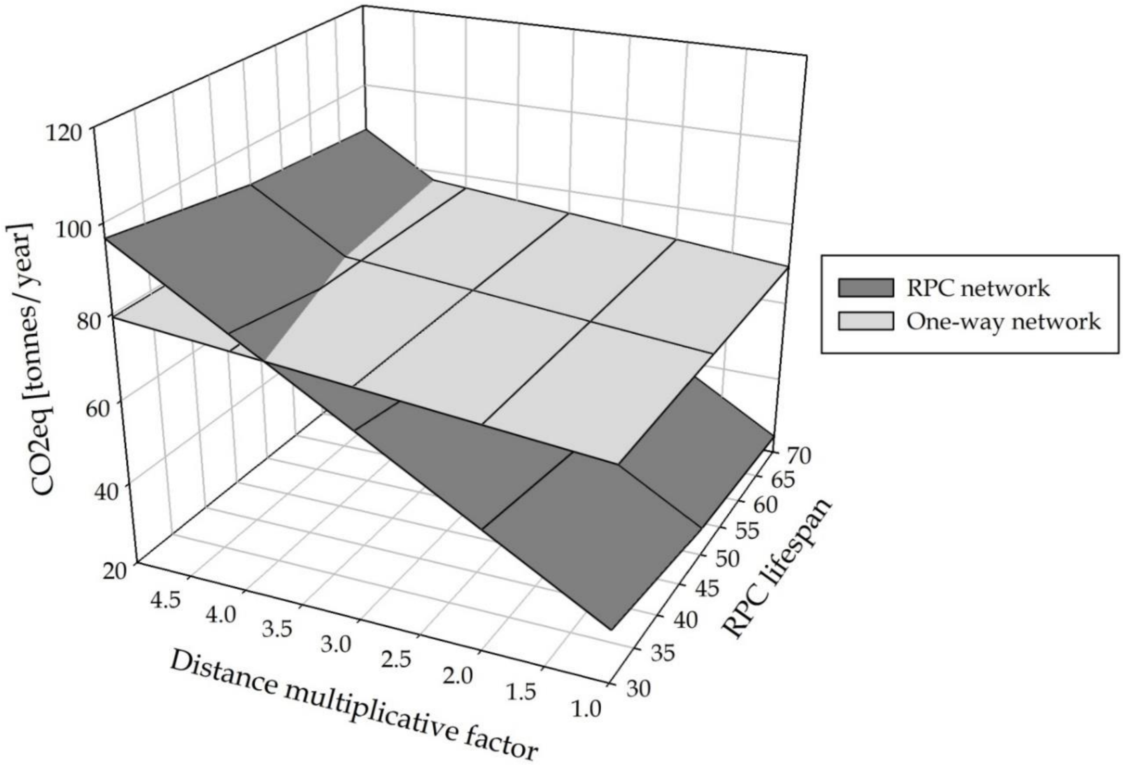

Figure 6.1.6 - Environmental impact multi-scenario analysis: comparison between RPC and single-use system

This graph illustrates the following three points:

- The environmental impact related to the RPC system is highly dependent on the geographical dispersion of network nodes due to the importance of transportation in the RPC life cycle.
- As RPC lifespans increase, the resultant CO2eq emissions exhibit an asymptotic trend, a finding also noted by (Levi et al., 2011).
- Most crucially, an environmental break-even point between the two packaging distribution systems can be determined given these two factors. The intersection of the planes illustrated in Figure 6.1.7 identifies the combination of lifespan and network dispersion in which the two packaging alternatives are equivalent.

6.1.7.2 Multi-scenario analysis and RPC network economic performance

In Figure 6.1.8, differential distribution costs are reported for each actor and for each combination of RPC lifespan and network size. The multi-scenario economic assessment demonstrates the minimal effect of the analysed factors (i.e. RPC lifespan and network size) upon customers' service costs but the large impact they have on the vendors' and farmers' benefits.

For each packaging lifespan scenario an economic break-even point, depending on the network distance amplitude, can be identified. For instance, consider a distribution network where farmers are far three hundred kilometres from the DC and the pooler, assuming a RPC lifespan of 30 cycles. Clearly, farmers would gain no economic benefit from the adoption of reusable packages unless they can expect a longer packaging lifespan or have a less scattered catering distribution network.

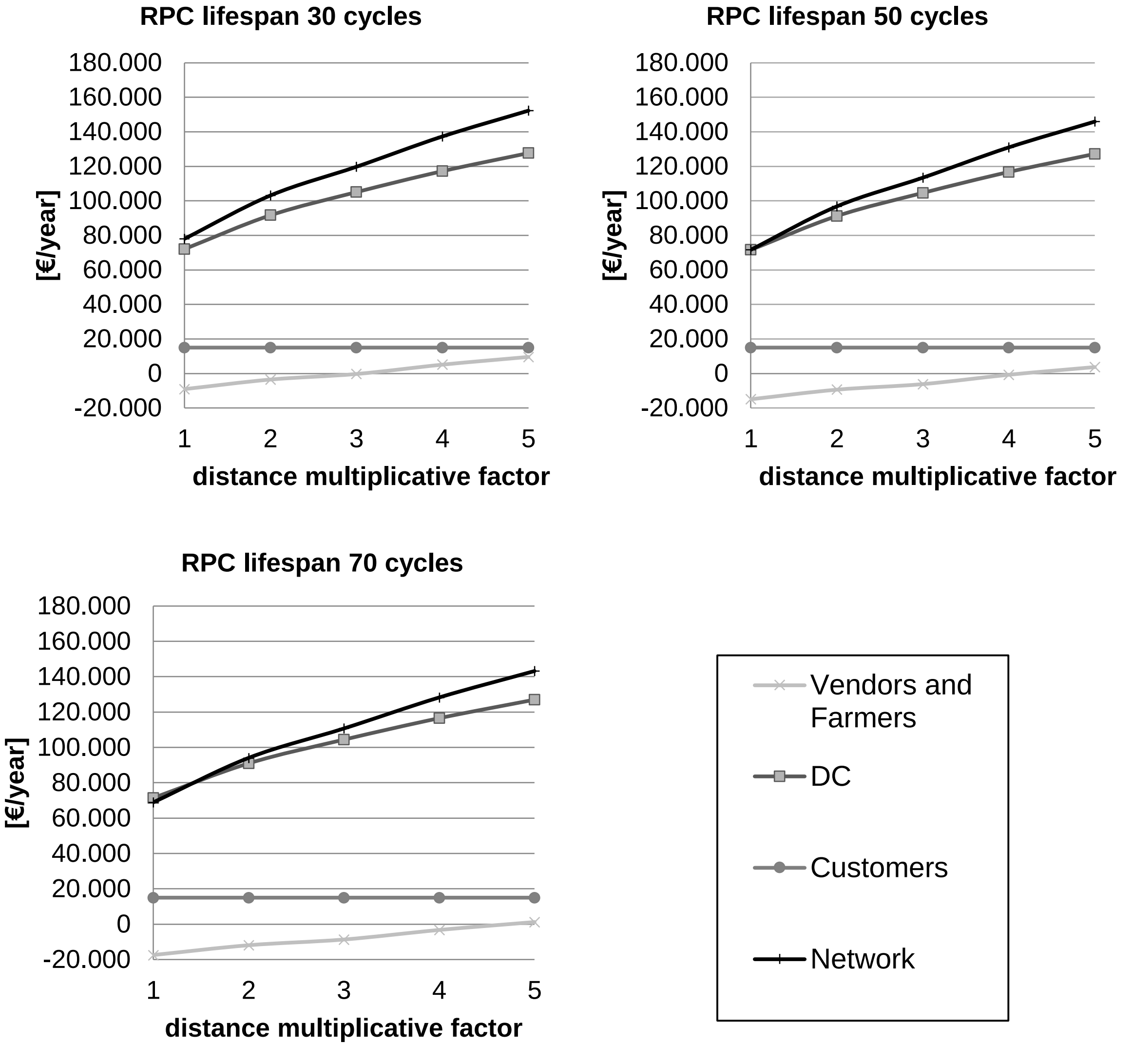

Figure 6.1.7 - Economic multi-scenario analysis

6.1.8 Conclusions and further research

This study presents an original framework and a significant application of the economic and environmental assessment of the adoption of a RPC packaging system, in lieu of single-use packaging in the food catering supply chain. This framework integrates environmental and economic analyses through performing an LCA and a LCC evaluation. The use of RPCs has been tested and applied to organic produce handled by the DC studied herein. The related operative and capital costs for each node of the supply chain, i.e. vendors, DC and customers, are estimated as well as the CF associated with each packaging life cycle stage.

The LCA demonstrates that the environmental impact associated to the single-use network is mainly caused within the manufacturing phase, due to the great volume of the packages required over the year. However, transportation significantly affects the sustainability of the RPC system. The environmental impact associated with a package’s end-of-life is highly dependent on the disposal policy, requiring the evaluation of different disposal scenarios for completeness. The unpredictability and influence of several parameters such as RPC lifespan, disposal treatments and network distribution can profoundly affect both the environmental and economic analysis, potentially leading to different conclusions.

In summary, the analysis shows that for the case study in question, adoption of an RPC system will lead to a reduced environmental impact in terms of CO2eq emissions. However, the overall economic return is projected to be negative, resulting in a cost increase of about 0.06€ per kilogram of handled food product. The DC is the chain partner that would bear most of the cost of adoption, due to increased management overhead. Farmers would be likely to achieve economic benefits from the adoption of RPC packages.

As discouraging as these results may be, it appears that RPC usage within the FCC may have potential, especially if a system can be implemented such that more favourable values for the key factors prevail. To this end, further research is warranted, and future studies might investigate:

- the evaluation of further packaging solutions and distribution system configuration (e.g. materials, shape and dimensions in primary and secondary packages, facility location issues, vehicle routing, delivery frequency, etc.);
- the adoption of different impact assessment methods for packaging life cycle analysis in order to consider more impact categories (e.g. human health, resource preservation, ecosystem quality);
- the identification of unique economic KPIs through the conversion of environmental impacts into economic drivers (e.g. carbon taxes, environmental externalities, eco-costs) for a coherent single-objective analysis, and finally;
- the analysis of different food supply chains with different geographical networks layout.

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6.2 OPTIMISATION MODEL FOR DESIGN AND PLANNING OF THE AUTOMOTIVE CLOSED-LOOP SUPPLY CHAIN

6.2.1 Introduction

During the last years, greater attention is paid, worldwide, to the complex issues of the environmental safeguard and the natural resource preservation. In such a context, the manufacturers are identified as key players in achieving progress with minimal environmental impact, while the analysis of products' Reverse Logistics (RL), integrated to their direct supply chain, could be a valuable tool for limiting the impacts of end-of-life (EoL) products on the supply chain. The study of the Closed-Loop Supply Chain (CLSC) has widespread in several industrial sectors (e.g. Electric and Electronic Equipment (EEE)) and it represents a challenge for all production fields according to the regulations actually in force. Particularly, several studies show how the RL laws and the Environmental Conscious Manufacturing (ECM) guidelines can be successfully applied to one of the most relevant industrial sectors: the automotive industry.

In Europe, more than 12 million vehicles are sold every year and as many are dismantled. During 2011, in Italy, about 1 million vehicles "ended" their lives. The Italian ELV recovery network includes more than 1600 demolition centres, 350 spare parts markets and 50 shredding facilities. A system of such a complexity is naturally managed by dedicated regulations that impose obligations but also represent an incentive to an efficient use of the available resources of the Original Equipment Manufacturer (OEM).

The Directive 2000/53/EC offers the fundamental guidelines for the ELV recovery. Its aim is to promote recovery (95% by weight per vehicle by 2015), reuse and recycling (85% by weight per vehicle by 2015) of ELVs and it binds the OEM to be responsible to the final recovery and disposal, also in economic terms. As all EU countries must acknowledge the directive, several authors based their studies on its indications, proposing recovery network design strategies and developing mathematical optimisation models. The necessity to conform the recovery networks to the Directive guidelines involves the opportunity to assess the economic benefit of the remanufacturing of ELV components by OEM, with the aim to avoid the production of the same components by raw materials. Moreover, the relevance of the compliance of the theoretical RL networks to the geographical context involves the necessity to verify the applicability of the models in accordance with the context features.

In this study, after a literature review on the state-of-art (section 6.2.2), a reverse logistics network for the ELV recovery, recycle, disposal and reuse is presented. Based on a conceptual model, an innovative MILP (Mixed Integer Linear Programming) model for the strategic recovery network planning, mainly aimed at the minimisation of the logistics costs, is presented (section 6.2.3). The proposed model is verified through its adoption to an Italian realistic case study, after which, a sensitivity analysis, obtained by varying a set of parameters, is presented to demonstrate its applicability and to identify the data most affecting the model results (section 6.2.4). Conclusions (section 6.2.5) and authors' comments on further research (section 6.2.6) are, finally, presented.

6.2.2 Literature review

In the last years the study of supply chain management (SCM) has been largely widespread, concerning different topics and approaches.

Several authors focus their studies on the design, the management and the optimisation of the supply chain (SC). (Levi et al., 2011) define a conceptual framework for the development of a new approach for the modelling of the production and distribution system design, with the aim of introducing an integrated approach for the design and management of a supply chain. A model for SC and network design and optimisation, referring to the facility location and the vehicle routing problem is proposed by (Levi et al., 2011), in which some effective tools to support the strategic, tactical and operational decisions of managers are proposed. The performance evaluation of the SC is a further key topic in literature. In this context, the optimisation of the SC is studied from a simulation performance perspective by (Levi et al., 2011), who proposed a hybrid simulation tool to model and simulate several operating conditions in combination with different SC configuration. Recently, Allesina et al. (2009) conduct an analysis on innovative indices for the performance assessment in the SC context.

Recent literature studies highlight the operational research (OR) and the linear programming models as suitable tools for the supply chain planning. In the context of logistics network design, facility location models based on MILP problems represent a standard and frequently adopted approach. Several examples are quoted in literature, from basic problems such as the un-capacitated Facility Location problem, to even more complex models such as the multi-level and multi-commodity Capacitated Facility Location problem. For example Manzini et al. (2006) study the design of a distribution logistic network within the use of a MILP model.

Recently, several studies focus on the principles of RL. Meade et al. (2007) provide a review of the literature on RL, with particular reference to the research opportunity in this field. They also highlight the necessity of both an economic and environmental perspective in the RL field. Setaputra and Mukhopadhyay (2010) introduce a framework for research in RL, by dividing this issue into six research categories, with the aim to help the future researchers to focus their work in the appropriate area. For each category the authors provide an extensive literature overview. A review on the strategic perspective for RL network design is also conducted by Sheriff et al. (2012), developing a framework to classify the various parameters affecting the strategic decisions in RL. A further framework for supporting the design of RL systems is presented by Lau et al. (2004), who underline the necessity to consider the costs of the EoL products' management, with a particular application in a telecommunication services supply company.

Several authors propose decision modelling for RL systems. Particularly, Abdessalem et al. (2012) underline the cost savings for companies in RL practices and propose a multi-criteria decision making model, that consider technical, economic and environmental factors. A mathematical programming model for EoL products' recovery processes in reverse supply chain is reported in Xanthopoulos and Iakovou (2010), presenting a five-phased strategic methodological model for the development of the reverse supply chains and an optimisation models for RL.

With reference to the models in the field of RL, the structure of the recovery networks and the related strategic planning methodologies often start from the traditional distributive logistic perspectives that are, then, extended to incorporate the return flows. There are fewer proposals in the literature for a simultaneous forward and reverse network planning. A significant review of the most important network architectures and models is in Fleischmann (2001) and Krikke (2001). The former introduces an un-capacitated MILP problem that considers single-product flows among different facilities; the model includes the remanufacturing process as an option for the product recovery. Jayaraman et al. (2003) develop a single-period multi-tier MILP that considers EoL product transfers among demand points, collection centres and various treatment plants. Kusumastuti et al. (2004) present a multi-objective multi-period problem for products with modular structure; the model considers a pre-existent distributive logistics network and it determines the optimal number of facilities to use for the reverse recovery flow. Salema et al. (2007) propose a multi-product problem that considers the recovery demand unpredictability. Lu and Bostel (2007) develop a facility location problem that simultaneously optimises both the forward and the reverse product flows. The study demonstrates that the recovery flow has significant influence on the location of plants and the allocation of material streams. Chandiran and Surya Prakasa Rao (2008) use MILP tools to solve the facility location problem for the closed-loop supply chain network. This model is applied to the automobile battery manufacturer context.

The ELV sector is, also, studied by the literature. Some contributions focus on RL of automobile organisation. Ravi and Shankar (2012) propose a multi-criteria decision model, based on the Analytic Network Process (ANP) to evaluate alternatives of RL in the automobile industries. Ravi et al. (2011) present a system dynamics methodology to evaluate the market scenarios for the automotive RL.

Furthermore, noteworthy contributions to the development of specific optimising models for ELV recovery networks are present. All the below-mentioned references cannot neglect the Directive 2000/53/EC on end-of-life vehicles. Schultmann et al. (2006) face the problem of automotive waste recovery in Germany, proposing a closed loop network with used part reintegration in the new product production line. The formulated model is a Vehicle Routing variant aimed at total transport cost minimisation. Cruz-Rivera and Ertel (2009) study a Capacitated Facility Location problem for Mexican ELV recovery network planning. As for the majority of the ELV network optimisation models, transport costs are considered as the key driver for the network strategic planning. Essential sources for this study are the Mutha and Pokharel (2009), and Mansour and Zarei (2008) contributions. The former presents a multi-period model including the modular structure of the vehicle and the different parts to be dismantled and recycled/reused for each module and it consider the product/module/material flows allocation as a function of the total logistics cost. Mansour and Zarei (2008), on the other hand, refer to the emerging Iranian market and propose a multi-period multi-product model neglecting, however, the multi-modular vehicle structure and the reintegration of the used parts in the production line or their distribution to the spare part market.

The vast majority of the studied models are deterministic; the characteristics of uncertainty that make a reverse logistics network different to a forward one are, in the most of the cases, neglected. Furthermore, some of the above-mentioned studies neglect such parameters as the temporal dimension or the product modularity. Furthermore, in most of the analysed models, the cost minimisation functions prevails over the profit maximisation functions, in accordance with the decision to consider a limited number of entities, such as those used for ELV collection, treatment and disposal.

Finally, models on ELV recovery network planning specific to Italy are all but absent in literature. Some authors (Cagno et al., 2004; Gamberini et al., 2008, 2007; Manzini and Bortolini, 2012; Melacini et al., 2010) consider Italian WEEE matter, proposing innovative models for the cost optimisation of an Italian recovery network. About ELVs, some studies conducted at CIELI (Centro Italiano di Eccellenza sulla Logistica Integrata) and aimed at a dynamic simulator development ("PMARRLelv"), are reported (Cagno et al., 2004; Gamberini et al., 2008, 2007; Manzini and Bortolini, 2012; Melacini et al., 2010). As a consequence, this paper is aimed at presenting a model useful to plan an ELV recovery closed-loop network (in accordance with Cagno et al., 2004; Gamberini et al., 2008, 2007; Manzini and Bortolini, 2012; Melacini et al., 2010) and able to consider the economic benefit in remanufacturing ELV components by OEM.

6.2.3 Model formulation

In this section an innovative model for the automotive closed-loop network planning is presented. Its aim is to support the manufacturer strategic decision for the design of an efficient ELV recovery and treatment network organising the distribution system of new vehicles and ensuring competitive quality of service. Recommendations from the (Cagno et al., 2004; Gamberini et al., 2008, 2007; Manzini and Bortolini, 2012; Melacini et al., 2010) are included. In addition, the model considers recovery and remanufacturing of vehicle individual components, which can be either reused within new vehicle production system or sold as spare parts to the market.

6.2.4 Conceptual model

The model founds its basis on the Extended Producer Responsibility (EPR) concept. This concept, strengthen by the (Cagno et al., 2004; Gamberini et al., 2008, 2007; Manzini and Bortolini, 2012; Melacini et al., 2010) and (Michelini and Razzoli, 2010) enactment, forces the OEM to ensure that the last holder and/or owner can entrust the end-of life vehicle to an authorised treatment facility without any cost. As a direct consequence, the manufacturer has to attend to the whole incurred costs for collection and treatment processes. Therefore, the manufacturer has the interest to design, control and manage the whole treatment chain and to develop effective recovery techniques to reduce and minimise the costs, focusing in deep to the logistics issues (transport and storage). Recovery network planning, treatment facilities allocation and flow management allow to minimise costs but also to optimise the component reuse and to maximise the recovered value. Figure 6.2.1 presents the aforementioned reference network indicating the stages of the treatment process. Forward and reverse flows are simultaneously considered. The forward flow deals with the supply of new vehicles and spare parts from the OEM to their respective markets. An external component supplier refurnishes the manufacturer of new components that are used both for the production of new products and sold to the spare part market.

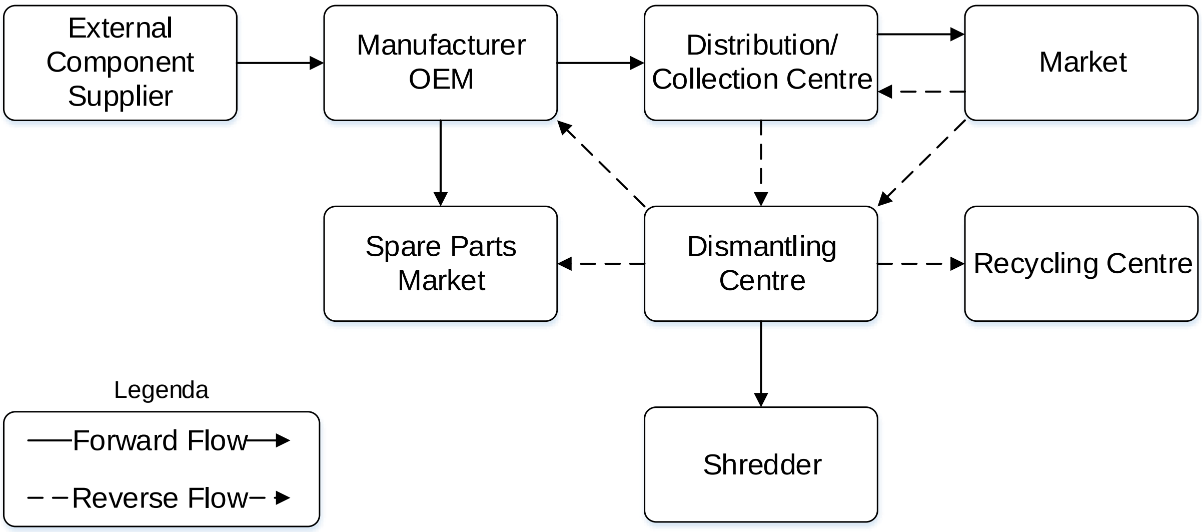

Figure 6.2.1 - The scheme of automotive closed-loop logistic network

In the reverse flow ELVs are collected, reclaimed and dismantled. The recyclable fraction is entrusted to a recycling plant while the automotive waste is delivered to a shredder. On the contrary, the reusable parts, after the remanufacturing/refurbishment operations, are used as raw components in the assembly of new cars or, even, sold as spare parts. According to their use, these modules are sent to a manufacturer facility or to the spare part market, respectively.

Within the proposed closed-loop supply chain, two nodes play a key role. The collection/distribution centres (C/D) represent one of the meeting points among the forward and the reverse flows. They have the dual role of collecting the vehicles at their end-of-life and to fulfil the distribution of new vehicles. Their location is a hot spot for the planning of the entire network. Equally important is the role of the dismantlers, in which the different fractions of ELVs are split. Their geographical position is reasonably considered a key point for the network optimisation. In fact, one of the model purposes is to establish a network of collection and treatment centres to recover the total estimated quantity of ELVs. At the same time, the model optimises the return of parts and components both to the spare parts market and to the manufacturers, on the basis of the remanufacturing cost minimisation and the return stream maximisation avoiding the recourse to external suppliers.

6.2.5 Presentation of the MILP model

The proposed MILP model aims to solve a multi-period, multi-echelon and multi-commodity capacitated location-allocation problem. In this section, the assumptions made for the model development and formulation are fully explained.

6.2.5.1 Hypotheses

The problem complexity entails fundamental working hypotheses funded both on the acquisition of data from the Italian context and on the observation of the currently widespread practices adopted in the major European countries. The proposed closed-loop network can be decomposed into two subnets: the former represents the automotive production and distribution network, the latter includes the ELV recovery network. The model aims to optimise the entire closed loop supply chain concerning the new vehicle flow and the ELV recovery stream. The existence of ELV collection/distribution centres is, also, considered. The main assumptions behind the model development are the following:

- The model considers a temporal dimension, i.e. time-dependence. It provides a time division of the planning horizon T into different sub-periods t
- A set M of market points m is assumed. It includes both the sources of ELVs and the final destinations of the new vehicles.
- At the end of their life, the vehicles can be still operable or not. In the former case the ELVs can be autonomously entrusted to a collection/distribution point or directly to a dismantler. In the latter case, higher shipment costs are expected due to the use of tow trucks.
- A set C of potential collection/distribution centres c is available. In case of substitution with a new vehicle, the customer can deliver its own ELV to each of these centres. Their most effective location is among the objects of the model.
- D is the set of the available dismantlers d. ELVs can be directly delivered from the customer point to one of such centres. It is assumed that all the ELVs delivered to the dismantlers are processed and disassembled in their fractions during the same time period.
- A subset W of the potential dismantlers d is affiliated to the OEM ($W \subseteq D$). For the dismantlers that belong to the set W, a fixed opening cost bearing on the OEM is assumed. Their location is among the purposes of the model. In case the OEM ships a vehicle to a non-affiliated dismantler, the former saves the fixed opening costs but it loses all the rights on delivered ELVs and, consequently, the possibility of reuse or sell of the reusable components.
- J is the set of the available shredders j. Their location is assumed as known. This assumption is due to the high fixed opening costs which do not justify a dedicated use for ELV shredding and by the scarcity of direct benefits given by raw materials within the vehicle manufacturing system.
- A set R of recycling plants r is considered. Their position is fixed. These facilities share the same hypotheses of the shredding centres.
- OEM can be assumed as a mere assembler of parts purchased from an external supplier or as a producer of both parts and vehicles. In the latter case, parts are produced by the OEM instead

of being purchased externally. Whatever the policy of in sourcing/outsourcing, there is no difference in the model application. Because of the uncertainty about the origin of new components, their delivery cost is neglected.

- In the model a vehicle modular structure is considered. Remanufacturing activities allow treating each vehicle module either as spare part or as component to be adopted to produce new vehicles. In the former case, higher unit revenues (selling price on spare parts market) and lower remanufacturing unit costs are assumed. In the latter case higher remanufacturing unit cost is expected because of the requested greater quality.
- The amount of the unmet manufacturer’s demand of reusable components is assumed to be covered by the external supplies. The manufacturer is, further, a potential supplier for the spare part market.
- The uncertainty on the quality of the ELVs delivered to the dismantling plants is overtaken by introducing an appropriate coefficient, in agreement with other studies (Mansour and Zarei, 2008). This factor determines both the percentage of the reusable ELV parts and the fraction that are sent to the shredding plants after the required operations of reclamation.
- After the shipment to the dismantling centre, the vehicle is reclaimed: hazardous fluids, dangerous and non-reusable materials are collected for recycling or disposal; reusable components are reworked and shipped to the replacement market or to the production system. Finally, the remains are allocated to the shredding facilities. The material that has to be landfill, because of its very low rate, is not considered. According to other studies (Mansour and Zarei, 2008), the flow of material sent to the shredding and recycling centres is considered fixed. Basing on the limits imposed, since 2006, by the respective EU Directive, the optimal material fluxes (ELVs to shredder and recycling centre) in terms of weight percentage (Table 6.2.1) are fixed.

Material stream by weight	**ELV with reusable parts**	**ELV without reusable parts**
Shredding Residue	2%	3%
Recyclable parts/materials	4%	3%
Reusable parts	56%	-
Hulk	38%	94%

Table 6.2.1 - Fixed material stream from ELV by weight

6.2.6 Detailed description of the MILP model

The indices, parameters, decisional variables, objective function and eligibility constraints of the model are listed and fully described in the sections below.

6.2.6.1 Model sets and indices

Table 6.2.2 introduces the model indices.

Set	Description
C	Available collection/distribution centres (index *c*)
D	Available dismantling centres (index *d*)
$W \subseteq D$	Affiliated dismantlers (index *d*)
S	Shredders (index *s*)
Z	Spare parts markets (index *z*)
R	Recycling centres (index *r*)
O	Manufacturers facilities (index *o*)
T	Scheduling time periods (index t=0…т)
P	Vehicle modules (index *p*)
M	Market (final costumer) points (index *m*)
V	ELV types (*v=1* for ELV with reusable parts; *v=2* for ELV without reusable parts)

Table 6.2.2 - Model sets and indices

6.2.6.2 Model variables

Model decisional variables are listed and described in Table 6.2.3.

Variable	Description
Y_d	=1 if dismantler *d* is open/served; =0 otherwise
Y_c	=1 if collection/distribution centre *c* is open; =0 otherwise
X_{cdt}	ELVs transported from C/D centre *c* to dismantler *d* during *t*
X_{oct}	New vehicles transported from manufacturer *o* to C/D centre *c* during *t*
X_{mct}	ELVs transported from market point *m* at C/D centre *c* during *t*
X_{cmt}	New vehicles transported from C/D centre *c* to market point *m* during *t*
X_{mdt}	ELVs transported from market point *m* at dismantler *d* during *t*
X_{dt}	Number of ELVs collected at dismantler *d* during *t*
W_{drt}	Material flow from dismantler *d* to recycling centre *r* during *t*
W_{dst}	Material flow from dismantler *d* to shredder *s* during *t*
Z_{pdzt}	Parts *p* transported from dismantler *d* to spare parts market *z* during *t*
Z_{pdot}	Parts *p* transported from dismantler *d* to manufacturer *o* during *t*
Z_{pot}	Demand of parts *p* by manufacturer *o* during *t*
Z_{pozt}	Parts *p* sent to spare parts market *z* from manufacturer *o* during *t*
Zs_{pdt}	Number of parts *p* stored at dismantler *d* during *t*
Zd_{pot}	Demand of parts *p* by manufacturer *o* during *t*

Table 6.2.3 - Model decision-making variables

6.2.6.3 Model parameters

The parameters considered in the model are presented in Table 6.2.4.

Parameter	Description
FC_c	Collection/distribution centre fixed opening cost
FC_d	Dismantler fixed opening cost
D_{cd}	Distance between collection/distribution centre c and dismantler d
D_{sd}	Distance between dismantler *d* and shredder *s*
D_{oc}	Distance between manufacturer *o* and collection/distribution centre *c*
D_{rd}	Distance between dismantler *d* and recycling centre *r*
D_{mc}	Distance between market point *m* and collection/distribution centre *c*
D_{zd}	Distance between dismantler *d* and spare parts market *z*
D_{od}	Distance between manufacturer *o* and dismantler *d*
D_{md}	Distance between market point *m* and dismantler *d*
D_{oz}	Distance between manufacturer *o* and spare parts market *z*
TCv	Vehicle/ELV transport unit variable cost
$TCtt$	ELV transport unit variable cost by using a tow truck
$TCttf$	ELV transport fixed cost by using a tow truck
$TCar$	ELV transport unit variable cost by using an auto rack
TCw	Unit transport cost by weight
ICp	Module storage cost per period
$Pbuy_p$	Part *p* purchase cost
Dpz_{pzt}	Demand of parts *p* by spare parts market *z* during *t*
Dnv_{mt}	Demand of new vehicles by market point *m* during *t*
RCz_p	Part *p* remanufacturing cost if the part is sent to spare parts markets
RCo_p	Part *p* remanufacturing cost if the part is sent to the OEM
$Delv_{mt}$	ELV that have to be taken-back from market point *m* during *t*
Ew	ELV weight
Pw_p	Part *p* weight
Pn_p	Part *p* quantity for each vehicle
$Psell_p$	Part *p* selling price at spare parts market
VC_d	Vehicle storage capacity at dismantler *d*
VC_c	Vehicle storage capacity at collection distribution centre *c*
PC_d	Part capacity at dismantler *d*
α_v	ELV type *v* weight percentage to be shredded
θ_v	ELV type *v* weight percentage to be recycled
β_v	Percentage of ELVs type *v*
ω_v	Percentage of operable ELVs
ε_{mt}	Percentage of ELV exchanged with a new vehicle at C/D centre
Nd_{mt}	=max$\{Delv_{mt} - Dnv_{mt}\ ; 0\}$
$Nelvd_{mt}$	= $Nelv_{mt}$- Nd_{mt}

Table 6.2.4 - Model parameters

6.2.6.4 Model objective function

The objective function is presented below. The function is split in members, from (1) to (20), in order to get the reading easier.

$$\min \quad \sum_{\boldsymbol{d \in W}} \boldsymbol{FC_d} \cdot \boldsymbol{Y_d} \tag{1}$$

$$+\sum_{c \in C} FC_c \cdot Y_c \tag{2}$$

$$+\sum_{o \in O} \sum_{c \in C} \sum_{t \in T} X_{oct} \cdot D_{oc} \cdot TCar \tag{3}$$

$$+\sum_{c \in C} \sum_{m \in M} \sum_{t \in T} X_{cmt} \cdot D_{mc} \cdot TCv \tag{4}$$

$$+\sum_{m \in M} \sum_{c \in C} \sum_{t \in T} X_{mct} \cdot D_{mc} \cdot TCv \cdot (\beta_1 \cdot \omega_1 + \ \beta_2 \cdot \omega_2) \tag{5}$$

$$+\sum_{m \in M} \sum_{c \in C} \sum_{t \in T} X_{mct} \cdot (D_{mc} \cdot TCtt + TCttf) \cdot [1 - (\beta_1 \cdot \omega_1 + \beta_2 \cdot \omega_2)] \tag{6}$$

$$+\sum_{m \in M} \sum_{d \in D} \sum_{t \in T} X_{mdt} \cdot D_{md} \cdot TCv \cdot (\beta_1 \cdot \omega_1 + \beta_2 \cdot \omega_2) \tag{7}$$

$$+\sum_{m \in M} \sum_{d \in D} \sum_{t \in T} X_{mdt} \cdot (D_{md} \cdot TCtt + TCttf) \cdot [1 - (\beta_1 \cdot \omega_1 + \beta_2 \cdot \omega_2)] \tag{8}$$

$$+\sum_{c \in C} \sum_{d \in D} \sum_{t \in T} X_{cdt} \cdot D_{cd} \cdot TCar \tag{9}$$

$$+\sum_{d \in D} \sum_{s \in S} \sum_{t \in T} W_{dst} \cdot D_{sd} \cdot TCw \tag{10}$$

$$+\sum_{d \in D} \sum_{r \in R} \sum_{t \in T} W_{drt} \cdot D_{rd} \cdot TCw \tag{11}$$

$$+\sum_{p \in P} \sum_{d \in W} \sum_{z \in Z} \sum_{t \in T} Z_{pdzt} \cdot D_{zd} \cdot Pw_p \cdot TCw \tag{12}$$

$$+\sum_{p \in P} \sum_{d \in W} \sum_{o \in O} \sum_{t \in T} Z_{pdot} \cdot D_{od} \cdot \ Pw_p \cdot TCw \tag{13}$$

$$+\sum_{p \in P} \sum_{o \in O} \sum_{z \in Z} \sum_{t \in T} Z_{pozt} \cdot D_{oz} \cdot \ Pw_p \cdot TCw \tag{14}$$

$$+\sum_{p \in P} \sum_{d \in W} \sum_{t \in T} ICp \ \cdot Zs_{pdt} \tag{15}$$

$$+\sum_{p \in P} \sum_{o \in O} \sum_{t \in T} Pbuy_p \cdot \ Z_{pot} \tag{16}$$

$$+\sum_{p \in P} \sum_{d \in W} \sum_{z \in Z} \sum_{t \in T} RCz_p \cdot \ Z_{pdzt} \tag{17}$$

$$+\sum_{p\in P}\sum_{d\in W}\sum_{o\in O}\sum_{t\in T} RCo_p \cdot Z_{pdot} \tag{18}$$

$$+\sum_{p\in P}\sum_{d\in W}\sum_{z\in Z}\sum_{t\in T} Psell_p \cdot Z_{pdzt} \tag{19}$$

$$+\sum_{p\in P}\sum_{o\in O}\sum_{z\in Z}\sum_{t\in T} Psell_p \cdot Z_{pozt} \tag{20}$$

The objective function members, i.e. the cost drivers of the model, are order and commented in the next sections.

6.2.6.4.1 Fixed opening costs

i. Fixed opening cost of the dismantling centre d

$$\sum_{d\in W} FC_d \cdot Y_d \tag{1}$$

ii. Fixed opening cost of collection/distribution centre c

$$\sum_{c\in C} FC_c \cdot Y_c \tag{2}$$

6.2.6.4.2 New vehicle transport costs

i. Transport cost for the shipment of new vehicles from the manufacturer o to the collection/distribution centre c. For this process, the use of auto rack is assumed.

$$\sum_{o\in O}\sum_{c\in C}\sum_{t\in T} X_{oct} \cdot D_{oc} \cdot TCar \tag{3}$$

ii. Transport cost for the shipment of new vehicles from the collection/distribution centre c to the market point m. These costs bear on final customers.

$$\sum_{c\in C}\sum_{m\in M}\sum_{t\in T} X_{cmt} \cdot D_{mc} \cdot TCv \tag{4}$$

6.2.6.4.3 ELV transport costs

The different ELV transport costs are defined below:

i. Operable ELVs from customer point to collection/distribution centre

$$\sum_{m\in M}\sum_{c\in C}\sum_{t\in T} X_{mct} \cdot D_{mc} \cdot TCv \cdot (\beta_1 \cdot \omega_1 + \beta_2 \cdot \omega_2) \tag{5}$$

ii. Inoperable ELVs from market to collection/distribution centre

$$\sum_{m\in M}\sum_{c\in C}\sum_{t\in T} X_{mct} \cdot (D_{mc} \cdot TCtt + TCttf) \cdot [1 - (\beta_1 \cdot \omega_1 + \beta_2 \cdot \omega_2)] \tag{6}$$

iii. Operable ELV from customer point to dismantler

$$\sum_{m\in M}\sum_{d\in D}\sum_{t\in T} X_{mdt} \cdot D_{md} \cdot TCv \cdot (\beta_1 \cdot \omega_1 + \beta_2 \cdot \omega_2) \tag{7}$$

iv. Inoperable ELV from market to dismantler

$$\sum_{m\in M}\sum_{d\in D}\sum_{t\in T} X_{mdt}\cdot(D_{md}\cdot TCtt + TCttf)\cdot[1-(\beta_1\cdot\omega_1+\beta_2\cdot\omega_2)] \tag{8}$$

v. Operable and inoperable ELVs from collection/distribution centre to dismantler

$$\sum_{c\in C}\sum_{d\in D}\sum_{t\in T} X_{cdt}\cdot D_{cd}\cdot TCar \tag{9}$$

Where $(\beta_1\cdot\omega_1 + \beta_2\cdot\omega_2)$ represents the amount of vehicles still operable at their EoL. For these vehicles an autonomous delivery to the dismantler is possible. For the other ELVs the use of tow truck, characterised by its fixed service cost, is required. Independently from the transport mode two destinations are available: collection/distribution centre and dismantler. In the first case, a subsequent delivery by auto rack to a dismantler is necessary.

6.2.6.4.4 ELV waste transport cost

After the dismantling phase, not reusable modules are dispatched to the shredders and the recycling plants.

i. Transport cost of vehicle parts to shredder

$$\sum_{d\in D}\sum_{s\in S}\sum_{t\in T} W_{dst}\cdot D_{sd}\cdot TCw \tag{10}$$

ii. Transport cost of vehicle parts to recycler

$$\sum_{d\in D}\sum_{r\in R}\sum_{t\in T} W_{drt}\cdot D_{rd}\cdot TCw \tag{11}$$

6.2.6.4.5 Vehicle module transport costs

Re-manufacturable and re-furbishable vehicle parts can be reused in new vehicle assembly or as spare parts. Manufacturer facility and spare part market are the correspondent destinations. In case of excessive remanufacturing costs or reusable parts scarcity, spare parts demand must be met by OEM. The transport costs associated to such vehicle part flows are listed below:

i. Parts delivery from dismantler to spare parts market

$$\sum_{p\in P}\sum_{d\in W}\sum_{z\in Z}\sum_{t\in T} Z_{pdzt}\cdot D_{zd}\cdot Pw_p\cdot TCw \tag{12}$$

ii. Transport of parts from dismantler to OEM

$$\sum_{p\in P}\sum_{d\in W}\sum_{o\in O}\sum_{t\in T} Z_{pdot}\cdot D_{od}\cdot Pw_p\cdot TCw \tag{13}$$

iii. Part supply of spare part market by manufacturer

$$\sum_{p\in P}\sum_{o\in O}\sum_{z\in Z}\sum_{t\in T} Z_{pozt}\cdot D_{oz}\cdot Pw_p\cdot TCw \tag{14}$$

6.2.6.4.6 Storage costs

The possibility of storing vehicle modules at the dismantler level allows the fluctuation of the part demand to be managed and the remanufactured part availability. As a consequence module storage costs are considered. Vehicle storage costs are, instead, neglected.

i. Storage cost of parts at dismantlers

$$\sum_{p\in P}\sum_{d\in W}\sum_{t\in T} ICp\cdot Zs_{pdt} \tag{15}$$

6.2.6.4.7 Purchase costs

The fraction of part demand from manufacturer for the production of new vehicles that cannot be satisfied by the reverse flow of reused parts has to be met by purchasing new modules by an external supplier. The associated supply costs are consequently considered.

i. Vehicle module purchasing costs

$$\sum_{p\in P}\sum_{o\in O}\sum_{t\in T} Pbuy_p \cdot Z_{pot} \tag{16}$$

6.2.6.4.8 Remanufacturing costs

Depending on the use of the reusable parts different remanufacturing costs are assumed.

i. Remanufacturing/refurbishment costs associated to the parts sold at spare part market

$$\sum_{p\in P}\sum_{d\in W}\sum_{z\in Z}\sum_{t\in T} RCz_p \cdot Z_{pdzt} \tag{17}$$

ii. Remanufacturing/refurbishment costs of parts used for the production of new vehicles

$$\sum_{p\in P}\sum_{d\in W}\sum_{o\in O}\sum_{t\in T} RCo_p \cdot Z_{pdot} \tag{18}$$

6.2.6.4.9 Revenues from part selling

The demand of spare parts can be met through the remanufacturing of reusable parts or through the manufacturing of new components. In the latter case OEM provide to fulfil the part demand of spare part market from an external supplier.

i. Revenues from selling remanufactured parts as spare parts

$$\sum_{p\in P}\sum_{d\in W}\sum_{z\in Z}\sum_{t\in T} Psell_p \cdot Z_{pdzt} \tag{19}$$

ii. Revenues from selling new component as spare parts

$$\sum_{p\in P}\sum_{o\in O}\sum_{z\in Z}\sum_{t\in T} Psell_p \cdot Z_{pozt} \tag{20}$$

6.2.6.5 Model constraints

The proposed model is subject to the following constraints:

6.2.6.5.1 Demand meeting constraints

i. For each market point and time period, if the amount of ELV to be recovered exceed the demand of new vehicles the surplus of end-of-life vehicles is shipped to a dismantling centre

$$Nd_{mt} \leq \sum_{d\in D} X_{mdt} \qquad \forall\, m \in M, t \in T \tag{21}$$

ii. Depending on the percentage of customers that replace their ELV with a new vehicle of the same brand, a fix quantity of ELV is directly shipped to a collection/distribution centre, which, in this case, accomplish both its functions

$$Nelvd_{mt} \cdot \varepsilon_{mt} \leq \sum_{c\in C} X_{mct} \qquad \forall\, m \in M, t \in T \tag{22}$$

iii. During each period the ELV take-back demand from the market has to be met by the vehicles shipped to the collection/distribution centres or directly to the dismantlers

$$\sum_{c\in C} X_{mct} + \sum_{d\in D} X_{mdt} = Delv_{mt} \qquad \forall\, m \in M, t \in T \tag{23}$$

iv. The ELV material amount addressed to shredding has to respect the defined allocation

$$\sum_{s\in S} W_{dst} = \sum_{v\in V} \alpha_v \cdot Ew \cdot \beta_v \ast X_{dt} \qquad \forall\, d \in D, t \in T \tag{24}$$

v. Recyclable material from ELV is transported to the recycling centres

$$\sum_{r\in R} W_{drt} = \sum_{v\in V} \theta_v \cdot Ew \cdot \beta_v \cdot X_{dt} \qquad \forall\, d \in D, t \in T \tag{25}$$

vi. The amount of new vehicles stored at the collection/distribution centres has to be strictly necessary to satisfy the correspondent market demand.

$$Dnv_{mt} = \sum_{c\in C} X_{mct} \qquad \forall\, m \in M, t \in T \tag{26}$$

vii. During each period, the OEM has to meet the market demand of new vehicles by delivering the required number of vehicles to its point of sale.

$$\sum_{m\in M} Dnv_{mt} = \sum_{o\in O} \sum_{c\in C} X_{oct} \qquad \forall\, t \in T \tag{27}$$

viii. The vehicle component demand by manufacturer directly depends on the amount of products to be assembled and on the new vehicle demand from the market.

$$Zd_{pot} = \sum_{m\in M} Dnv_{mt} \cdot Pn_p \qquad \forall\, p \in P, o \in O, t \in T \tag{28}$$

ix. For each period, the manufacturer need of parts has to be fulfilled either by the supply of reusable parts from agreed dismantlers or by purchasing new components from an external supplier.

$$Zd_{pot} + \sum_{z\in Z} Z_{pozt} = \sum_{d\epsilon W} Z_{pdot} + Z_{pot} \qquad \forall\, p \in P, o \in O, t \in T \tag{29}$$

x. A similar constraint regulates the demand meeting of components by spare part markets

$$Dpz_{pzt} = \sum_{d\epsilon W} Z_{pdzt} + \sum_{o\in O} Z_{pozt} \qquad \forall\, p \in P, z \in Z, t \in T \tag{30}$$

6.2.6.5.2 Flow conservation

i. For each period and collection/distribution centre the amount of new sold vehicles has to correspond to the vehicle supplied by the OEM

$$\sum_{m\in M} X_{cmt} = \sum_{o\in O} X_{oct} \qquad \forall\, c \in C, t \in T \tag{31}$$

ii. At the end of each period, the amount of ELV disposed by the market must be collected at dismantled

$$X_{dt} = \sum_{c\in C} X_{cdt} + \sum_{m\in M} X_{mdt} \qquad \forall\, d \in D, t \in T \tag{32}$$

iii. For each collection/distribution centre and time period, the quantity of the collected ELVs must be delivered to dismantlers

$$\sum_{d\in D} X_{cdt} = \sum_{m\in M} X_{mct} \qquad \forall\, c \in C, t \in T \tag{33}$$

iv. For each period t and for the dismantlers affiliated to OEM, only, the part output flow must respect the availability of parts, which is defined by the number of ELVs collected during the time period t and the amount of parts stored at the end of the previous period.

$$\sum_{z\in Z} Z_{pdzt} + \sum_{o\in O} Z_{pdot} \leq (\beta_1 \cdot X_{dt} \cdot Pn_p) + Zs_{pd(t-1)} \quad \forall\, p \in P, d \in W, t \in T \text{ and } T > 0 \qquad (34)$$

v. For each dismantler, the amount of stored parts at the end of each period is defined by the inflow of components from the dismantled ELVs and the stock level due to the component surplus of the previous period

$$Zs_{pdt} = Zs_{pd(t-1)} + (\beta_1 \cdot X_{dt} \cdot Pn_p) - \sum_{z\in Z} Z_{pdzt} - \sum_{o\in O} Z_{pdot} \quad \forall\, p \in P, d \in W, t \in T \text{ and } T > 0 \qquad (35)$$

6.2.6.5.3 Capacity limit

i. The maximum collection/distribution centre capacity has to be respected;

$$\sum_{o\in O} X_{oct} + \sum_{m\in M} X_{mct} \leq VC_c \cdot Y_c \qquad \forall\, c \in C, t \in T \qquad (36)$$

ii. The maximum dismantling centre capacity, in vehicles, cannot be exceeded;

$$X_{dt} \leq VC_d \cdot Y_d \qquad \forall\, d \in D, t \in T \qquad (37)$$

iii. For each dismantler, the maximum number of storable parts is defined by its maximum storage capacity

$$Zs_{pdt} \leq PC_d \cdot Y_d \qquad \forall\, p \in P, d \in D, t \in T \qquad (38)$$

iv. At the beginning of the first period, there are no parts stored at the dismantler level.

$$Zs_{pd(t=0)} = 0 \qquad \forall\, p \in P, d \in W \qquad (39)$$

v. Manufacturers cannot manage non-affiliated dismantler activity. Their stock level at the end of each period is assumed to be null.

$$Zs_{pdt} = 0 \qquad \forall\, p \in P, d \notin W, t \in T \qquad (40)$$

6.2.6.5.4 Variable feasibility

i. $Y_d, Y_c \in \{0,1\}$ (41)

ii. all the other variables ≥ 0 and integer (42)

6.2.7 Model implementation and testing

In order to validate the logical scheme proposed in previous Figure 6.2.1 and to measure the computational performance, the proposed mathematical model is solved adopting an algebraic modelling language (AMPL-A Mathematical Programming Language). Gurobi for AMPL v. 6.0.0, on an Intel® Core™ 2quad with CPU Q6600 2.40GHz and 3.24 GB RAM, is chosen as the computational solver. With the aim of testing the potential and the accuracy of the proposed model, its application on an Italian realistic case study is proposed in the following. In addition, the results of an extended sensitivity analysis are shown and properly commented.

6.2.8 Case study

In this section, the application of the proposed model to a realistic Italian case study is reported. A vehicle closed-loop supply chain for the Emilia-Romagna region (Northern Italy) is designed by the appliance of the previously introduced mathematical MILP model.

The starting case study features and hypotheses are following listed: four scheduling periods, each one representing a quarter of year, are considered; the closed-loop supply chain is crossed by a standard representative utility car in which eleven components are potentially re-manufacturable; 18,400 and 14,000 are the number of representative vehicles respectively sold and retired in the considered geographic area every year; a single manufacturer facility located in Torino (Italy) is assumed; nine are the potential collection/distribution centres, one for each regional province as well as nine is the number of the available dismantlers, all of them are affiliated to the OEM; two shredders, one recycling plant and five spare part markets are located within the regional territory; nine market points are located in each province barycentre. This application case represents a scenario, starting from which the sensitivity analysis is carried out. It is called Scenario 0 in the following. Figure 6.2.2 represented the Scenario 0 before solving the model.

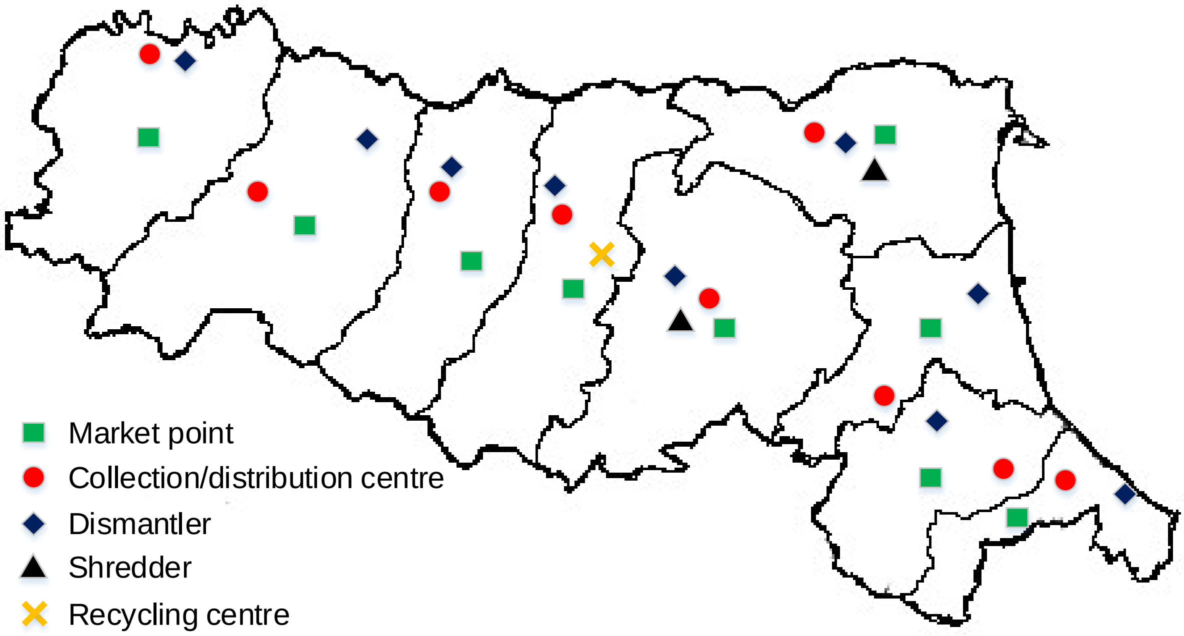

Figure 6.2.2 - Scenario 0: centre locations before model solving

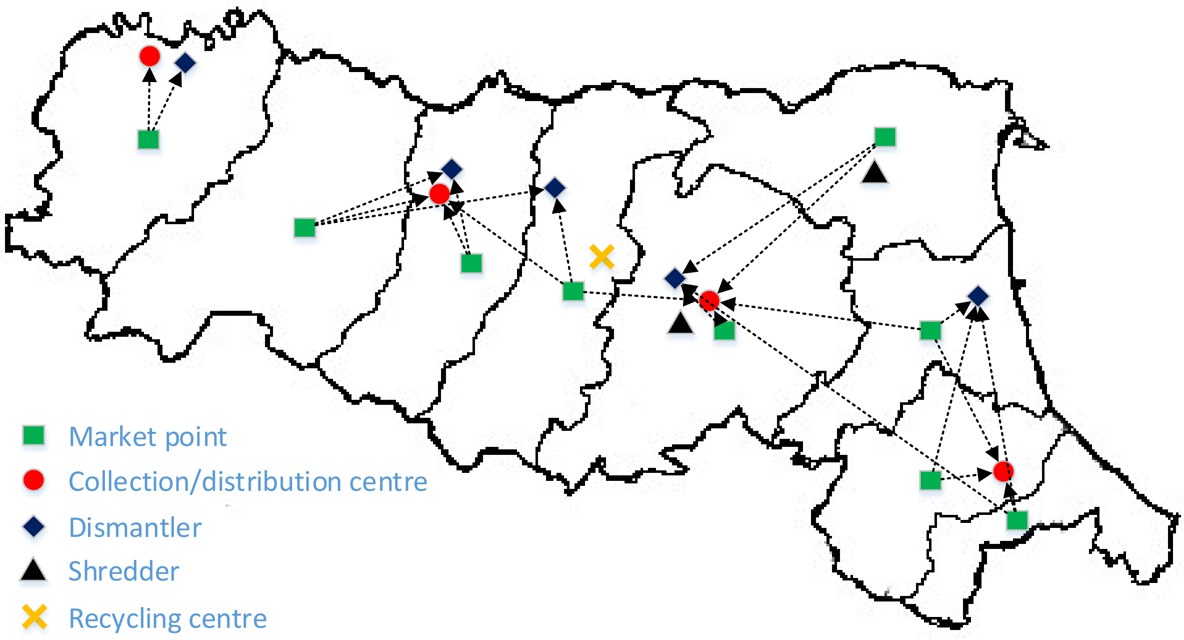

Figure 6.2.3 - Scenario 0: centre location and ELV collection flow allocation after model solving

Scenario 0 solution highlights that only four out of nine collection/distribution centres and five out of nine dismantlers are activated in the proposed closed-loop supply chain. Figure 6.2.3 shows the locations of such facilities crossed by the vehicle closed-loop supply chain and the ELV collection flows from customer points to collection/distribution centres and dismantlers.

Some other interesting results are presented in Table 6.2.5, in which the network costs, revenues from spare parts sale and objective function value are listed.

Scenario 0 results	**Value**	**Percentage on total costs**
Number of open collection/distribution centres	4 (out of 9)	-
Number of open dismantlers	5 (out of 9)	-
Annual transport costs	€ 2,972,850	4.18%
Annual fixed costs	€ 1,350,000	1.90%
Annual storage costs	€ 24,750	0.03%
Annual part purchasing costs	€ 56,703,500	79.66%
Annual remanuf. costs of parts for spare parts market	€ 7,603,330	10.68%
Annual remanuf. costs of parts for new vehicle prod.	€ 2,526,540	3.55%
Annual total network cost	€ 71,180,970	100.00%
Annual revenues from spare parts selling	€ 32,292,000	-
Objective function value	€ 38,888,900	-

Table 6.2.5 - Scenario 0 results

The number of hypothesised centres is sufficient to meet the ELV recovery demand and new vehicles distribution. Moreover, the logistic costs (transport, facility opening, storage) appear exiguous (4.18% of the total network cost) if compared to the external supply costs (79.66%) and the remanufacturing costs (14.33%). Referring to these last results, a strong dependence of the model outcomes from the remanufacturing unit cost and part purchasing price is expected. Remanufactured parts are split and sent either to spare part markets or to OEM facility, depending on the most profitable solution. About the 20% of the reusable modules is utilised for new vehicle production, while the remainder produces more than 86% of the OEM revenues from spare part sale. As a consequence, the contribution of the reusable parts in new vehicle manufacturing is almost negligible. Only 6.84% of the new vehicle components is represented by remanufactured ELV modules. These results are coherent with the ELV availability in the considered area, with the supposed market demand of new vehicles, with the general higher profitability in selling parts rather than assembly them in new cars, with the distance between customers, with the spare parts markets and, finally, with the OEM facility.

In order to better understand the model behaviour and to identify the parameters that most affect the results a sensitivity analysis is now discussed.

6.2.8.1 Sensitivity analysis

In the proposed sensitivity analysis seven different scenarios are computed by varying an equal number of parameter sets, i.e. fixed opening/service costs of collection/distribution centres and affiliated dismantlers, part remanufacturing unit costs, part purchasing unit price, transport unit costs, spare parts demand, market demand of new vehicles, ELV recovery demand. For each scenario, the values of the set of parameters are varied from the values assumed in Scenario 0, in a range -30%, +30%. Table 6.1.6 shows the variation of the model objective function value in response to the variation of the parameters.

Within the group of cost parameters, part purchasing unit costs represent one of the most influencing values. However, its variation does not generate any modification to the network structure. The low sensitivity of the model to the variations of the fixed facility opening and transport unit costs demonstrates the low relevance of logistic costs on the model decisions. On the contrary, the fluctuation of the demand parameters implies significant changes in the location of the network nodes. The increase of the ELV recovery demand increases the number of the required dismantlers and collection/distribution centres as well as more collection/distribution centres are served in case of growing demand for new vehicles. A further collection/distribution centres and a further dismantler are necessary in case of 30% growth of the ELV recovery demand. Two additional collection/distribution centres are open in response to a 30% increase of the market new vehicle demand. An inverse trend occurs between the ELV recovery demand and the model objective function values. The availability of a greater amount of ELV reusable parts introduces important savings in the external component purchase.

	Parameter variation			
	-30%	-15%	+15%	+30%
Parameters	**Objective function variation**			
Fixed opening costs	-1.04%	-0.52%	+0.52%	+1.04%
Part remanufacturing unit costs	-7.77%	-3.87%	+3.96%	+7.84%
Part purchasing unit costs	-43.72%	-21.84%	+21.88%	+43.77%
Transport unit costs	-2.29%	-1.15%	+1.15%	+2.29%
Spare parts demand	+10.44%	+5.13%	-5.07%	-10.00%
Market demand of new vehicles	-47.08%	-23.62%	+23.46%	+47.06%
ELV recovery demand	+24.91%	+12.46%	-12.46%	-24.91%

Table 6.2.6 - Objective function sensitivity estimation by parameter values variation

Further scenarios (D1, D2, and D3 in the following) are generated by introducing, increasingly, non-affiliated dismantlers in the case study area. As explained in section 6.2.5.1, the involvement of non-affiliated dismantlers implicates cost savings for OEM but, at the same time, it generates the loss of the possibility to use the ELV components. Aim of these scenarios is the evaluation of the economic benefit for OEM in getting served by affiliated dismantlers. Three scenarios with different numbers of non-affiliated dismantlers are proposed. Three out of nine dismantlers are non-affiliated in D1 scenario, six out of nine in D2 scenario, while all the dismantlers are non-affiliated in D3 scenario. Results are compared to scenario 0. Particularly, in D3 scenario, a 28% increase of costs for OEM is experienced. The 42% fixed cost savings does not counterbalance the loss of savings given by the reuse of ELV components. This disadvantage decreases to the reduction of the number of available external dismantlers. So, from the results of model computation emerges the convenience for the OEM to provide for a network of affiliated dismantling facilities.

6.2.9 Summary and conclusions

In this study an automotive closed-loop supply chain network is proposed, in addition to a MILP model developed for its optimisation, with the aim to be a valid support for the manufacturer strategic decisions in the automotive context.

The literature survey reports a synthesis of fundamental studies related to the RL context, some of them specifically concerning the ELV recovery issue and sharing, as starting point, the (Mansour and Zarei, 2008)53/EC and the EPR concept. In this study, an innovative structure for automotive closed-loop supply chain network is proposed. Consequently, a MILP model for network design optimisation is presented. Its strength consists in the evaluation of a potential ELV recovery scenario that considers both the current procedures and the associated regulations actually in force. The proposed network includes a set of centres and facilities, which are crossed both by new and ELV. It entails an extended model objective function, aimed not only at logistics global costs minimisation (most of which bearing on the OEM), but also focused on maximising the manufacturer revenues, by spare parts sale, and savings, through the reuse of ELV remanufactured components. In this model a large number of entities involved in the ELV recovery (e.g. customers, manufacturer, external component supplier, etc.) are included. Vehicle modularity, limitations in facility capacity (in vehicles and modules) and new and ELV demand fluctuation are carefully considered.

The presented MILP model is tested on a realistic case study based on the Emilia-Romagna region closed-loop supply chain for a single manufacturer. Results point out the high impact of the remanufacturing costs and the purchase price (or production cost) of vehicle parts. Logistic costs appear exiguous if compared to the network global cost. The sensitivity analysis applied to the model confirms the low impact of transport, storage and fixed facility costs. Negligible network structural modifications are introduced by the variation of logistic unit costs. On the contrary, the most considerable costs are related to the external supplies and remanufacturing operations. These drivers are, in addition to the spare part sale price, the key factors for an automotive closed-loop network development. Finally, the economic benefit for the manufacturer in providing for a controlled ELV recovery system is assessed by introducing, in the analysed case study, a set of external dismantlers. Model results demonstrate the effectiveness of an automotive closed-loop supply chain directly controlled by OEMs.

6.2.10 Discussion and future research

This section presents a discussion on the possible evolutions of the herein presented study and suggests potential improvements that are related to the following issues: network and model complexity; model scope and logistic implications; model objective.

6.2.10.1 Network and model complexity

The conceptual network that underlies the proposed optimisation model exemplifies the complexity of the supply network on which the automobile industry relies and considers the nodes and processes that most affect an automotive closed-loop supply chain design. However, in order to provide a more detailed planning tool, the boundaries of the analysed system can be expanded to consider additional nodes (e.g. producers of raw materials, landfills, incinerators), processes (e.g. recovery of raw materials, processing of the ASR) and transportation systems (e.g. maritime and rail transport in case long distances have to be covered).

Similarly, the model can also achieve a further degree of complexity. A modification of the model, from mono-product to multi-product, could ensure a greater degree of closeness between model and reality. Moreover, the inclusion of a set of external component suppliers among the problem parameters could ensure an increase in the reliability of the vehicle module flow allocation.

6.2.10.2 Model scope and logistic implications

With regard to the scope of the presented optimisation model, in this study an example of a small geographical network is presented. It is certainly desirable to expand the boundaries of the supply network and test the model against greater geographical distances. In fact, the effects of the increasing off shoring, of both market and production, may affect the convenience of the entire reverse flow of used components from the market to the OEM. The task of the model is to identify the boundaries beyond which a closed-loop system may involve economic disadvantages for the OEM. It might be interesting to apply the planning model to a case study of European dimensions, e.g. a European OEM in the EU27 market, which is subject to Directive 2000/53/EC, but also a case study of continental dimensions, with extra-EU flows of components. A so extensive analysis brings to two main evaluations. Firstly, the estimation of the economic benefits for the OEMs given by the remanufacturing and reuse of ELV components in a large influence area. Secondly, it could be shown the supply chain management implications for the OEM in terms of facility locations and flow allocation in a network characterised by long distances, high number of actors involved and, eventually, significant dispersion degree of the market points.

6.2.10.3 Model objective

Finally, the proposed model focuses on the minimisation of the network economic cost, in particular that one bearing on the OEMs, but it neglects the environmental impact caused by the logistic choices. Particularly, if the closed loop network is thought with the purpose to minimise the environmental burden introduced by ELV, there is no explicit demonstration that the remanufacturing and reuse of ELV components leads to the reduction of the impact associated to vehicle life cycle. One of the potential improvements on this study is the evaluation, “ex post” of the environmental burden associated to different network planning. As an alternative, the model can be modified to include the environmental impact objective function close to the cost objective function.

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7 MULTI-CRITERIA DECISION ANALYSIS (MCDA)

7.1 MCDA FOR SUSTAINABLE DESIGN DECISION-MAKING

As discussed in Chapter 3 and demonstrated in Chapter 6, sustainable design requires the identification and selection of options from a set of alternatives by balancing economic, environmental and social aspects of certain design choices. As well as for sustainable design and development, Design for Environment and Green Supply Chain Network Design and Planning involve the need to identify and manage economic and environmental trade-offs. Such a problem entails quite complex decision-making process, which can be affected by several difficulties. For example, decision-making in the context of Green Supply Chain Management involves a number of different stakeholders who have conflicting interests and, often, conflicting objectives. In addition, decision-makers may have to consider and compare a number of possible alternatives using a large number and type of decision criteria. Sometimes it may be unclear what the alternatives are or which decision criteria are relevant for a particular decision-making problem. In order to ease the decision-making processes, taking a structured approach to problem solving is recommended. Multiple Criteria Decision Analysis (MCDA) provides assistance in sustainability decision-making. MCDA helps decision-makers in the organisation and synthesis of information, in understanding the problem, in the identification of decision-making criteria and in the selection of the best solution. Therefore, MCDA is a tool that can help decision-makers to make good or optimal decisions rather than prescribing how decisions should be made.

MCDA enables effective management of subjectivity rooted in decision-makers' value system. Values influence each stage of the decision-making process, from trying to understand the problem to choosing the right solution. Failure to acknowledge subjectivity and to respect different value positions is usually a cause of conflict between different stakeholders. This is particularly important in the decision-making contexts related to sustainable development, where multiple decision-makers often hold opposing views on a particular issue or problem.

Examples of MCDA techniques are multi-objective optimisation, goal programming, value-based and outranking approaches. These techniques are briefly discussed in the following section.

7.2 MCDA APPLICATION AND TECHNIQUES

Azapagic and Perdan (2005a, 2005b) present a structured framework for providing decision-makers with a systematic guidance based on the use of MCDA. This framework considers a problem-solving approach in three steps: problem structuring, problem analysis and problem resolution. Problem structuring includes the identification of stakeholders and indicators relevant for a particular decision problem, where indicators are used as decision criteria for the identification and choice of feasible options. Then, in problem analysis step, decision makers articulate their preferences for different decision criteria by using MCDA techniques, such as multi-objective optimisation, goal programming, value-based and outranking approaches. Finally, after having compared and evaluated the alternatives, in problem resolution decision-makers make the final choice of the best alternative. This section deepens the problem analysis step and presents a panel of MCDA methods.

7.2.1 Decision-making problem analysis through MCDA techniques

Most MCDA methods are based on the assumption that decision-makers strive to make rational choices that maximise their satisfaction, and they do it in a structured and logical manner. MCDA methods use mathematical logic to develop systems to rank alternative options.

MCDA techniques can be classified into two main groups:

- Programming methods. This category includes:
    - Optimisation approaches, e.g. Multi-Objective Optimisation (MOO);
    - Satisficing approaches, e.g. Goal Programming (GP).
- Multi-attribute decision analysis (MADA). This group contains
    - Elementary;
    - Value-based;
    - Outranking approaches.

7.2.1.1 Programming methods

7.2.1.1.1 Multi-Objective Optimisation techniques

In multi-objective optimisation (MOO) methods, the decision problem is formulated by a mathematical model, which is then simultaneously optimised, maximised or minimised, on a number of decision criteria, i.e. objectives, subject to a set of constraints. Multi-objective optimisation problems can be formulated as Linear Programming (LP), Non-linear Programming (NLP), Mixed Integer Linear Programming (MILP) or Mixed Integer Non-linear Programming (MINLP) problems. The optimisation process yields a range of Pareto optimal solutions. For each Pareto optimal solution, no one alternative is better on all criteria than any other alternative. One of the main characteristics, and advantages, of the MOO approaches is that they do not require “a priori” articulation of preferences, so that the whole set of optimum solutions can be explored in the post-optimal analysis.

In case decision-makers' preferences want to be considered prior to or during the optimisation process, decision-makers specify the weights that reflect the relative importance of any objective functions. The weights are then used to aggregate the objective functions into a single function so that the above MOO problem reduces to a single objective optimisation problem. However, for a specified set of weights of importance, a single-objective problem generates one single solution, which may be optimal but perhaps not acceptable to decision-makers.

On the contrary, MOO generates a range of alternatives so that decision-makers can explore the trade-offs among them. This is particularly important in situations with multiple decision-makers, as trading-off can show explicitly what can be gained and what lost by each alternative and so help decision-makers to compromise and resolve any disputes. This the reason why MOO methods are suitable for decision support in Design for Environment and Green Supply Chain Design problems.

The main limit to MOO approaches is that they require specialist knowledge and mathematical modelling so that their use will depend on the problem complexity and awareness. Furthermore, the number of alternatives obtained in MOO can still be too large for decision-makers to be able to choose the preferred one, particularly where a large number of criteria need to be considered, as is often the case in decision-making for sustainability. Therefore, to guide the choice of the best solution, MOO will normally have to be followed by a post-optimal elicitation and aggregation of preferences by using, for example, multi-attribute decision analysis methods. In that case, MOO is not used a tool for the choice of best solution but as a pre-screening method for the elimination of non-optimal alternatives

7.2.1.1.2 'Satisficing' approaches

Methods in this category are based on the calculation of an ideal solution, unattainable in the real context, and definition of a maximum acceptable distance from that solution. Different mathematical methods can be applied to find the feasible solution that is closest to the ideal solution. Goal Programming (GP) is probably the most used approach in this category of methods. GP requires decision-makers to set goals for each objective that they want to attain. A preferred solution is then defined as the one that minimises the deviations from the set goals.

A disadvantage in the use of this method is that it may be difficult for decision-makers to define meaningful goals a priori. Instead, by using an interactive approach for identification of goals, an initial set of goals can be specified for each criterion, to find a starting GP solution. This solution then serves as a starting point for modifying the goals and generating the next solutions and so on, until the decision-maker is satisfied. Like MOO, GP and the related methods can also be used for screening purposes in either operational or strategic types of decisions. However, it may be difficult for decision-makers to identify goals or reference levels that will lead to truly 'satisfying' options. Such limitations must be considered whether the 'satisficing' approaches are used as a tool for developing a final decision choice.

7.2.1.2 MADA techniques

Three general types of MADA techniques are distinguished in MCDA literature: elementary; value- and utility-based; and outranking.

Elementary methods do not require explicit evaluation of quantitative trade-offs between criteria. The value-based and outranking approaches, on the other hand, assume that decision-makers are able to articulate and quantify their preferences. To facilitate this process, the value-based approaches use scores and weights to model decision-maker's preference in the form of value or utility function, while outranking methods use outranking relations in a pairwise comparison of criteria.

Examples of elementary methods are: lexicographic method; conjunctive and disjunctive methods; Maxmin and Maximax methods. Value function methods are Multi-attribute value theory (MAVT); Multi-attribute utility theory (MAUT); and Analytic hierarchy process (AHP). Outranking methods include the family ELECTRE, PROMETHEE and MELCHIOR. Further details are reported in Azapagic and Perdan (2005b)

7.2.2 Characteristics of MCDA techniques

In addition to elicitation of preferences and the models for their preferences the MCDA methods also differ with respect to:

- Type of decision criteria;
- Type and number of alternatives;
- Approach to compensation among decision criteria; and
- Preference ordering.

These factors will influence the decision-making process and its outcome, so that the main challenge is to choose the MCDA method that is most appropriate for a particular decision-making situation.

7.2.2.1 Decision criteria

In multiple criteria analysis the following four types of criteria are used:

- Cardinal or measurable criterion: enables preferential comparison of intervals of the evaluation scale.
- Ordinal or qualitative criterion: defines only an order of alternatives, thus the evaluation scale is discrete.
- Probabilistic criterion: used to describe the level of uncertainty in the outcome of an alternative.
- Fuzzy criterion: describes imprecise and ambiguous information by using the membership function to indicate to what extent a certain statement is true.

Sustainability indicators can be represented in any of the above forms. All programming and most value-based approaches use cardinal information, while the elementary and outranking methods can deal with ordinal, cardinal or mixed type of information.

7.2.2.2 Alternatives

Multi Criteria Decision Making techniques are often distinguished according to the problems they address with respect to the number and type of alternatives decision-makers have to choose from so that they are classified as:

- Continuous problems with an infinite number of alternatives;
- Discrete problems with a finite set of alternative options.

Problems addressed by programming methods are considered continuous, while those analysed by MADA are considered discrete. Before multi-objective optimisation (MOO) or goal programming (GP) is performed, there is an infinite number of possible alternatives. However, the main aim of both MOO and GP is to generate a set of large but finite and discrete alternatives. As already noted, in MOO, they are known as Pareto optimal or efficient solutions, while in GP they are described as solutions that best satisfy some pre-specified goal. In both cases, the decision-maker is then faced with the problem of identifying the preferred out of a number of solutions so that the problem in effect is that of choosing from a set of discrete rather than continuous alternatives. Therefore, programming techniques can be used as a screening tool to reduce an infinite number of alternatives to a smaller, discrete set of options.

7.2.2.3 Compensation

With respect to assessment of the performance in one criterion relative to another, the MCDA methods can either be:

- Compensatory: a bad performance on one criterion can be compensated by a good performance on another;
- Non-compensatory: no compensation is accepted between the different criteria whereby decision-makers consider that all criteria are important enough to refuse any kind of compensation or trade-off;
- Partially compensatory: some kind of compensation is accepted between the different criteria; the major problem here is to evaluate the degree of compensation for each criterion.

The choice of the MCDA technique with respect to compensation is particularly important in the context of Green Supply Chain Management, because the question of compensation raises a question on the feasibility of a solution that, for example, compensates good economic benefits with poor environmental performance, or vice versa. Answering this question is also part of the decision-making process, particularly in multiple decision-maker situations and it should be explored thoroughly by the stakeholders before an MCDA method is chosen.

7.2.2.4 Preference ordering

As most MCDA methods use decision-makers' preferences to identify the best alternative, the choice of appropriate model for preference ordering is fundamental for decision-making. This is particularly important in the context of sustainability decision-making because of the multiplicity of decision criteria and interest groups, so that the choice of the MCDA technique must take into account how strongly decision-makers feel about different criteria and alternatives and what is the most meaningful approach to ranking the alternatives

7.2.3 Choice of MCDA method

The choice of the right MCDA method depends on many factors: problem complexity; ease of use; transparency of the logic of the method to decision-makers; ambiguity regarding interpretation of inputs required from decision-makers; data requirements; time and human resource requirements for the analysis; software availability. In addition to these general parameters, in Design for Environment and Green Supply Chain Network Design, there are particular characteristics of MCDA methods that need to be taken into accounting for the selection and use of a decision-making support technique. The choice of the most suitable MCDA method in sustainability decision-making is not an easy task because none of the methods is ideal, so that sometimes a combination of approaches may be necessary. Multi-attribute decision analysis methods approaches appear to be most widely used in strategic decision situations, while MOO and GP have found wider application in operational types of decision.

Multi-objective optimisation does not require the statement of preferences and considers all decision criteria to be of equal importance. It is suitable for screening purposes to separate out non-efficient from efficient solutions, where the choice among the latter can then be facilitated by any of the Multi-Attribute methods. MOO is used in corporate decision-making for operational types of decision. One of the advantages of MOO is that it provides decision-makers with a range of Pareto efficient alternatives so that the trade-offs between them can be fully explored.

Goal programming and reference point methods are suitable for situations in which decision- makers find it difficult to express trade-offs or importance weights, but are able to identify the aspirations or goals for the outcomes of alternatives that they would find satisfying. Like MOO, these methods are also more suited for use in early stages of problem analysis, to generate a short-list of alternatives for more detailed evaluation in later stages of the analysis.

7.3 REFERENCES

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8 ENVIRONMENTAL AND ECONOMIC MULTI-OBJECTIVE OPTIMISATION

8.1 MULTI-OBJECTIVE OPTIMISATION MODEL FOR FRESH FOOD SUPPLY CHAIN DESIGN AND PLANNING

8.1.1 Introduction

Sustainable supply chain management (SSCM) is an increasingly important topic as companies respond more and more to internal and external pressures from stakeholders, policymakers, consumers, governments, and organisations dedicated to environmental, social and corporate responsibility (Ageron et al., 2012). SSCM is defined as “the consideration of environmental, social and economic performance in the management of information, material and capital flow” (Seuring and Müller, 2008). Such a global definition includes the concept of Green Supply Chain Management (GSCM), which is defined by Srivastava (2007) as “the integration of environmental thinking into supply chain management activities: from product design, to delivery of the final product, to end-of-life treatment”. According to this definition, two main research streams are distinguished i.e. green design for products and green operations. This research falls in the latter category and focuses on one of the most relevant issues in SSCM and GSCM: Supply Chain Network Design and Planning (SCNDP). SCNDP is one of the most comprehensive strategic and tactical decision problems that needs to be optimised for long-term efficient operations of the whole supply chain (Wang et al., 2011). SCNDP problems are characterised by the need of determination of number, capacity and location of network facilities, the allocation of material flow through network echelons, the fulfilment of customers’ demand in a multi-period horizon. SCNDP is a typical problem in any industrial sector, and it has already been discussed in Chapter 6.3, with regards to the automotive supply chain, and in Chapter 6.2 (Accorsi et al., 2014), focused on the supply chain of fresh food. With regards to the latter, the relevance of the sustainability issue in food supply chain has been largely discussed both in this thesis and in literature (Mattson and Sonesson, 2003). This makes the context of fresh food supply chain eligible for a further investigation and for the application innovative methods for the sustainable SCNDP. Akkerman et al. (2010) present ad extended literature about quantitative models for supply chain management: from network design and planning to transportation management. The survey shows that Mixed Integer Linear Programming models, simulations, heuristics and meta-heuristics methods are the most common approaches for food SCNDP problems. Relevant contribution are from Köksalan and Süral (1999), Van der Vorst et al. (2009), Wouda et al. (2002), who modelled the network design problem through MILP modelling. Fresh produce distribution is faced by Blackburn and Scudder (2009), who focused on the transportation mode selection in order to minimise products’ value loss. MILP modelling is also adopted for supply chain network planning (Ahumada and Villalobos, 2009; Bilgen and Günther, 2009; Rong et al., 2011). Akkerman et al. (2010) conclude that the majority of MILP models for food SCNDP are cost-driven and the issues of environmental and social sustainability are usually completely neglected. The same conclusion is shared by Devika et al. (2014), who present a taxonomy of SCND studies classified by model objective, number and type of echelons, modelling, solution method and output. Their review demonstrates that, despite the fact the large majority of SCNDP problems are faced through Single-objective optimisation, recent literature is taking interest of Multi-Objective Optimisation as an approach for green/sustainable SCND. Relevant contributions to MOO in GSCM and SCND are in Chaabane et al. (2012), Hugo and Pistikopoulos (2005), Frota Neto et al. (2008), Govindan et al. (2014), Wang et al. (2011). All these studies present MOO models aimed at the definition of the Pareto frontier of optimal solutions, which represent the best trade-off between different objective functions i.e. minimisation of network economic cost and minimisation of network environmental impact.

This study addresses the issue of SCNDP and presents a Multi-Objective Mixed Integer Linear Programming (MOMILP) model developed as support to decision-makers for fruit and vegetables SCNDP. Such a research represents the evolution of the study presented in Chapter 6.2 (Accorsi et al. 2014), in which a fresh food supply chain is analysed through Life Cycle Assessment and Life Cycle Costing methodologies. Design process entails choices on facility location, fresh food flow allocation, packaging selection and packaging flow allocation, and transportation mean selection in a multi-period timeline. This model can be distinguished from the previous studies in the following directions. Firstly, the forward and reverse logistics are integrated in a Closed Loop Supply Chain (CLSC). Secondly, the model is focused on the role of packaging in fruit and vegetable distribution: depending on the different nature of packages i.e. reusable or disposable, two different sub-networks can be selected for fresh product distribution, presented in Figure 8.1.1 and Figure 8.1.2, respectively. As in a real fresh food supply chain, these two sub-networks coexist and the decision maker, usually the grocery store, can choose between a supply network fully based on disposable packages, a network completely based on reusable packages or, any possible mixed solution. Figure 8.1.3 presents the scheme of the reference network, which is the exact overlapping of the two single-packaging system, on which the model is based. Consequently, the model allows the decision-maker to compare from both environmental and economic point of views the use of alternative packaging systems and, in turn, different logistics systems.

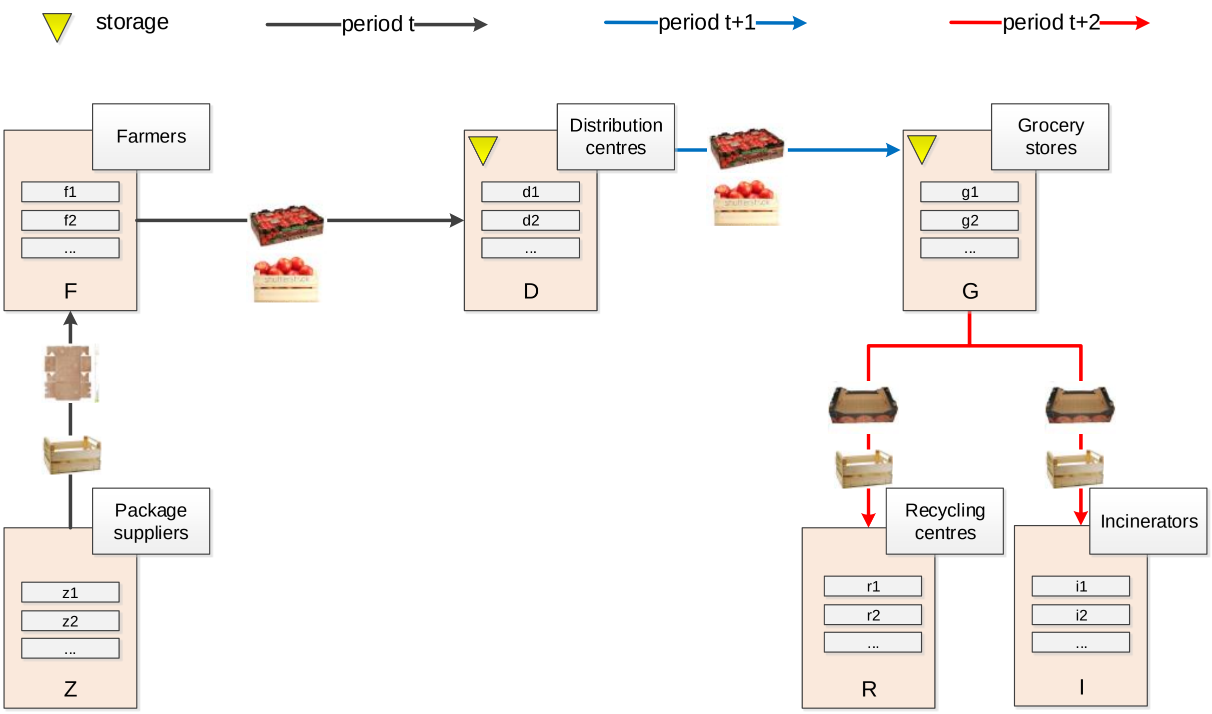

Figure 8.1.1 - Scheme of FFSC network with disposable crates

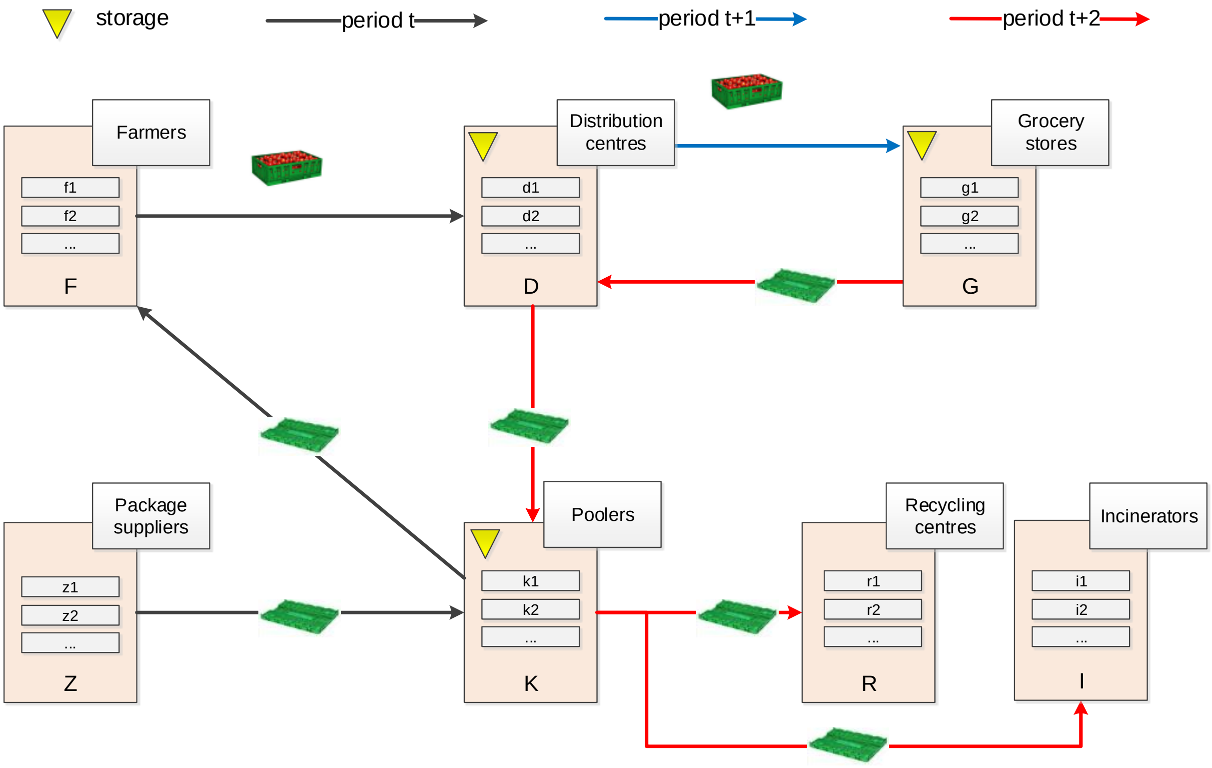

Figure 8.1.2 - Scheme of FFSC network with Reusable Plastic Containers

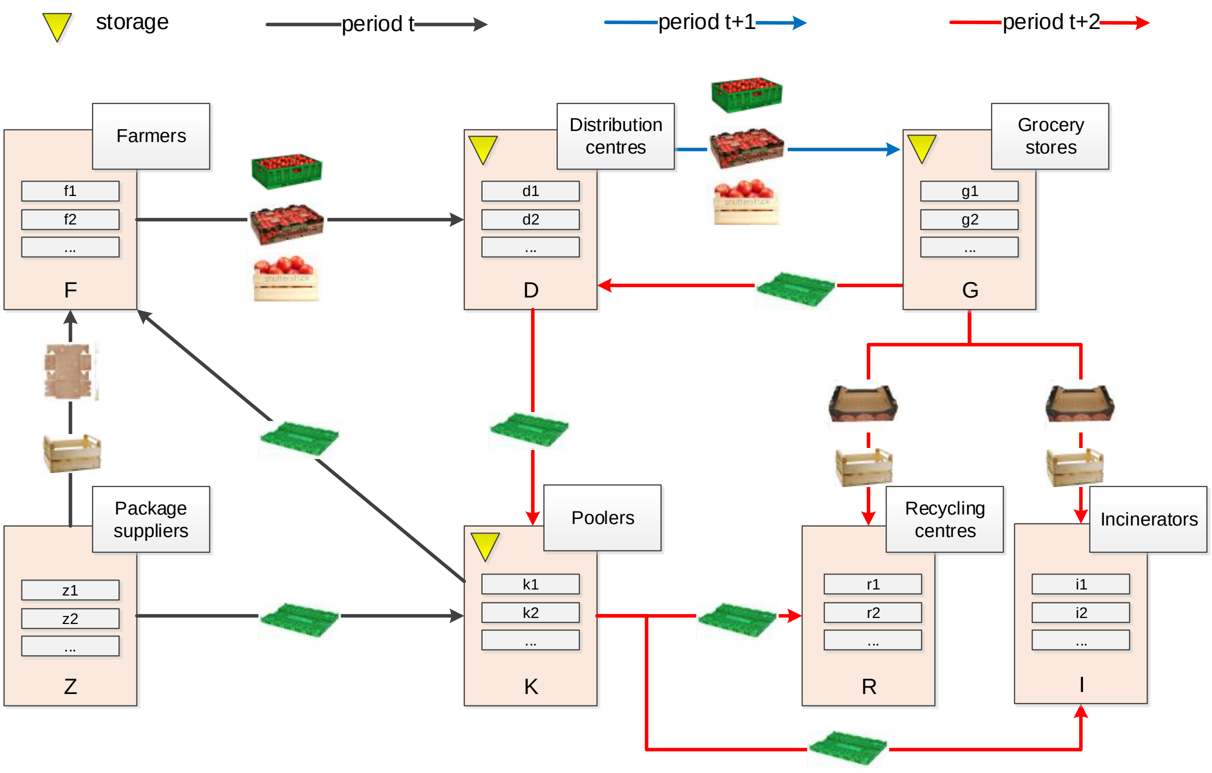

Figure 8.1.3 - Reference network scheme

Fresh food flow is allocated along three echelons: from farmers, to distribution centres (DC), to grocery stores (GS) where crops can be temporarily stored. Disposable packages move along a five echelon sub-network: from package suppliers, to end-of-life treatment centres (i.e. recycling centres and incinerators), travelling through the food supply sub-network. For reusable packages, an additional echelon is required. Poolers are the core node for their closed loop chain. At poolers, reusable crates are collected, washed, inspected, stored and made available for further cycles depending on the packaging lifespan. Further details on network operations are reported in Chapter 6.1 (Accorsi et al., 2014). On the basis of this reference network a MOMILP model has been developed. The model takes into account each activity conducted within the network e.g. packaging manufacturing, transportations, food cold storage, package recycling and incineration, washing of reusable crates, crate storage. To each activity an economic and an environmental impact value is identified and assumed as a parameter of the model.

8.1.2 Model formulation

The following sections introduce sets, variables and parameters of the model.

8.1.2.1 Sets

Table 8.1.1 reports model sets. In addition to the facilities, presented in Figure 8.1.3, a set of periods, fresh products, disposable and reusable types of packaging and different transportation means can be introduced in the modelling. Although the location of farmers, GCs and DCs, recycling and incineration centres are supposed to be known, the DCs and poolers are subject to a capacitated facility location problem.

Description	**Set**	**Index**
Farmers and Vendors	F	f
Grocery Stores	G	g
Distribution Centres	D	d
Poolers	K	k
Recycling Centres	R	r
Incinerators	I	i
Packaging suppliers	Z	z
Periods	T	t
Products	V	v
Disposable crates	U	u
Reusable crates	W	w
Crates	$Q \text{ s.t. } U \cup W$	q
Transport mean types	M	m

Table 8.1.1 - Problem sets and indices

8.1.2.2 Problem variables

Table 8.1.2 introduces the list of variables of the model. They represent the output of the problem solution, which can be resumed as follows: definition of the optimal location for DCs and selection of the poolers supplying the reusable crate service; allocation of fresh products along the routes from farmers to DCs, from DCs to GCs; definition of the optimal amount of products that can be stored at DCs and GCs; packaging selection and flow allocation of crate flows within the network. Except for location problem variables, all allocation problem variables are continues and not integer. Such a decision allows a faster computation of problem optimal solution. It means that amounts of packages travelling within the supply chain are not necessarily integer. However, given the magnitude of crate flow, an output that considers a fractional value can be considered an acceptable approximation.

According to this choice, the flows of containers are representative of the transportation processes between the network nodes. In other words, the optimal number of trips between the nodes is not considered explicitly. In the real world, a flow of products corresponds to a transportation activity so, the consideration in the model of the number of trips along each crossed route as integer variables, would be a closer representation of the reality. However, this choice introduces the need of additional constraints that, in turn, introduce a significant problem in the computational time. For this reason, the main model does not approximate the number of trips to the nearest integer value, and accept to find an optimal solution based a non-integer value of trips. However, an extended version of the model is proposed in section 8.1.3.

Variable	Type	Description
Y_{dt}	binary	Open distribution centre for the period t
Y_{kt}	binary	Open pooler for the period t
X_{vft}	≥0	Products v produced by f in t
X_{vdt}	≥0	Products v in d in t
X_{vgt}	≥0	Products v in g in t
X_{vfdmt}	≥0	Products v delivered from f to d by m in t
X_{vdgmt}	≥0	Products v delivered from d to g by m in t
Z_{qgrmt}	≥0	Crates q delivered from g to r by m in t
Z_{qkrmt}	≥0	Crates q delivered from k to r by m in t
Z_{qgimt}	≥0	Crates q delivered from g to i by m in t
Z_{qkimt}	≥0	Crates q delivered from k to i by m in t
Z_{qzfmt}	≥0	Crates q delivered from z to f by m in t
Z_{qzkmt}	≥0	Crates q delivered from z to k by m in t
Z_{qkfmt}	≥0	Crates q delivered from k to f by m in t
Z_{qdgmt}	≥0	Crates q delivered from d to g by m in t
Z_{qgdmt}	≥0	Crates q delivered from g to d by m in t
Z_{qfdmt}	≥0	Crates q delivered from f to d by m in t
Z_{qdkmt}	≥0	Crates q delivered from d to k by m in t
Z_{qft}	≥0	Number of crates type q required by f in t
Z_{qkt}	≥0	Amount of package q in k in t
Z_{qdt}	≥0	Amount of package q in d in t
Z_{qgt}	≥0	Amount of package q in g in t
W_{qkt}	≥0	Crates q waiting for washing in k in t

Table 8.1.2 - Model variables

8.1.2.3 Parameters

Table 8.1.3 lists the parameters of the model. The optimisation problem takes into account a demand of fresh crops by the market, a time-dependant productivity of farmers, technical characteristics of both reusable and disposal crates (e.g. capacity, lifespan, volume when empty/filled, and recyclability, purchasing cost, manufacturing environmental impact), end-of-life treatment cost and impact for each type of crate, cost and emission related to reusable container washing, transportation mean features (e.g. unit cost and emissions, vehicle capacity), facility properties (e.g. produce storage cost, fixed opening costs and emissions associated with facility operations, storage capacity by produce weight and stored crate number), and distances between network nodes.

Parameter	**Description**
dem_{vgt}	demand of products v by g in t
pro_{vft}	productivity of v by farmer f in t
ve_q	crate volume when empty
vf_q	crate volume when filled
cp_q	weight capacity of crate q
ar_q	recyclability coefficient package q
lf_q	package life cycle
vt_m	mean m capacity by volume
c_d	DC d capacity in weight
c_k	pooler processing capacity
em_q	emission for packaging manuf.
er_q	recycling emission per package
ei_q	incineration emission per package
et_m	unit emission with mean m
es_q	package washing emission
ef_d	fixed emission DC d
ef_k	fixed emission pooler k
e_{vd}	product storage emission in d
cf_d	fixed operating cost DC d
cf_k	fixed operating cost pooler k
cm_q	package unit purchasing cost
cr_q	recycling cost per package
ci_q	incineration cost per package
ct_m	unit transport cost with mean m
cs_q	package washing cost
s_{vd}	Storage cost of products v in d
s_{qg}	storage cost in g of one package q
s_{qk}	storage cost in k of one package q
d_{zf}	distance between z and f
d_{fd}	distance between f and d
d_{dg}	distance between d and g
d_{dk}	distance between d and k
d_{kf}	distance between k and f
d_{zk}	distance between z and k
d_{ki}	distance between k and i
d_{kr}	distance between k and r
d_{gi}	distance between g and i
d_{gr}	distance between g and r
BIG_M	big-m

Table 8.1.3 - Model parameters

8.1.2.4 Objective functions

The main feature of the MOMILP model is the consideration of two objective functions: one for each target of the model. The former, the economic objective function, aims at the minimisation of the economic cost of the whole supply chain; the latter, the environmental objective function aims at the minimisation of the environmental impact of the supply chain, where the environmental impact is measured by the carbon footprint of the activities conducted within the supply chain operations. The activities assumed in this model are summarised as follows: opening of distribution centres and poolers; transportations of empty containers and transportation of containers with fresh food; production of both disposable and reusable containers by packaging manufacturers; temporary cold storage of fresh food in crates at the distribution centres; temporary storage of empty containers at grocery stores and poolers; washing of reusable containers at poolers; end-of-life treatments

8.1.2.4.1 Economic objective function

It expresses the minimisation of: fixed costs associated with the opening of DCs and poolers, (1) and (2), the costs of the transportation of fresh food in containers and empty crates along the network, from (3) to (13); the purchasing cost of crates from packaging supplier, (14) and (15); service costs related to reusable crates collection and washing (16); the incineration/recycling costs of crates, from (17) to (20); the cold storage costs of products at distribution centres and the storage of empty crates at distribution centres and poolers, from (21) to (23).

$$\min \sum_{\boldsymbol{d\in D,t\in T}} \boldsymbol{Y_{dt}\cdot cf_d} \tag{1}$$

$$+\sum_{k\in K,t\in T} Y_{kt}\cdot cf_k \tag{2}$$

$$+\sum_{q\in Q,f\in F,d\in D,m\in M,t\in T} Z_{qfdmt}\cdot\frac{vf_q}{vt_m}\cdot d_{fd}\cdot ct_m \tag{3}$$

$$+\sum_{q\in Q,d\in D,g\in G,m\in M,t\in T} Z_{qdgmt}\cdot\frac{vf_q}{vt_m}\cdot d_{dg}\cdot ct_m \tag{4}$$

$$+\sum_{q\in Q,g\in G,r\in R,m\in M,t\in T} Z_{qgrmt}\cdot\frac{ve_q}{vt_m}\cdot d_{gr}\cdot ct_m \tag{5}$$

$$+\sum_{q\in Q,g\in G,i\in I,m\in M,t\in T} Z_{qgimt}\cdot\frac{ve_q}{vt_m}\cdot d_{gi}\cdot ct_m \tag{6}$$

$$+\sum_{q\in Q,z\in Z,f\in F,m\in M,t\in T} Z_{qzfmt}\cdot\frac{ve_q}{vt_m}\cdot d_{zf}\cdot ct_m \tag{7}$$

$$+\sum_{q\in W,z\in Z,k\in K,m\in M,t\in T} Z_{qzkmt}\cdot\frac{ve_q}{vt_m}\cdot d_{zk}\cdot ct_m \tag{8}$$

$$+\sum_{q\in W,k\in K,f\in F,m\in M,t\in T} Z_{qkfmt}\cdot\frac{ve_q}{vt_m}\cdot d_{kf}\cdot ct_m \tag{9}$$

$$+\sum_{q\in W,k\in K,r\in R,m\in M,t\in T} Z_{qkrmt}\cdot\frac{ve_q}{vt_m}\cdot d_{kr}\cdot ct_m \tag{10}$$

$$+ \sum_{q\in W,k\in K,i\in I,m\in M,t\in T} Z_{qkimt} \cdot \frac{ve_q}{vt_m} \cdot d_{ki} \cdot ct_m \tag{11}$$

$$+ \sum_{q\in W,d\in D,k\in K,m\in M,t\in T} Z_{qdkmt} \cdot \frac{ve_q}{vt_m} \cdot d_{dk} \cdot ct_m \tag{12}$$

$$+ \sum_{q\in W,g\in G,d\in D,m\in M,t\in T} Z_{qgdmt} \cdot \frac{ve_q}{vt_m} \cdot d_{dg} \cdot ct_m \tag{13}$$

$$+ \sum_{q\in U,z\in Z,f\in F,m\in M,t\in T} Z_{qzfmt} \cdot cm_q \tag{14}$$

$$+ \sum_{q\in W,k\in K,f\in F,m\in M,t\in T} Z_{qkfmt} \cdot \frac{cm_q}{lf_q} \tag{15}$$

$$+ \sum_{q\in W,k\in K,t\in T} Wqkt_{qkt} \cdot cs_q \tag{16}$$

$$+ \sum_{q\in W,k\in K,r\in R,m\in M,t\in T} Z_{qkrmt} \cdot cr_q \tag{17}$$

$$+ \sum_{q\in W,k\in K,i\in I,m\in M,t\in T} Z_{qkimt} \cdot ci_q \tag{18}$$

$$+ \sum_{q\in U,g\in G,r\in R,m\in M,t\in T} Z_{qgrmt} \cdot cr_q \tag{19}$$

$$+ \sum_{q\in U,g\in G,i\in I,m\in M,t\in T} Z_{qgimt} \cdot ci_q \tag{20}$$

$$+ \sum_{v\in V,d\in D,t\in T} X_{vdt} \cdot s_{vd} \tag{21}$$

$$+ \sum_{q\in Q,g\in G,t\in T} Z_{qgt} \cdot s_{qg} \tag{22}$$

$$+ \sum_{q\in W,k\in K,t\in T} (Z_{qkt} + W_{qkt}) \cdot s_{qk} \tag{23}$$

8.1.2.4.2 Environmental objective function

The environmental objective function considers the same activities taken into account in the economic function however, instead of the economic cost, the associated environmental impact is considered. In particular the function aims at the minimisation of: fixed emissions associated with the opening of DCs and poolers, (24) and (25), the emissions related to the transportation of fresh food in containers and empty crates along the network, from (26) to (36); the impact of the manufacturing of crates by packaging suppliers, (37) and (38); the emissions related to reusable crates collection and washing (39); the incineration/recycling emissions of crates, from (40) to (43); the direct and indirect emissions caused by the cold storage of products at distribution centres, (44). The storage of containers is assumed to have an economic cost but with no effects on the environment, so the storage of containers is neglected in the environmental function.

$$\min \quad \sum_{\boldsymbol{d\in D,t\in T}} \boldsymbol{Y_{dt}\cdot ef_{d}} \tag{24}$$

$$+\sum_{k\in K,t\in T} Y_{kt}\cdot ef_{k} \tag{25}$$

$$+\sum_{q\in Q,f\in F,d\in D,m\in M,t\in T} Z_{qfdmt}\cdot\frac{vf_{q}}{vt_{m}}\cdot d_{fd}\cdot et_{m} \tag{26}$$

$$+\sum_{q\in Q,d\in D,g\in G,m\in M,t\in T} Z_{qdgmt}\cdot\frac{vf_{q}}{vt_{m}}\cdot d_{dg}\cdot et_{m} \tag{27}$$

$$+\sum_{q\in Q,g\in G,r\in R,m\in M,t\in T} Z_{qgrmt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{gr}\cdot et_{m} \tag{28}$$

$$+\sum_{q\in Q,g\in G,i\in I,m\in M,t\in T} Z_{qgimt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{gi}\cdot et_{m} \tag{29}$$

$$+\sum_{q\in U,z\in Z,f\in F,m\in M,t\in T} Z_{qzfmt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{zf}\cdot et_{m} \tag{30}$$

$$+\sum_{q\in W,z\in Z,k\in K,m\in M,t\in T} Z_{qzkmt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{zk}\cdot et_{m} \tag{31}$$

$$+\sum_{q\in W,k\in K,f\in F,m\in M,t\in T} Z_{qkfmt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{kf}\cdot et_{m} \tag{32}$$

$$+\sum_{q\in W,k\in K,r\in R,m\in M,t\in T} Z_{qkrmt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{kr}\cdot et_{m} \tag{33}$$

$$+\sum_{q\in W,k\in K,i\in I,m\in M,t\in T} Z_{qkimt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{ki}\cdot et_{m} \tag{34}$$

$$+\sum_{q\in W,d\in D,k\in K,m\in M,t\in T} Z_{qdkmt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{dk}\cdot et_{m} \tag{35}$$

$$+\sum_{q\in W,g\in G,d\in D,m\in M,t\in T} Z_{qgdmt}\cdot\frac{ve_{q}}{vt_{m}}\cdot d_{dg}\cdot et_{m} \tag{36}$$

$$+\sum_{q\in U,z\in Z,f\in F,m\in M,t\in T} Z_{qzfmt}\cdot em_{q} \tag{37}$$

$$+ \sum_{q \in W, k \in K, f \in F, m \in M, t \in T} Z_{qkfmt} \cdot \frac{em_q}{lf_q} \tag{38}$$

$$+ \sum_{q \in W, k \in K, t \in T} W_{qkt} \cdot es_q \tag{39}$$

$$+ \sum_{q \in W, k \in K, r \in R, m \in M, t \in T} Z_{qkrmt} \cdot er_q \tag{40}$$

$$+ \sum_{q \in W, k \in K, i \in I, m \in M, t \in T} Z_{qkimt} \cdot ei_q \tag{41}$$

$$+ \sum_{q \in U, g \in G, r \in R, m \in M, t \in T} Z_{qgrmt} \cdot er_q \tag{42}$$

$$+ \sum_{q \in U, g \in G, i \in I, m \in M, t \in T} Z_{qgimt} \cdot ei_q \tag{43}$$

$$+ \sum_{v \in V, d \in D, t \in T} X_{vdt} \cdot e_{vd} \tag{44}$$

8.1.2.5 Model constraints

A set of constraint expressions model the network behaviour and define the set of feasible solutions. The model constraints have purpose of forcing the solution to have the following rules: for each period market demand of produce must be met; capacity of facilities, crates and vehicles cannot be overcome; inflow, outflow and inventory level of produce and crates must be balanced; according to their nature, crates circulates in the dedicated sub-network; containers cannot exceed their lifespan, and the end of which they must be delivered to the appropriate end-of-life treatment. According to these rules, constraints are grouped as follows.

8.1.2.5.1 Initialisation constraints

In this study, levels of stock of products and crates are assumed null at the beginning of the simulation. However, the initialisation constraints that follow can be set in order to model any state of the network.

i. In period 0 farmers f have no products

$$\boldsymbol{X_{vft} = 0} \qquad \forall \boldsymbol{v} \in \boldsymbol{V},\ \boldsymbol{f} \in \boldsymbol{F},\ \boldsymbol{t = t_0} \tag{45}$$

ii. In period 0 there are no products at DCs d

$$\boldsymbol{X_{vdt} = 0} \qquad \forall \boldsymbol{v} \in \boldsymbol{V},\ \boldsymbol{d} \in \boldsymbol{D},\ \boldsymbol{t = t_0} \tag{46}$$

iii. There are no products at grocery stores g in period 0

$$X_{vgt} = 0 \qquad \forall v \in V,\ d \in D,\ t = t_0 \tag{47}$$

iv. No packages at farmers f in period 0

$$Z_{qft} = 0 \qquad \forall q \in Q,\ f \in F,\ t = t_0 \tag{48}$$

v. In period 0 no packages are stored at DCs

$$Z_{qdt} = 0 \qquad \forall q \in Q,\ d \in D,\ t = t_0 \tag{49}$$

vi. No packages at grocery stores in period 0

$$Z_{qgt} = 0 \qquad \forall q \in Q,\ g \in G,\ t = t_0 \tag{50}$$

vii. No packages at poolers in period 0

$$Z_{qkt} = 0 \qquad \forall q \in Q,\ k \in K,\ t = t_0 \tag{51}$$

viii. In period 0 there are no containers waiting for washing at poolers

$$W_{qkt} = 0 \qquad \forall q \in Q, k \in K, t = t_0 \tag{52}$$

8.1.2.5.2 Facility opening

i. Once a DC has been opened it must be kept open for all the subsequent periods

$$Y_{dt} \ \geq \ Y_{d(t-1)} \qquad \forall d \in D,\ t \in T - \{t_0\} \tag{53}$$

ii. Once a pooler k has been opened it must be kept open for all the subsequent periods

$$Y_{kt} \ \geq \ Y_{k(t-1)} \qquad \forall k \in K,\ t \in T - \{t_0\} \tag{54}$$

8.1.2.5.3 Constraints on products demand, and flow balance

i. For each period, for each grocery store and for each product, the amount of product at GS must equal the demand of products

$$X_{vgt} \ = \ dem_{vgt} \qquad \forall v \in V,\ g \in G,\ t \in T \tag{55}$$

ii. For each period, farmer and product the total production cannot exceed the periodic productivity of the farm for that product

$$X_{vft} \leq pro_{vft} \qquad \forall v \in V, f \in F, t \in T \tag{56}$$

iii. For each period, farmer and product the amount of product in travel towards distribution centres by any mean and any route must equal the amount of product at the source

$$X_{vft} = \sum_{d \in D,\, m \in M} X_{vfdmt} \qquad \forall v \in V, f \in F, t \in T \tag{57}$$

iv. For each product, distribution centre and period, the amount of product available at the DC at the beginning of period t equals the sum between the previous initial stock and the amount of products previously delivered from farmers minus the quantity of products previously delivered to grocery stores

$$\boldsymbol{X_{vdt}} = \boldsymbol{X_{vd(t-1)}} + \sum_{\boldsymbol{f \in F,\, m \in M}} \boldsymbol{X_{vfdm(t-1)}} - \sum_{\boldsymbol{g \in G, m \in M}} \boldsymbol{X_{vdgm(t-1)}} \qquad \forall \boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{t} \in \boldsymbol{T} - \{\boldsymbol{t_0}\} \tag{58}$$

v. For each product, distribution centre and period the amount of product travelling towards grocery stores by any vehicle type and any route cannot overcome the availability of product at the source

$$\boldsymbol{X_{vdt}} \geq \sum_{\boldsymbol{g \in G,\, m \in M}} \boldsymbol{X_{vdgmt}} \qquad \forall \boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{t} \in \boldsymbol{T} \tag{59}$$

vi. For each period, grocery store and product the amount of product delivered to the GS must equal the amount of product travelling from distribution centres by any vehicle type and any route

$$\boldsymbol{X_{vgt}} = \sum_{\boldsymbol{d \in D,\, m \in M}} \boldsymbol{X_{vdgmt}} \qquad \forall \boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{t} \in \boldsymbol{T} \tag{60}$$

8.1.2.5.4 Product-packaging matching

i. For each period, mean and route between distribution centres and grocery stores, the total number of packages, of any type, is defined by the amount of product to be transported.

$$\sum_{\boldsymbol{v \in V}} \boldsymbol{X_{vdgmt}} \leq \sum_{\boldsymbol{q \in Q}} \boldsymbol{cp_q} \cdot \boldsymbol{Z_{qdgmt}} \qquad \forall\, \boldsymbol{d} \in \boldsymbol{D},\ \boldsymbol{g} \in \boldsymbol{G},\ \boldsymbol{m} \in \boldsymbol{M}, \boldsymbol{t} \in \boldsymbol{T} \tag{61}$$

ii. For each period, for each mean and each route between farmers and distribution centres, the total number of packages, of any type, is defined by the amount of product that must be transported.

$$\sum_{\boldsymbol{v \in V}} \boldsymbol{X_{vfdmt}} \leq \sum_{\boldsymbol{q \in Q}} \boldsymbol{cp_q} \cdot \boldsymbol{Z_{qfdmt}} \qquad \forall\, \boldsymbol{f} \in \boldsymbol{F},\ \boldsymbol{d} \in \boldsymbol{D},\ \boldsymbol{m} \in \boldsymbol{M}, \boldsymbol{t} \in \boldsymbol{T} \tag{62}$$

8.1.2.5.5 Facility capacity and facility opening

i. For each period and DC the amount of products cannot exceed the capacity of the centre

$$\sum_{\boldsymbol{v \in V}} \boldsymbol{X_{vdt}} \leq \boldsymbol{cd_d} \cdot \boldsymbol{Y_{dt}} \qquad \forall \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{t} \in \boldsymbol{T} \tag{63}$$

ii. Any flow of containers from suppliers to the pooler opens the pooler

$$\sum_{q\in W,\, z\in Z, m\in M} \boldsymbol{Z_{zqzkmt}} \leq \boldsymbol{BIG\_M} \cdot \boldsymbol{Y_{kt}} \qquad \forall \boldsymbol{k} \in \boldsymbol{K}, \forall \boldsymbol{t} \in \boldsymbol{T} \tag{64}$$

iii. Any flow of crates from grocery stores to DCs opens the DC

$$\sum_{q\in W,\, g\in G, m\in M} \boldsymbol{Z_{qgdmt}} \leq \boldsymbol{BIG\_M} \cdot \boldsymbol{Y_{dt}} \qquad \forall \boldsymbol{d} \in \boldsymbol{D}, \forall \boldsymbol{t} \in \boldsymbol{T} \tag{65}$$

iv. For each period and pooler the number of reusable packages delivered to the pooler for washing must cannot overcome the pooler processing capacity

$$\sum_{q\in W,\, d\in D, m\in M} \boldsymbol{Z_{zqdkmt}} \leq \boldsymbol{ck_k} \cdot \boldsymbol{Y_{kt}} \qquad \forall \boldsymbol{k} \in \boldsymbol{K}, \forall \boldsymbol{t} \in \boldsymbol{T} \tag{66}$$

8.1.2.5.6 Disposable packaging flow balancing

i. For each disposable package type, farmer and period, the number of crates delivered from supplier to farmer must equal the number of crates temporary stored at the farmer

$$\boldsymbol{Z_{qft}} = \sum_{z\in Z,\, m\in M} \boldsymbol{Z_{qzfmt}} \qquad \forall \boldsymbol{q} \in \boldsymbol{U}, \boldsymbol{f} \in \boldsymbol{F}, \boldsymbol{t} \in \boldsymbol{T} \tag{67}$$

ii. For each disposable crate type, distribution centre and period, the number of crates available at the beginning of the period t at DC equals the sum between the previous availability and the amount of crates delivered to the centre minus the flow of crates that left the centre

$$\boldsymbol{Z_{qdt}} = \boldsymbol{Z_{qd(t-1)}} - \sum_{g\in G, m\in M} \boldsymbol{Z_{qdgm(t-1)}} + \sum_{d\in D, m\in M} \boldsymbol{Z_{qfdm(t-1)}}$$
$$\forall \boldsymbol{q} \in \boldsymbol{U}, \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{t} \in \boldsymbol{T} - \{\boldsymbol{t_0}\} \tag{68}$$

iii. For each period, disposable package type and grocery store, packages stored in the previous period must be delivered to recycling depending on the recyclability of the crate type

$$\sum_{m\in M,\, r\in R} \boldsymbol{Z_{qgrmt}} = \boldsymbol{Z_{qg(t-1)}} \cdot \boldsymbol{ar_q} \qquad \forall \boldsymbol{q} \in \boldsymbol{U}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{t} \in \boldsymbol{T} - \{\boldsymbol{t_0}\} \tag{69}$$

iv. For each period, disposable container type and grocery store, packages stored in the previous period must be delivered to incinerator depending on the recyclability of the package

$$\sum_{m\in M,\, i\in I} \boldsymbol{Z_{qgimt}} = \boldsymbol{Z_{qg(t-1)}} \cdot (\boldsymbol{1} - \boldsymbol{ar_q}) \qquad \forall \boldsymbol{q} \in \boldsymbol{U}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{t} \in \boldsymbol{T} - \{\boldsymbol{t_0}\} \tag{70}$$

8.1.2.5.7 Reusable packaging forward flow balancing

i. For each period, pooler and reusable package, the number of reusable packages sent from the pooler to farmers and DCs cannot overcome the number of clean packages stored in the pooler and the number of packages purchased from the external supplier

$$\boldsymbol{Z_{qkt}} + \sum_{z\in Z,\, m\in M} \boldsymbol{Z_{qzkmt}} \geq \sum_{f\in F, m\in M} \boldsymbol{Z_{qkfmt}} \qquad \forall \boldsymbol{q} \in \boldsymbol{W}, \boldsymbol{k} \in \boldsymbol{K}, \boldsymbol{t} \in \boldsymbol{T} \tag{71}$$

ii. For each reusable package type, farmer and period, the number of crates delivered from pooler to farmer must equal the number of crates temporary stored at the farmer

$$\boldsymbol{Z_{qft}} = \sum_{k\in K,\, m\in M} \boldsymbol{Z_{qkfmt}} \qquad \forall \boldsymbol{q} \in \boldsymbol{W}, \boldsymbol{f} \in \boldsymbol{F}, \boldsymbol{t} \in \boldsymbol{T} \tag{72}$$

iii. For each reusable package type, distribution centre and period, the number of crates available at the beginning of the period t at DC equals the previous availability plus the quantity of crates containing fresh food delivered to the centre minus the amount of containers that leave the centre for the grocery stores

$$\boldsymbol{Z_{qdt}} = \boldsymbol{Z_{qd(t-1)}} - \sum_{g\in G, m\in M} \boldsymbol{Z_{qdgm(t-1)}} + \sum_{f\in F, m\in M} \boldsymbol{Z_{qfdm(t-1)}} \\ \forall \boldsymbol{q} \in \boldsymbol{W}, \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{t} \in \boldsymbol{T} - \{\boldsymbol{t_0}\} \tag{73}$$

8.1.2.5.8 Reusable packaging reverse flow

i. For each period, grocery store and reusable package type, the amount of packages in back flow, from the grocery store to any open distribution centre delivered by any vehicle type, must equal the number of reusable packages stored in the previous period

$$\sum_{d\in D, m\in M} \boldsymbol{Z_{qgdmt}} = \boldsymbol{Z_{vg(t-1)}} \qquad \forall \boldsymbol{q} \in \boldsymbol{W}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{t} \in \boldsymbol{T} - \{\boldsymbol{t_0}\} \tag{74}$$

ii. For each period, grocery store and reusable package type, the amount of packages in reverse flow coming from distributions centres must be redirected to pooler

$$\sum_{k\in K, m\in M} \boldsymbol{Z_{qdkmt}} = \sum_{g\in G, m\in M} \boldsymbol{Z_{qgdmt}} \qquad \forall \boldsymbol{q} \in \boldsymbol{W}, \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{t} \in \boldsymbol{T} - \{\boldsymbol{t_0}\} \tag{75}$$

iii. For each period, pooler and reusable package, the number of crates waiting for washing is equal to the amount of packages delivered to the pooler from the DCs minus the percentage of crates disposed as they ended their life

$$W_{qkt} = \sum_{d\in D,\, m\in M} Z_{qdkmt} - \sum_{r\in R, m\in M} Z_{qkrmt} - \sum_{i\in I, m\in M} Z_{qkdmt} \qquad (76)$$

$$\forall q \in W, k \in K, t \in T$$

iv. For each period, pooler and reusable package, the number of containers available is given by the number of crates previously washed and stored plus the flow of crates supplied from the manufacturer minus the amount of containers delivered to farmers in the previous period

$$Z_{qkt} = Z_{qk(t-1)} + W_{qk(t-1)} + \sum_{z\in Z,\, m\in M} Z_{qzkm(t-1)} - \sum_{f\in F, m\in M} Zq_{qkfm(t-1)} \qquad \forall q \in W, k \in K, t \in T - \{t_0\} \qquad (77)$$

v. For each period, pooler and reusable package, the percentage of packages (given by the package type specific lifespan) that ends its life is delivered to recycling depending on the recyclability rate

$$\sum_{r\in R,\, m\in M} Z_{qkrmt} = \sum_{d\in D,\, m\in M} Z_{qdkmt} / lf_q \cdot ar_q \qquad (78)$$

$$\forall q \in W, k \in K, t \in T - \{t_0\}$$

vi. For each period, pooler and reusable package, the percentage of packages (given by the package type specific lifespan) that ends its life is sent to incineration depending on the recyclability rate

$$\sum_{i\in I,\, m\in M} Z_{qkimt} = \sum_{d\in D,\, m\in M} Z_{qdkmt} / lf_q \cdot (1 - ar_q) \qquad (79)$$

$$\forall q \in W, k \in K, t \in T - \{t_0\}$$

8.1.2.5.9 Mixed reusable and disposable packaging flow

i. For each package type, farmer and period, the number of crates temporary stored at the farmer must equal the number of packages delivered from farmer to DCs.

$$\sum_{d\in D,\, m\in M} Z_{qfdmt} = Zqft_{qft} \qquad \forall q \in Q, f \in F, t \in T \qquad (80)$$

ii. For each package type, distribution centre and period, the number of crates delivered to the grocery stores cannot overcome the number of crates q available at dc in t

$$\sum_{g \in G, m \in M} \boldsymbol{Z_{qdgmt}} \leq \boldsymbol{Z_{qdt}} \qquad \forall \boldsymbol{q} \in \boldsymbol{Q}, \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{t} \in \boldsymbol{T} \tag{81}$$

iii. For each period, grocery store and package type, the number of packages delivered from distribution centres must equal the number of packages stored in the grocery store for the whole period

$$\boldsymbol{Z_{qgt}} = \sum_{d \in D,\, m \in M} \boldsymbol{Z_{qdgmt}} \qquad \forall \boldsymbol{q} \in \boldsymbol{Q}, \boldsymbol{g} \in \boldsymbol{G}, \boldsymbol{t} \in \boldsymbol{T} \tag{82}$$

8.1.2.5.10 Variable feasibility

i. Facility opening can assume only a binary value, i.e. open or close

$$\boldsymbol{Y_{dt}}, \boldsymbol{Y_{kt}} \in \{\boldsymbol{0}; \boldsymbol{1}\} \qquad \forall \boldsymbol{d} \in \boldsymbol{D}, \boldsymbol{k} \in \boldsymbol{K}, \boldsymbol{t} \in \boldsymbol{T} \tag{83}$$

ii. All the other variables must be non-negative real

$$\begin{gathered} \boldsymbol{X_{vft}}, \boldsymbol{X_{vdt}}, \boldsymbol{X_{vgt}}, \boldsymbol{X_{vfdmt}}, \boldsymbol{X_{vdgmt}}, \boldsymbol{Z_{qft}}, \boldsymbol{Z_{qkt}}, \boldsymbol{Z_{qdt}}, \boldsymbol{Z_{qgt}}, \boldsymbol{W_{qkt}}, \boldsymbol{Z_{qgrmt}}, \boldsymbol{Z_{qkrmt}}, \boldsymbol{Z_{qgimt}}, \boldsymbol{Z_{qkimt}}, \\ \boldsymbol{Z_{qzfmt}}, \boldsymbol{Z_{qzkmt}}, \boldsymbol{Z_{qkfmt}}, \boldsymbol{Z_{qdgmt}}, \boldsymbol{Z_{qgdmt}}, \boldsymbol{Z_{qfdmt}}, \boldsymbol{Z_{qdkmt}} \in \boldsymbol{R}^{+} \end{gathered} \tag{84}$$

8.1.3 Extended model

As explained in 8.1.2.2, the model presented above considers the value of the flows of goods and containers along the potential routes of the network as continuous decision-making variables of the problem. However, in reality, goods travel in an integer number of vehicles and/or for an integer number of trips. For example, if problem solving suggested a flow of a single container between two nodes of the network, in reality this solution should be converted in an integer number of trips: in this case, zero or one. Therefore, a significant improvement of the model would be given by the consideration of the problem of the rounding of trips. The following sections present an extension of the model, in which additional constraints (from (85) to (95)) forces the solution to an integer number of trips for the representation of the flow and, consequently, in the objective functions the transport costs are considered as a function of the number of trips travelled between two nodes, and not as a function of the amount of goods carried.

8.1.3.1 Additional variables

Variable	Type	Description
N_{grmt}	≥0 integer	Number of trips/vehicles from g to r by m in t
N_{krmt}	≥0 integer	Number of trips/vehicles from k to r by m in t
N_{gimt}	≥0 integer	Number of trips/vehicles from g to i by m in t
N_{kimt}	≥0 integer	Number of trips/vehicles from k to i by m in t
N_{zfmt}	≥0 integer	Number of trips/vehicles from z to f by m in t
N_{zkmt}	≥0 integer	Number of trips/vehicles from z to k by m in t
N_{kfmt}	≥0 integer	Number of trips/vehicles from k to f by m in t
N_{dgmt}	≥0 integer	Number of trips/vehicles from d to g by m in t
N_{gdmt}	≥0 integer	Number of trips/vehicles from g to d by m in t
N_{fdmt}	≥0 integer	Number of trips/vehicles from f to d by m in t
N_{dkmt}	≥0 integer	Number of trips/vehicles from d to k by m in t

Table 8.1.4 - Additional variables of the extended model

8.1.3.2 Additional constraints

$$\boldsymbol{N_{fdmt}} \geq \sum_{\boldsymbol{q\in Q}} \boldsymbol{Z_{qfdmt}} \cdot \frac{\boldsymbol{vf_q}}{\boldsymbol{vt_m}} \qquad \forall\, \boldsymbol{f} \in \boldsymbol{F},\ \boldsymbol{d} \in \boldsymbol{D},\ \boldsymbol{m} \in \boldsymbol{M},\ \boldsymbol{t} \in \boldsymbol{T} \tag{85}$$

$$N_{dgmt} \geq \sum_{q\in Q} Z_{qdgmt} \cdot \frac{vf_q}{vt_m} \qquad \forall\, d \in D,\ g \in G, m \in M,\ t \in T \tag{86}$$

$$N_{grmt} \geq \sum_{q\in U} Z_{qgrmt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, g \in G,\ r \in R,\ m \in M,\ t \in T \tag{87}$$

$$N_{gimt} \geq \sum_{q\in U} Z_{qgimt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, g \in G,\ i \in I,\ m \in M,\ t \in T \tag{88}$$

$$N_{zfmt} \geq \sum_{q\in U} Z_{qzfmt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, z \in Z,\ f \in F,\ m \in M,\ t \in T \tag{89}$$

$$N_{zkmt} \geq \sum_{q\in W} Z_{qzkmt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, z \in Z,\ k \in K,\ m \in M,\ t \in T \tag{90}$$

$$N_{kfmt} \geq \sum_{q\in W} Z_{qkfmt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, k \in K,\ f \in F,\ m \in M,\ t \in T \tag{91}$$

$$N_{krmt} \geq \sum_{q\in W} Z_{qkrmt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, k \in K,\ r \in R,\ m \in M,\ t \in T \tag{92}$$

$$N_{kimt} \geq \sum_{q\in W} Z_{qkimt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, k \in K,\ i \in I,\ m \in M,\ t \in T \tag{93}$$

$$N_{dkmt} \geq \sum_{q\in W} Z_{qdkmt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, d \in D,\ k \in K,\ m \in M,\ t \in T \tag{94}$$

$$N_{gdmt} \geq \sum_{q\in W} Z_{qgdmt} \cdot \frac{ve_q}{vt_m} \qquad \forall\, g \in G,\ d \in D,\ m \in M,\ t \in T \tag{95}$$

$$N_{fdmt}, N_{dgmt}, N_{grmt}, N_{gimt}, N_{zfmt}, N_{zkmt}, N_{kfmt}, \\ N_{krmt}, N_{kimt}, N_{dkmt}, N_{gdmt} \geq 0 \; and \; integer \tag{96}$$

8.1.3.3 Changes in the objective functions

8.1.3.3.1 Changes in Economic objective function

$$+ \sum_{\mathbf{f \in F, d \in D, m \in M, t \in T}} \mathbf{N_{fdmt} \cdot d_{fd} \cdot ct_m} \qquad \textit{replaces (3)} \tag{97}$$

$$+ \sum_{d \in D, g \in G, m \in M, t \in T} N_{dgmt} \cdot d_{dg} \cdot ct_m \qquad \textit{replaces (4)} \tag{98}$$

$$+ \sum_{g \in G, r \in R, m \in M, t \in T} N_{grmt} \cdot d_{gr} \cdot ct_m \qquad \textit{replaces (5)} \tag{99}$$

$$+ \sum_{g \in G, i \in I, m \in M, t \in T} N_{gimt} \cdot d_{gi} \cdot ct_m \qquad \textit{replaces (6)} \tag{100}$$

$$+ \sum_{z \in Z, f \in F, m \in M, t \in T} N_{zfmt} \cdot d_{zf} \cdot ct_m \qquad \textit{replaces (7)} \tag{101}$$

$$+ \sum_{z \in Z, k \in K, m \in M, t \in T} N_{zkmt} \cdot d_{zk} \cdot ct_m \qquad \textit{replaces (8)} \tag{102}$$

$$+ \sum_{k \in K, f \in F, m \in M, t \in T} N_{kfmt} \cdot d_{kf} \cdot ct_m \qquad \textit{replaces (9)} \tag{103}$$

$$+ \sum_{k \in K, r \in R, m \in M, t \in T} N_{krmt} \cdot d_{kr} \cdot ct_m \qquad \textit{replaces (10)} \tag{104}$$

$$+ \sum_{k \in K, i \in I, m \in M, t \in T} N_{kimt} \cdot d_{ki} \cdot ct_m \qquad \textit{replaces (11)} \tag{105}$$

$$+ \sum_{d \in D, k \in K, m \in M, t \in T} N_{dkmt} \cdot d_{dk} \cdot ct_m \qquad \textit{replaces (12)} \tag{106}$$

$$+ \sum_{g \in G, d \in D, m \in M, t \in T} N_{gdmt} \cdot d_{dg} \cdot ct_m \qquad \textit{replaces (13)} \tag{107}$$

8.1.3.3.2 Changes in Environmental objective function

$$+ \sum_{\mathbf{f \in F, d \in D, m \in M, t \in T}} \mathbf{N_{fdmt} \cdot d_{fd} \cdot et_m} \qquad \textit{replaces (26)} \tag{108}$$

$$+ \sum_{d \in D, g \in G, m \in M, t \in T} N_{dgmt} \cdot d_{dg} \cdot et_m \qquad \textit{replaces (27)} \tag{109}$$

$$+ \sum_{g \in G, r \in R, m \in M, t \in T} N_{grmt} \cdot d_{gr} \cdot et_m \qquad \textit{replaces (28)} \tag{110}$$

$$+ \sum_{g \in G, i \in I, m \in M, t \in T} N_{gimt} \cdot d_{gi} \cdot et_m \qquad \textit{replaces (29)} \tag{111}$$

$$+\sum_{z\in Z,f\in F,m\in M,t\in T} N_{zfmt}\cdot d_{zf}\cdot et_m$$ *replaces (30)* (112)

$$+\sum_{z\in Z,k\in K,m\in M,t\in T} N_{zkmt}\cdot d_{zk}\cdot et_m$$ *replaces (31)* (113)

$$+\sum_{k\in K,f\in F,m\in M,t\in T} N_{kfmt}\cdot d_{kf}\cdot et_m$$ *replaces (32)* (114)

$$+\sum_{k\in K,r\in R,m\in M,t\in T} N_{krmt}\cdot d_{kr}\cdot et_m$$ *replaces (33)* (115)

$$+\sum_{k\in K,i\in I,m\in M,t\in T} N_{kimt}\cdot d_{ki}\cdot et_m$$ *replaces (34)* (116)

$$+\sum_{d\in D,k\in K,m\in M,t\in T} N_{dkmt}\cdot d_{dk}\cdot et_m$$ *replaces (35)* (117)

$$+\sum_{g\in G,d\in D,m\in M,t\in T} N_{gdmt}\cdot d_{dg}\cdot et_m$$ *replaces (36)* (118)

8.1.3.4 Considerations

Although the extended model considers a more accurate representation of the reality that involves the computation of integer variables, which significantly increase the solving time, to such an extent that even for small size problems a solution cannot be obtained in a reasonable time. Therefore, because of its computational complexity, the application of the extended model is omitted in this study. Moreover, since the analysed problem focus on a strategic planning of the supply chain, more than on its operational planning, the simplification associated with the non-extended model must be considered acceptable for the purpose of this study, such that the case study analysed in the following sections has been solved through the application of the reduced model.

8.1.4 Pareto frontier generation method

The problem presented in this study has two conflicting objectives. There is a trade-off between economic and environmental objectives, which makes not possible to reach a single optimal solution that optimises the value of both objectives simultaneously. Such a trade-off leads to a set of non-dominated solutions, called “Pareto optimal” solutions, which constitute a “Pareto frontier”. For each feasible point of Pareto frontier, it is impossible to improve any objective without deteriorating the other one. Therefore, Pareto frontier generation provide the decision maker with a portfolio of alternative optimal solutions. A typical approach for the generation of Pareto optimal solutions is to use an aggregate objective function by varying the numerical scalar weights, where each set of weights coincides with a Pareto solution. The more the Pareto solutions are evenly distributed the greater is the identification that the design space is well represented in the Pareto frontier and the easier is the decision process for the decision maker. However, most methods do not generate evenly distributed set of Pareto solutions (Das and Dennis, 1998; Ismail-Yahaya and Messac, 2002; Messac and Mattson, 2002). Therefore, in this study the method chosen for the generation of the Pareto frontier is the Normalised Normal Constraint Method (NNCM) presented (Das and Dennis, 1998; Ismail-Yahaya and Messac, 2002; Messac and Mattson, 2002). NNCM do not need an initial weight for each objective and can lead to the generation of a well-distributed set of all available Pareto solutions. NNCM can be applied to any multi-objective problem. However, since the study presented here deal with two objectives alone, only the NNCM for bi-objective problems presented in the following section.

8.1.4.1 Overview on the Normalised Normal Constraint Method (NNCM) for bi-objective problems

Given a multi-objective optimisation problem *P1*, defined as follow:

$$\boldsymbol{min_x}\,\{\,\boldsymbol{\mu_1(x)}\quad \boldsymbol{\mu_2(x)}\} \tag{119}$$

$$subject\ to$$

$$g_j(x) \le 0, \quad (1 \le j \le r) \tag{120}$$

$$h_k(x) = 0, \quad (1 \le k \le s) \tag{121}$$

$$x_{li} \le x_i \le x_{ui}, \quad (1 \le i \le n_x) \tag{122}$$

Where $\boldsymbol{x}$ is the $\boldsymbol{n_x}$ dimension vector of design variables to optimise, $\boldsymbol{\mu_i(x)}$ define the *i*-th objective function, (A) is the vector of problem objectives, (B) and (C) represent the *r* inequality and the *s* equality constraints, respectively, and (D) is the side constraint, where x_{li} and x_{ui} are the lower and upper constraint limits in the $\boldsymbol{n_x}$ dimensions of search space, respectively.

There are also defined:

- Optimal decision vector x^{i*} such that $x^{i*} \in R^{2x}$;
- Generic *i*-th optimal objective μ_i^*, with $\mu_i^* = \mu_i(x^{i*})$ such that $\mu_i^* \in R^2$;
- Anchor points μ^{i*} (where $\mu^{i*} \in R^2$), defined as the end of the Pareto frontier, are yield when the *i*-th objective is calculated independently;
- Utopia Line P^u= the 2-dimension vector of the two anchor points μ^{i*} such that $i = (1,2)$.
- Utopia Point μ^u, where $\mu^u = [\mu_1^*, \mu_2^*]^T \in R^2$, represents a point where its components are the optimum vertices (anchor points);

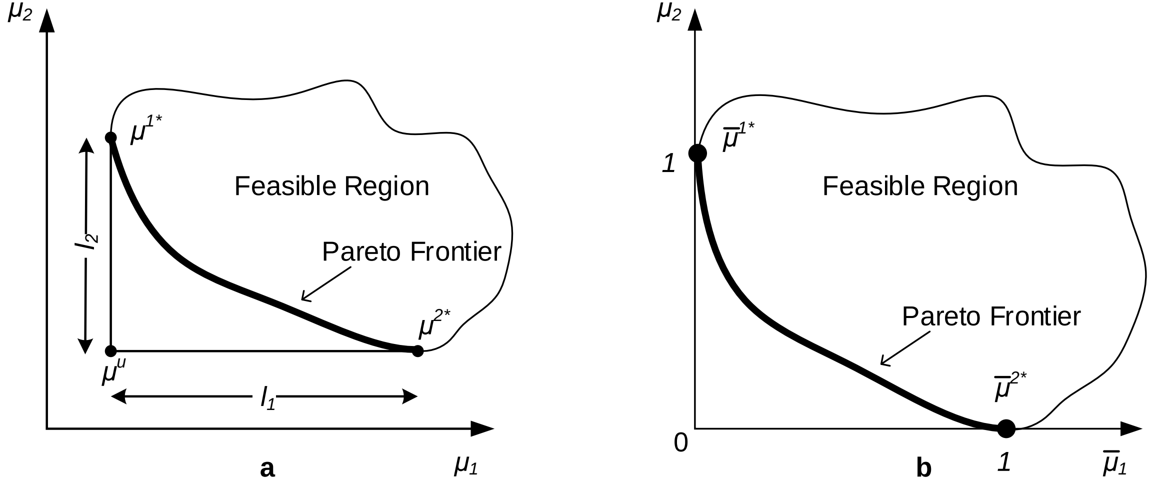

Figure 8.1.4 - Normalised space

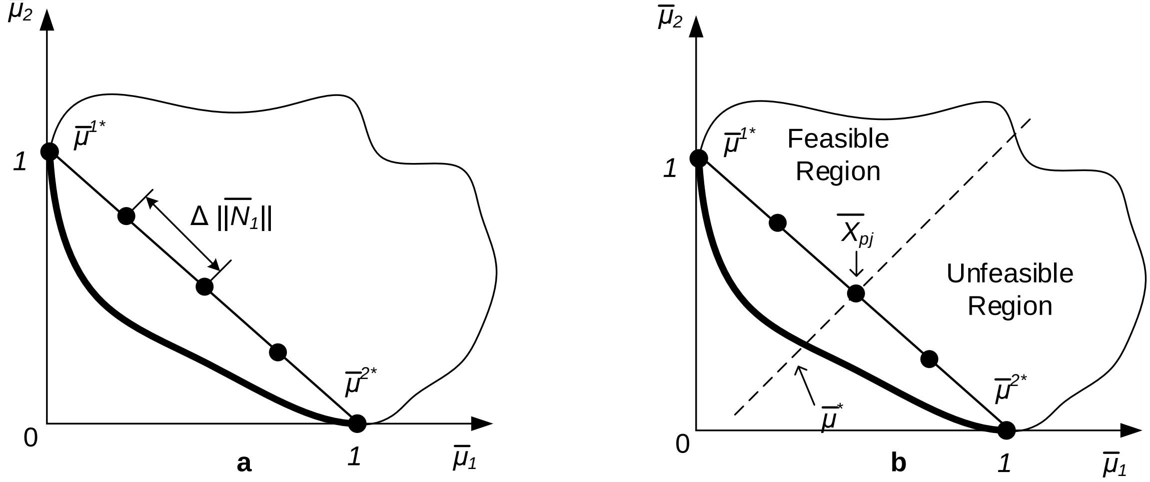

Figure 8.1.5 - NNCM in bi-objective case and m_1=5

The main steps for the application of NNCM for bi-objective problems can be summarised as follows:

1. Identification of Anchor points, Utopia point, Utopia line

   The anchor points, or optimum vertices, are obtained by solving the problem PU$_i$ defined as follows:

$$\boldsymbol{min_x\, \mu_i(x), \quad (1 < i \leq 2)} \tag{123}$$

$$subject\ to$$

$$g_j(x) \leq 0, \quad (1 \leq j \leq r) \tag{124}$$

$$h_k(x) = 0, \quad (1 \leq k \leq s) \tag{125}$$

$$x_{li} \leq x_i \leq x_{ui}, \quad (1 \leq i \leq n_x) \tag{126}$$

Solving the two problems PU$_1$ and PU$_2$ returns the two anchor points μ^{1*} and μ^{2*}, respectively.

2. Normalisation

   Let $\bar{\mu}$ be the normalised form of μ, the Utopia point is defined as

   $$\boldsymbol{\mu^u} = [\boldsymbol{\mu_1}(\boldsymbol{x^{1*}}) \quad \boldsymbol{\mu_2}(\boldsymbol{x^{2*}})]^{\boldsymbol{T}} \tag{127}$$

   Let l_1 and l_2 the distances between μ^{2*} and μ^{1*}, and the Utopia point μ^u, respectively, such that:

   $$\boldsymbol{l_1} = [\boldsymbol{\mu_1}(\boldsymbol{x^{2*}}) - \boldsymbol{\mu_1}(\boldsymbol{x^{1*}})] \tag{128}$$

   $$l_2 = [\mu_2(x^{1*}) - \mu_2(x^{2*})] \tag{129}$$

   Therefore, the normalisation factor can be evaluated as follows

   $$\boldsymbol{\bar{\mu}} = \left\{ \frac{\boldsymbol{\mu_1}(\boldsymbol{x}) - \boldsymbol{\mu_1}(\boldsymbol{x^{1*}})}{\boldsymbol{l_1}} \quad \frac{\boldsymbol{\mu_2}(\boldsymbol{x}) - \boldsymbol{\mu_2}(\boldsymbol{x^{2*}})}{\boldsymbol{l_2}} \right\} \tag{130}$$

3. Identification of Utopia Line vector

   Define $\overline{N_1}$ as the direction from $\bar{\mu}^{1*}$to $\bar{\mu}^{2*}$, yielding

   $$\overline{\boldsymbol{N_1}} = \boldsymbol{\bar{\mu}^{2*}} - \boldsymbol{\bar{\mu}^{1*}} \tag{131}$$

4. Interval definition

   Compute a normalised increment $\delta_1$along the direction N_1 for a prescribed number of solutions m_1 as

   $$\boldsymbol{\delta_1} = \frac{\boldsymbol{1}}{\boldsymbol{m_1} - \boldsymbol{1}} \tag{132}$$

5. Generation of Utopia Line points

   Evaluate a set of evenly distributed points on the Utopia line as:

   $$\boldsymbol{\bar{X}_{pj}} = \boldsymbol{\alpha_{1j}}\boldsymbol{\bar{\mu}^{1*}} + \boldsymbol{\alpha_{2j}}\boldsymbol{\bar{\mu}^{2*}} \tag{133}$$

   Where

   $$\boldsymbol{0} \leq \boldsymbol{\alpha_{1j}} \leq \boldsymbol{1} \tag{134}$$

   $$\sum_{k=1}^{2} \alpha_{kj} = 1 \tag{135}$$

6. Pareto Points generation

   Using the set of evenly distributed points on the Utopia line, generate a corresponding set of Pareto points by solving a succession of optimization runs of problem P2. Each optimisation run corresponds to a point on the Utopia line. Specifically, for each generated point on the Utopia line, solve for the *j*-th point. Problem *P2* for *j*-th point is defined as follows:

$$\boldsymbol{min_x}\ \boldsymbol{\bar{\mu}_2(x)} \tag{136}$$

$$subject\ to$$

$$g_j(x) \leq 0, \quad (1 \leq j \leq r) \tag{137}$$

$$h_k(x) = 0, \quad (1 \leq k \leq s) \tag{138}$$

$$x_{li} \leq x_i \leq x_{ui}, \quad (1 \leq i \leq n_x) \tag{139}$$

$$\overline{N_1}(\bar{\mu} - \bar{X}_{pj})^T \leq 0 \tag{140}$$

$$\bar{\mu}^u = [\bar{\mu}_1(x) \quad \bar{\mu}_2(x)]^T \tag{141}$$

7. Find the non-normalised Pareto points

   The non-normalised design metrics can be obtained by using the relation

$$\boldsymbol{\mu} = [\boldsymbol{\bar{\mu}_1 l_1 + \bar{\mu}_1(x^{1*})} \quad \boldsymbol{\bar{\mu}_2 l_2 + \bar{\mu}_1(x^{2*})}]^{\boldsymbol{T}} \tag{142}$$

8.1.5 Case study and results

8.1.5.1 Case study presentation

In order to present an example of application of the model, a case study is considered, modelled and solved. The network is structured as follow: 8 grocery stores, 6 farmers, 4 potential DC, 3 packaging supplier, 3 potential pooler, 2 recycling centres, 2 incinerators. Network nodes are represented in Figure 8.1.6.

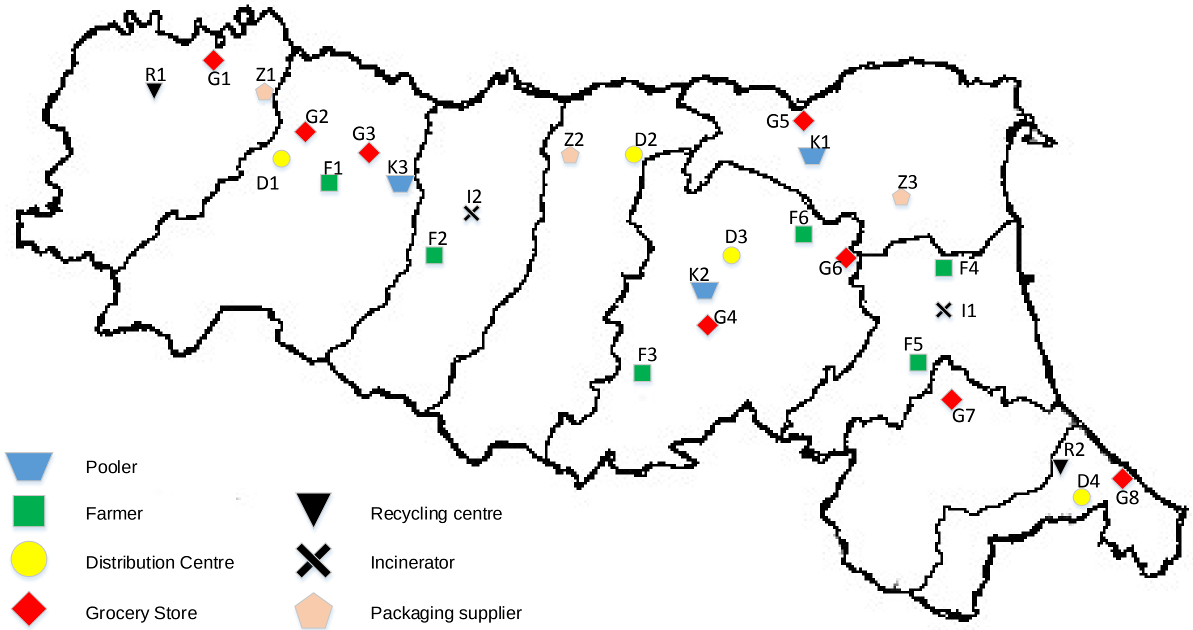

Figure 8.1.6 - Network nodes

Container	**U1**	**U2**	**W1**	**W2**
Material	Plywood	Corrugated Cardboard	Polypropylene	Polypropylene
Dimension A [mm]	600	600	600	600
Dimension B [mm]	400	400	400	400
Dimension C [mm]	240	240	240	120
Thickness [mm]		3.5	60	40
Weight [kg]	0.9	0.785	2	1.3
kg CO2 per kg manufactured	0.43	1.18	3.4	3.4
kg CO2 per kg recycled	0.075	0.295	0.3	0.3
kg CO2 per kg incinerated	0.009	0.032	2.60	2.60
kg CO2 per kg washed	0	0	0.012	0.012
€ per kg recycled	0.23	0.12	0.23	0.23
€ per kg incinerated	0.1	0.06	0.1	0.1
ve [dm3]	57.6	2.52	14	9.6
vf [dm3]	57.6	57.6	57.6	28.8
cp [kg]	10	10	10	5
ar [%]	0.5	0.6	0.8	0.8
lf	1	1	30	40
em [kg CO2e]	0.387	0.926	6.8	4.42
er [kg CO2e]	0.068	0.232	0.6	0.39
ei [kg CO2e]	0.008	0.025	5.209	3.386
es [kg CO2e]	0	0	0.024	0.016
cm [€]	0.35	0.4	5.5	3.5
cr [€]	0.207	0.094	0.46	0.299
ci [€]	0.09	0.047	0.2	0.13
cs [€]	0	0	0.32	0.24

Table 8.1.5 - Technical features and model parameters of containers

Along the network, four different products must be supplied to the market for a period of 10 weeks, during which a demand of about 470 tonnes of fresh fruit and vegetables must be fulfilled. Three types of trucks, different in capacity, transportation emissions and costs, are available for the deliveries. Packaging suppliers offers a set of four types of crates: wooden box (U1), cardboard box (U2), reusable plastic containers (RPC) in two sizes (W1 and W2). Table 8.1.5 and Table 8.1.6 report the technical features and model parameter related to containers and vehicle types assumed in the case study.

Vehicle type	**M1**	**M2**	**M3**
Consumption [l/km]	0.4	0.32	0.27
Emission [kgCO2/l]	3	2.4	2
Internal dim A [m]	13.6	10.2	6.8
Internal dim B [m]	2.5	2.5	2.5
Internal dim C [m]	2.5	2.5	2.5
vt [m3]	85	63.75	42.5
et [kgCO2e/km]	1.2	0.768	0.54
ct [€/km]	1.72	2.076	2.486

Table 8.1.6 - Technical features and model parameters of vehicle types

8.1.5.2 Technical instruments and computational solver

Both the model and the input data are coded in AMPL language and processed adopting Gurobi Optimizer© v.5.5 solver. An Intel® Core™ i7-3770 CPU @ 3.40GHz and 16.0GB RAM workstation has been used. The solving time of the branch-and-bound algorithm is approximately of 14,400 seconds for each point of the Pareto frontier.

8.1.5.3 Solving results

Figure 8.1.7 presents the Normalised Pareto Frontier of optimal solution obtained through the application NNCM on a set of 20 intervals (m_1=20). Points C and E represent the anchor points of the curve i.e. the best economic solution and the best environmental solution, respectively. All the other points of the curve represent trade-off solutions calculated through the solving of the succession of optimisation runs of problem P2, as explained in 8.1.4.1. Sub-optimal solutions dominated by the solutions of Pareto frontier are coloured in red (points S1 and S2).

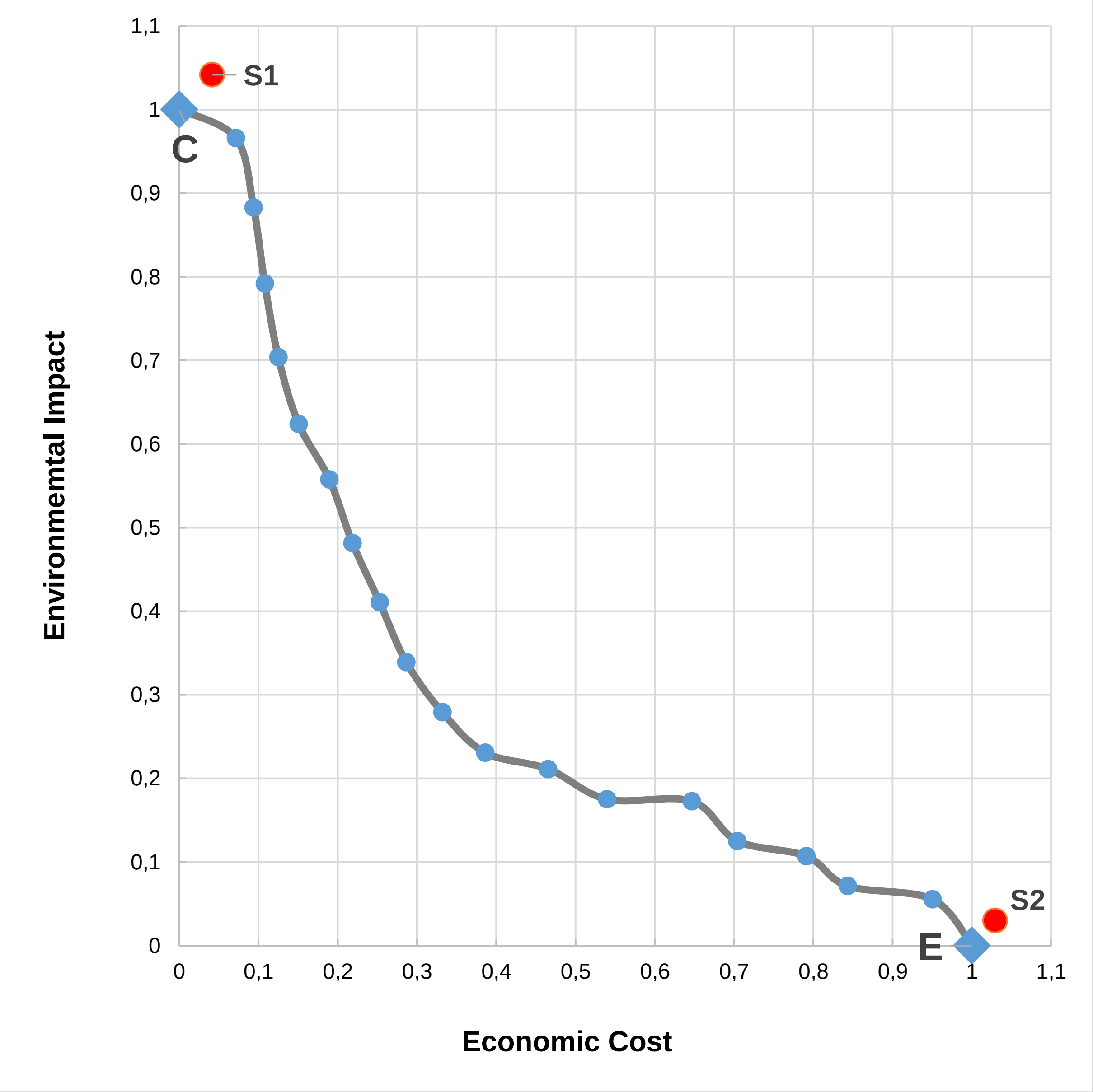

Figure 8.1.7 - Normalised Pareto Frontier of optimal solutions

Figure 8.1.8 presents the Pareto frontier of optimal solutions for the analysed problem, which is obtained by the transformation of the normalised curve with expression (142). The axis measure the values of total economic cost and total environmental impact associated with the operations considered in the model in the assumed period. From C to E, to an increase of about 51% of costs corresponds an almost equal reduction of CO2e emissions, vice versa from solution E to C. Between the two anchor points a set of 18 calculated solutions define a set of possible trade-offs. Each solving generated a different point of the Pareto frontier, to which a different configuration of the network and/or a different optimal packaging mix is related. However, for the sake of brevity and for the purpose of this study, in the Pareto frontier of Figure 8.1.8, in addition to anchor points C and E, only two noteworthy solutions are indicated, i.e. P1 and P2 that correspond to the 13th and 16th solving of the problem respectively. P1 and P2 represent relevant break points in the Pareto frontier, which involve appreciable modification of network structures, as shown in the paragraphs below.

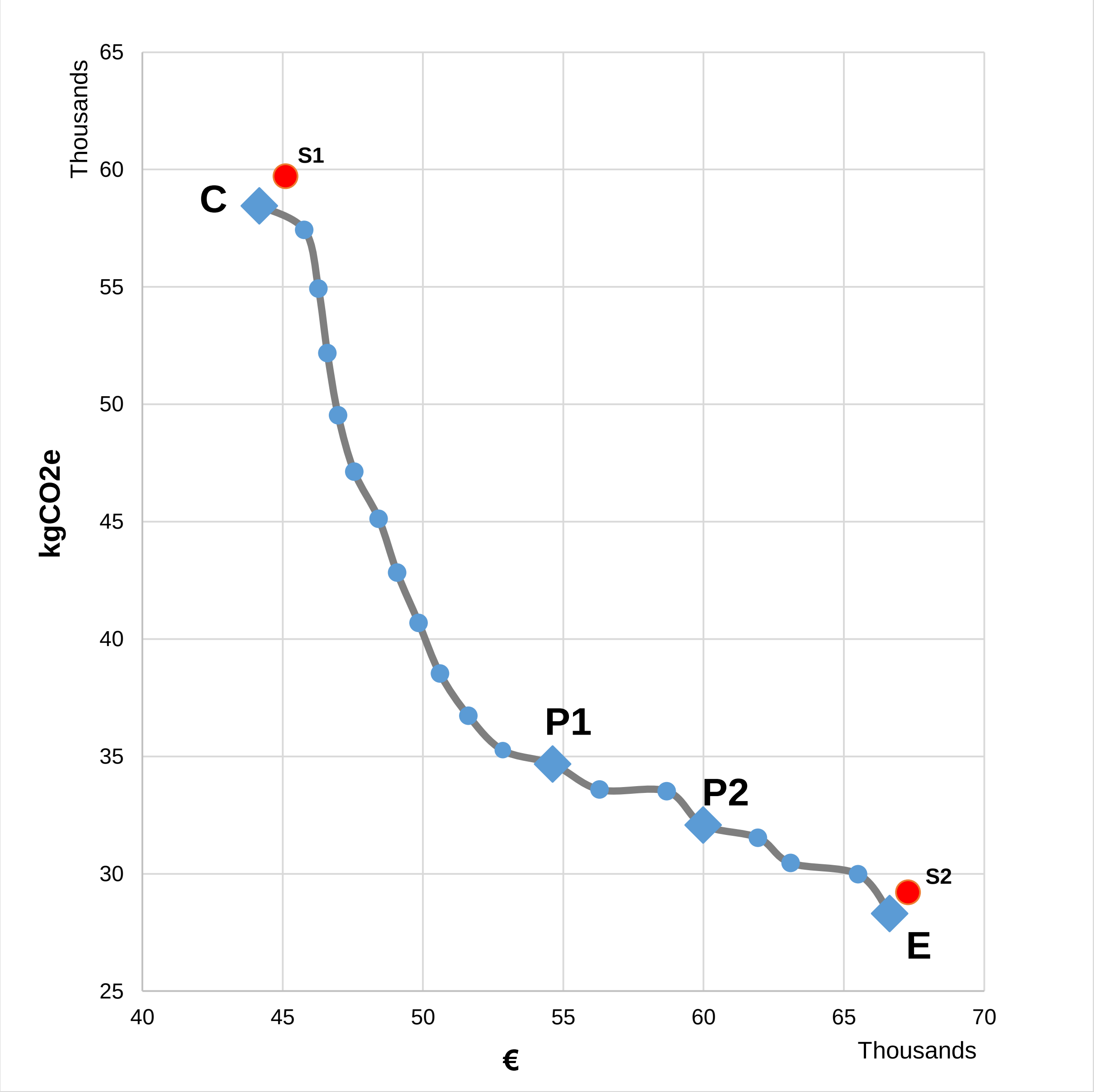

Figure 8.1.8 - Pareto Frontier of optimal solutions

Table 8.1.7 resumes the comparison between solutions C, P1, P2, and E. In all solutions, only two DCs out of three are open. In C a mix of disposable crates, where cardboard boxes represent almost the 90% of containers, is selected as the optimal choice. Moving to P1, disposable crates are still the most preferable containers, but a prevalence of wooden boxes and, most of all, the introduction of RPCs in the network are noted. The introduction of RPCs involves the opening of a pooler, where reusable containers are handled and washed. P1 does not present a reduction in total crates, since RPCs are used only in the last three intervals of simulation, which is an interval too short for a second use cycle. On the contrary, in P2, the quantity of crates produced decreases of about 21%, because of the significant reduction in disposable crates to the benefit of a larger use in reusable containers. In this case, RPCs are indeed reused, starting from the forth interval, which means an anticipation, compared to P1, in the opening of the pooler. Finally, solution E, i.e. the environmental optimum, suggests the phasing out of disposable crates and the full adoption of reusable containers. RPC system comes into play since the first interval and allows a significant reduction in the total number of crates introduced within the network. With regard to the problem of vehicle type selection, the economic optimum is given by the selection of M1 that implies the lowest unit cost, while the environmental optimum corresponds with the selection of M2, since it introduces the lowest ratio of emissions per unit weight transported. Between these extremes, combinations of the three vehicle types are proposed.

	Solution			
	C	P1	P2	E
Number of open DCs per number of periods	14	14	14	14
Number of open pooler per number of periods	0	3	7	10
Wooden boxes (U1) purchased	4907	39554	19440	0
Cardboard boxes (U2) purchased	41877	0	0	0
RPCs (W1) purchased	0	7230	17278	21501
RPCs (W2) purchased	0	0	0	0
Total Crates purchased	46784	46784	36718	21501
Vehicle types adopted	M1	M1, M2, M3	M1, M2, M3	M2

Table 8.1.7 - Resume of solutions C, P1, P2, E

Table 8.1.8 lists detailed values of cost and emission items associated with the reference solutions C, P1, P2 and E. Each item corresponds to a member of the two objective functions. The values of economic cost and environmental impact refer to the whole simulation period (10 weeks).

Solution	**C**	**P1**	**P2**	**E**
Economic cost [€]	**44,172.70**	**54,622.80**	**59,987.50**	**66,634.70**
Operating cost at distribution centres [€]	14,000.00	14,000.00	14,000.00	14,000.00
Operating cost at poolers [€]	0.00	3,000.00	7,000.00	10,000.00
Transport cost from F to D [€]	1,526.10	2,119.09	2,333.35	2,455.96
Transport cost from D to G [€]	3,633.00	4,884.27	5,341.21	5,846.60
Transport cost from G to R [€]	97.94	1,692.81	785.48	0.00
Transport cost from G to I [€]	48.68	1,341.19	677.60	0.00
Transport cost from Z to F [€]	327.03	2,248.68	1,212.84	0.00
Transport cost from Z to K [€]	0.00	150.98	360.80	722.54
Transport cost from K to F [€]	0.00	163.25	603.95	1,203.07
Transport cost from K to R [€]	0.00	2.35	25.47	59.45
Transport cost from K to I [€]	0.00	0.35	3.59	8.96
Transport cost from D to K [€]	0.00	55.77	175.74	405.05
Transport cost from G to D [€]	0.00	24.02	507.34	1,536.10
Purchasing cost of disposable crates [€]	18,468.30	13,843.80	6,803.98	0.00
Purchasing cost of reusable crates [€]	0.00	1,325.55	5,013.08	8,577.07

Washing cost of reusable crates [€]	0.00	823.94	6,940.65	12,954.10
Recycling cost of reusable crates [€]	0.00	32.67	275.23	513.70
Incineration cost of reusable crates [€]	0.00	3.55	29.92	55.84
Recycling cost of disposable crates [€]	2,366.91	4,058.63	2,012.03	0.00
Incineration cost of disposable crates [€]	788.97	1,764.62	874.80	0.00
Storage cost of products in D [€]	576.54	619.30	673.02	576.54
Storage cost of crates in G [€]	2,339.20	2,339.20	2,339.20	2,339.20
Storage costs of crates in K [€]	0.00	128.74	1,998.20	5,380.58
Environmental impact [kgCO2e]	**58,451.00**	**34,674.80**	**32,076.20**	**28,304.20**
Operating emission at distribution centres [kgCO2e]	7,000.00	7,000.00	7,000.00	7,000.00
Operating emission at poolers [kgCO2e]	0.00	750.00	1,750.00	2,500.00
Transport emission from F to D [kgCO2e]	1,064.72	1,240.37	1,278.98	908.56
Transport emission from D to G [kgCO2e]	2,534.65	2,553.70	2,434.48	2,162.90
Transport emission from G to R [kgCO2e]	68.33	1,173.79	543.75	0.00
Transport emission from G to I [kgCO2e]	33.96	910.64	451.33	0.00
Transport emission from Z to F [kgCO2e]	228.16	1,547.79	846.17	0.00
Transport emission from Z to K [kgCO2e]	0.00	105.33	251.72	267.30
Transport emission from K to F [kgCO2e]	0.00	90.58	303.25	445.07
Transport emission from K to R [kgCO2e]	0.00	1.64	12.86	21.99
Transport emission from K to I [kgCO2e]	0.00	0.25	1.98	3.31
Transport emission from D to K [kgCO2e]	0.00	20.63	104.46	149.85
Transport emission from G to D [kgCO2e]	0.00	16.76	300.05	568.27
Purchasing emission of disposable crates [kgCO2e]	40,689.90	15,307.30	7,523.26	0.00
Purchasing emission of reusable crates [kgCO2e]	0.00	1,638.86	6,198.00	10,604.40
Washing emission of reusable crates [kgCO2e]	0.00	61.80	520.55	971.56
Recycling emission of reusable crates [kgCO2e]	0.00	42.62	359.00	670.04
Incineration emission of reusable crates [kgCO2e]	0.00	92.51	779.28	1,454.44
Recycling emission of disposable crates [kgCO2e]	5,829.33	1,333.27	660.96	0.00
Incineration emission of disposable crates [kgCO2e]	425.34	167.63	83.10	0.00
Storage emission of products in D [kgCO2e]	576.54	619.30	673.02	576.54

Table 8.1.8 - Detailed results: cost and emission items for solutions C, P1, P2, E

Figure 8.1.9 and Figure 8.1.10 summarise the results reported in Table 8.1.8. Cost items and emission items are groped in seven main categories: facility opening, transport, disposable crate purchasing/manufacturing, reusable crate purchasing/manufacturing, RPC washing, EoL treatments, storage. For each item category, the related cost and emission is reported. Aim of the two figures is to show of the relevance of each activity on the economy and the sustainability of the supply chain. For both problem dimensions, the manufacturing/purchasing of containers is relevant. In scenarios where RPC are largely used (i.e. P2 and E), container handling and washing has a significant impact on total costs. Storage costs appear not relevant, in particular from the environmental point of view. This is entirely due to logistics optimisation obtained by the problem solving, thanks to which, product and packaging flow is managed in order to follow the just-in-time strategy and, in turn, to minimise the level of stocks along the chain. End-of-life treatment costs decrease with increasing use of reusable containers, while emissions from EoL decrease with reducing use of wooden containers. Transportation costs and emissions are rather stable in all solutions. An exception is noted in solution C where, the complete use of disposable crates and the exclusion of reusable crates imply no reverse flows, therefore a shorter logistics chain, resulting in shorter distances to be covered.

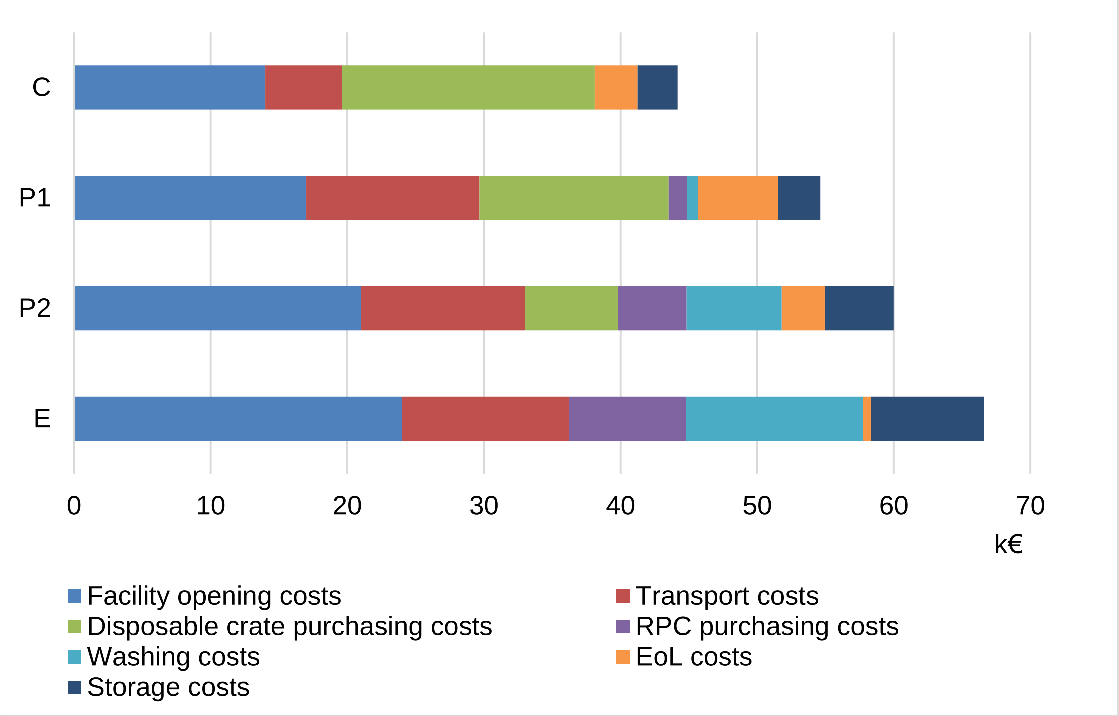

Figure 8.1.9 - Cost items in solutions C, P1, P2, and E

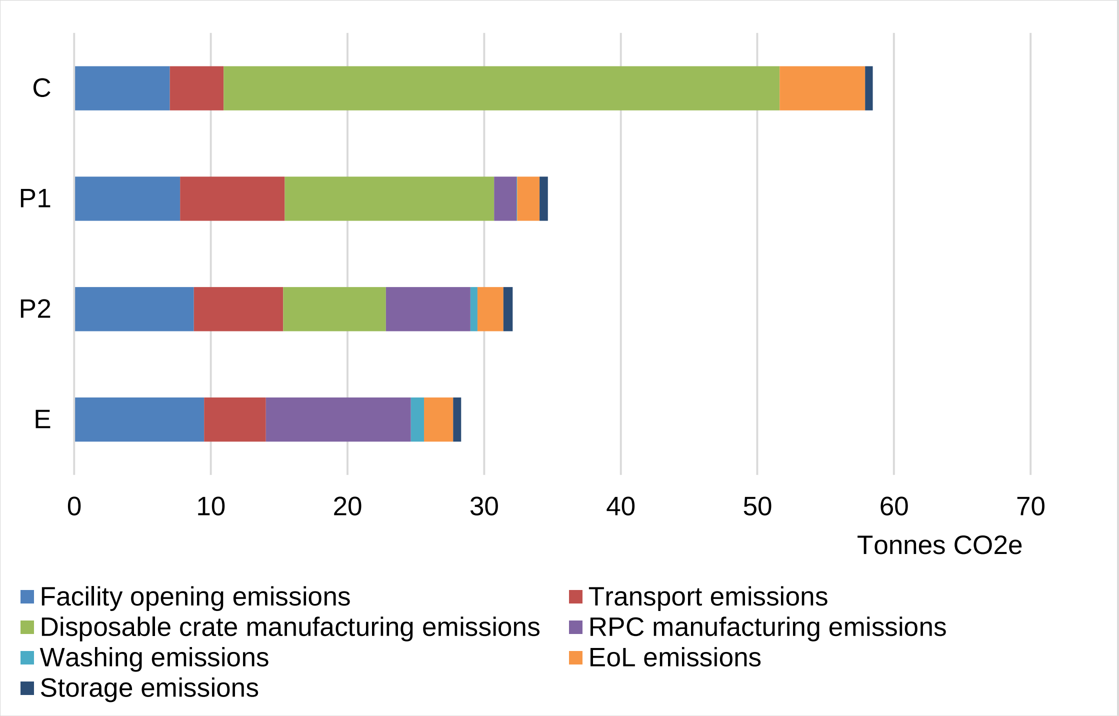

Figure 8.1.10 - Emission items in solutions C, P1, P2, and E

A better understanding on the effects of problem solving on the final configuration of the network is proposed below. 8.1.11, Figure 8.1.12, Figure 8.1.13, and Figure 8.1.14 show the network configuration corresponding with solution C, P1, P2 and E, respectively. In all maps, the dotted lines represent the transportation routes chosen by the model solution.

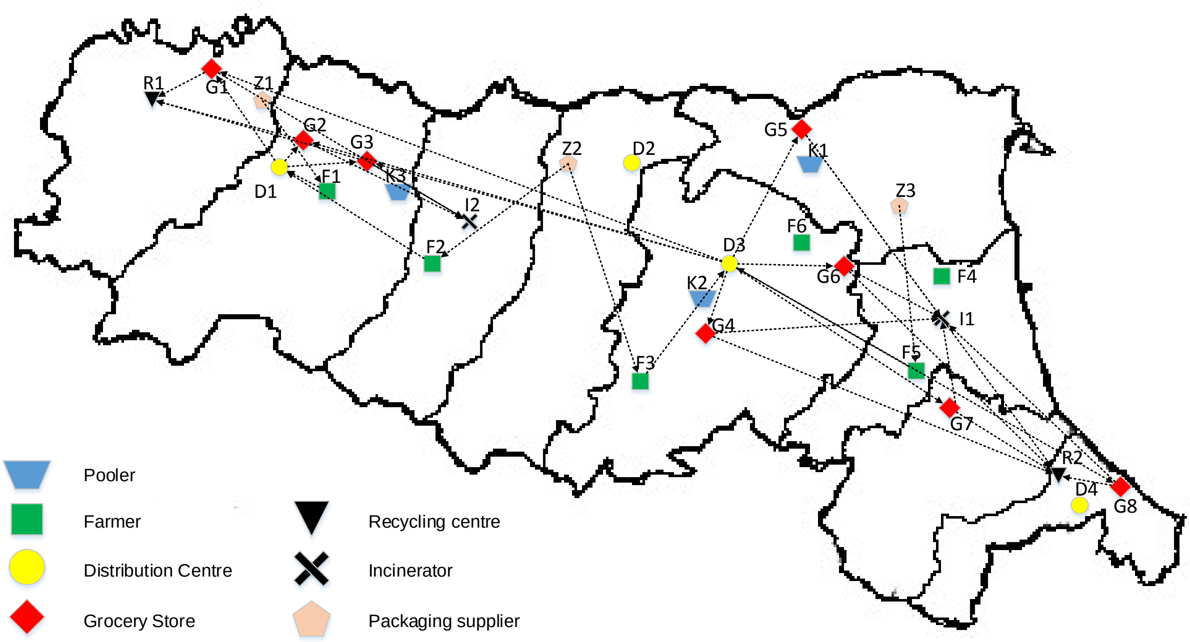

Figure 8.1.11 - Network configuration - Solution C

Solution C is characterised by a linear logistic flow. Disposable containers are supplied from manufacturers to farmers, then to distribution centres and grocery stores. Finally, they are sent to EoL treatment facilities depending on their characteristics.

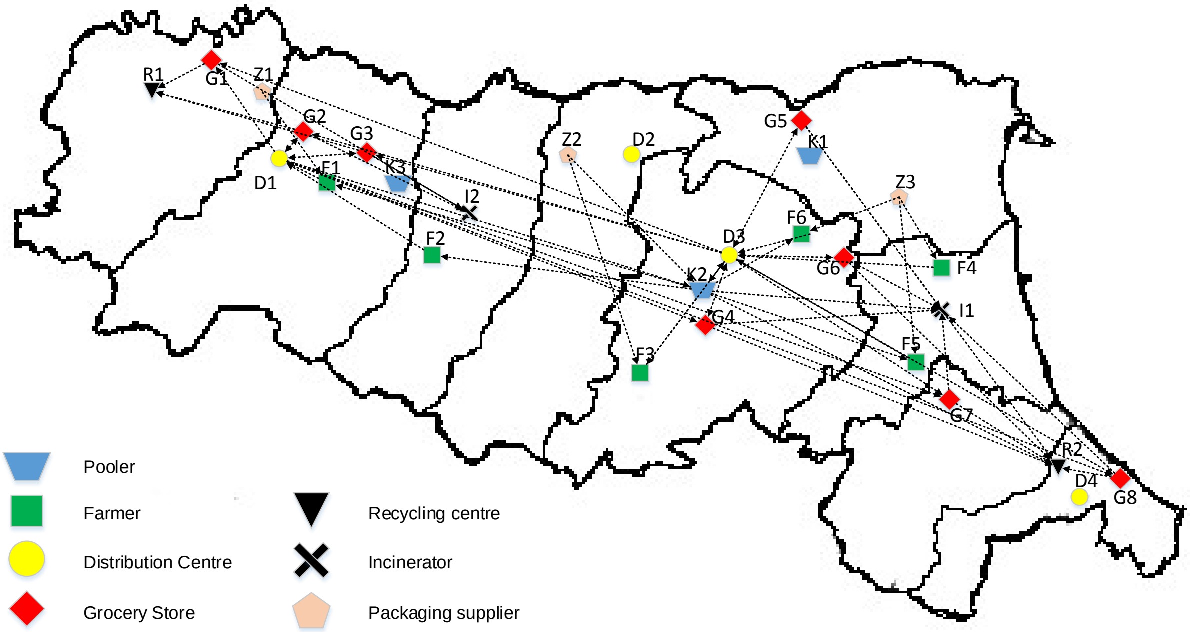

Figure 8.1.12 - Network configuration - Solution P1

Solution P1 suggests the opening of a pooling centre for the handling of reusable crates. The demand of RPCs, and the opening costs and emissions implies the use of only one pooler, out of three available.

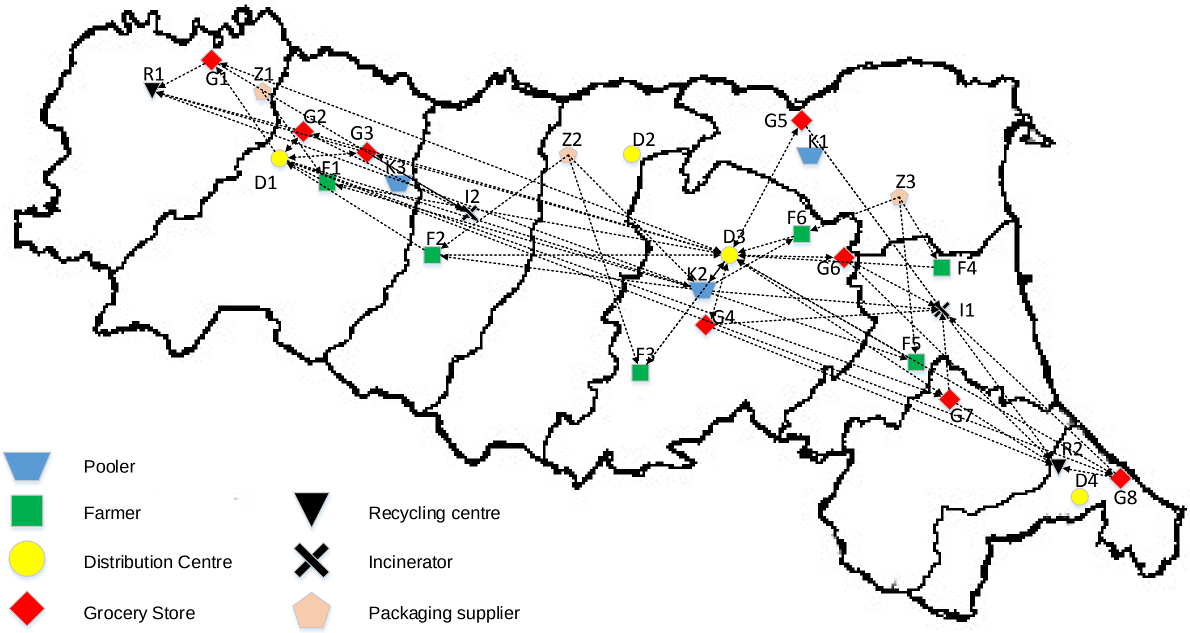

Figure 8.1.13 - Network configuration - Solution P2

The structure of the network in option P2 is almost equal to that proposed by P1, with very few exceptions. On the contrary, solution E is completely different from the previous ones. The number of routes is minimal. Centre K2 is the pivot of the network: all flows of containers pass through the pooler. The supply of containers from manufacturers is limited to the flow from Z2 to K2. Flows to EoL treatment facilities are limited to those from K2 to I1 and R2.

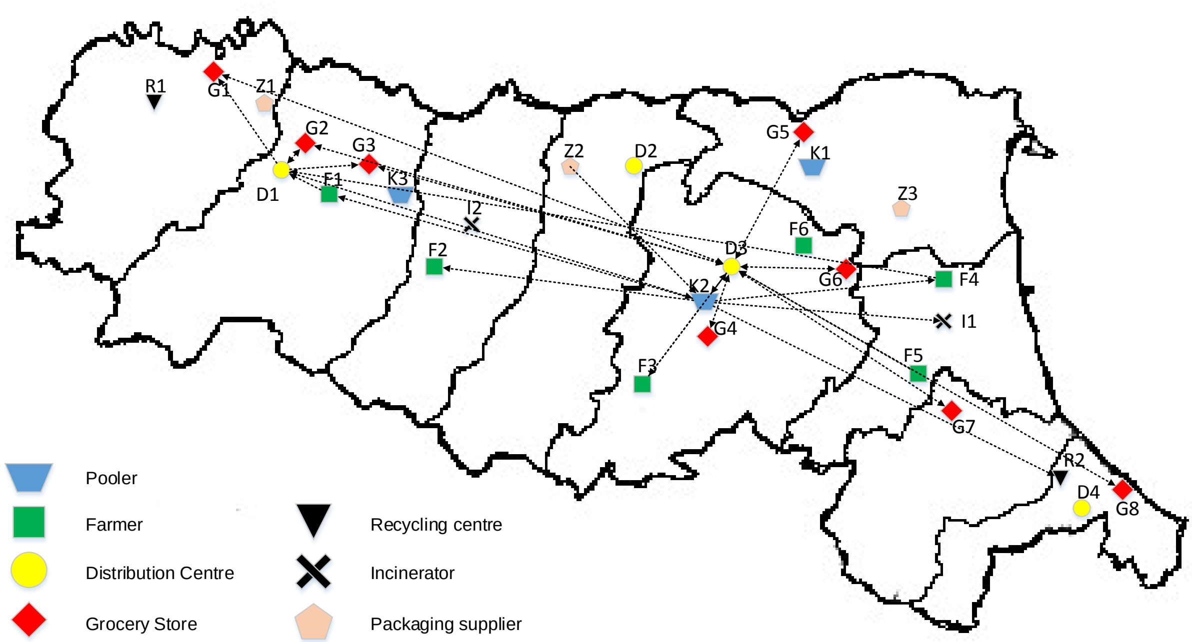

Figure 8.1.14 - Network configuration - Solution E

Figure 8.1.15 shows a summary of the four solutions C, P1, P2 and E and indicates, for each one, the optimal mix of containers chosen during the simulation period. From C to E, container mix moves from a high selection of cardboard boxes to the option that consider only RPCs. With reference to the two type of RPCs, W1 is always preferred to W2: the technical characteristics of W1 (size, weight, capacity) imply both lower unit cost and unit environmental impact than W2.

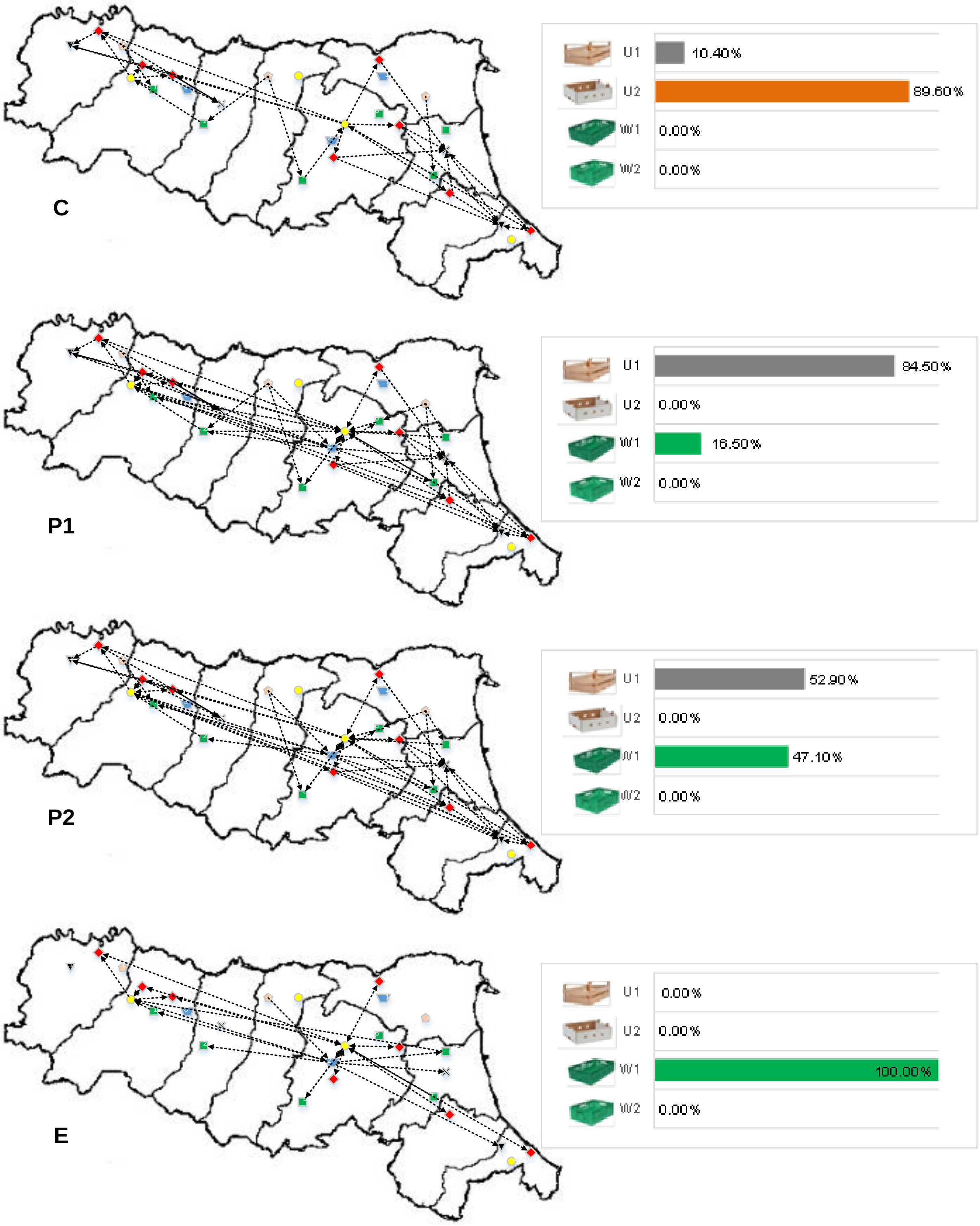

Figure 8.1.15 - Final comparison - Solutions C, P1, P2, E

8.1.6 Discussion and further research

8.1.6.1 Multi-Objective Mixed Integer Linear Programming in decision-making process

As demonstrated in the literature, the Multi-Objective Optimisation is a method that is having growing interest in the areas of GSCM and SCND. Multi-Objective Optimisation allows the finding of sets of optimal solutions that take into account multiple problem dimensions. This methodology is particularly useful in case of unconstrained optimisation, namely when problem targets are not defined by imposed thresholds (such as in presence of specific regulations or standards to comply with), but represent objectives that companies can pursue in order to follow a specific marketing strategy or, on a broader level, to improve their performances. This study focuses on the SCND problem from the economic and environmental perspectives. In particular, having a set of multiple solutions helps the decision maker in market positioning, and in the satisfaction of a constantly evolving demand For a more profit-oriented strategy or for a market that gives to low prices the highest priority, the company will opt for a solution that is closest to C. However, a strategy focused on the minimisation of supply chain costs, does not involve automatically high profits, which are influences by customers' response to certain company choices, such as on the sustainability of their supplier. In order to satisfy a clientele that appreciates the environmental sustainability of their fresh food supplier, the decision maker will opt for a solution that is closest to the environmental optimum. For a balanced position, the intermediate area of the curve indicates optimum solutions for an environmental and economic balanced performance. Figure 8.1.16 presents the relationship between the Pareto Frontier obtained in the analysed case study and the possible main strategy options for the decision makers involved in the supply chain.

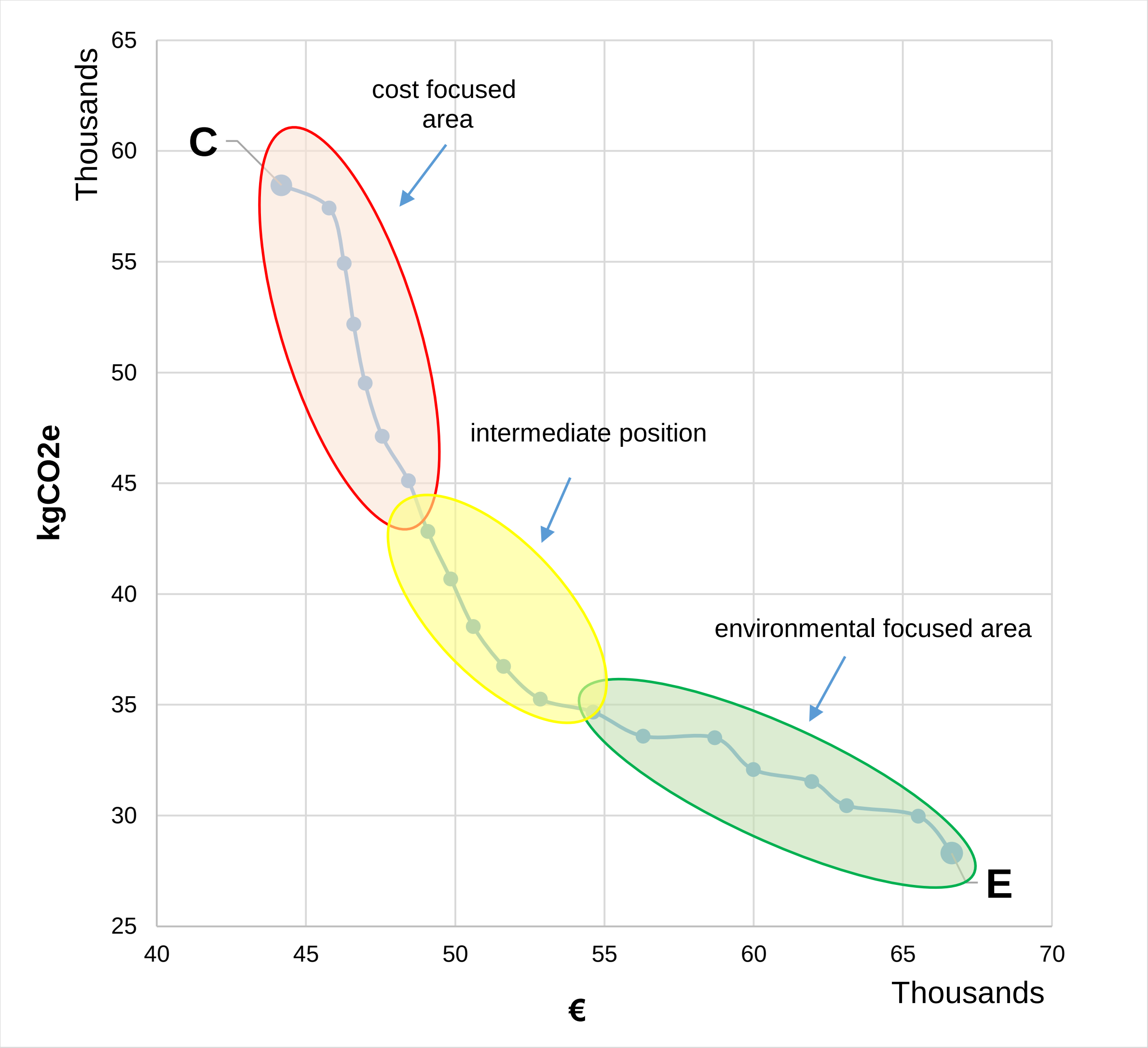

Figure 8.1.16 - Pareto frontier and company strategy

Although in some cases is not possible for decision makers to apply the desired optimal solution, mainly because of the idiosyncrasy between the reality and its simplified modelling, the resolution of the problem helps anyway to locate a benchmark for a comparison between the as-is state of the supply chain and its optimal performance, and to drive to improvement actions.

The consideration of the social dimension in the solving of a SCND problem would complete the sustainability framework. In the Fresh Food Supply Chain analysed in this study, a further improvement can be the consideration of the effects of packaging system selection on workers' labour quality: RPC system is expected to entail greater human labour (e.g. folding, opening, registration of RPCs), in particular at poolers (e.g. sorting and washing of RPCs), than the disposable crate system, where labour is concentrated in container manufacturing and end-of-life. Since the subject of the analysed supply chain is fresh food, a further side that should be integrated in the decision-making problem is the consideration of customers' lead-time and its effects on product quality given the problem of food perishability. Perishability is extremely important in food supply chains. As (Das and Dennis, 1998; Ismail-Yahaya and Messac, 2002; Messac and Mattson, 2002) suggest, perishability is a dimension of the problem, so a possible improvement for the proposed model could be the introduction of its consideration in network planning. Further research is recommended for the implementation of the abovementioned potential extensions.

8.1.6.2 Discussion on economic-environmental MOMILP model for fresh food supply chain network design

The MOMILP model presented in this study is characterised by modularity and flexibility. Through the setting of the available parameters, by using the model is possible to plan a supply chain network based on disposable crates alone, on a reusable container system, or on any mixed solution. The model is also extensive and takes into account multiple real characteristics that are the basis for an optimal selection of crate and vehicle types, and for the solving of location-allocation logistics problem.

The model has been developed as a support to strategic and tactical planning. For this reason, the flow of products and containers are optimised by using continuous variables. The model could support operational decisions through the inclusion of additional constraints and variables. However, as explained in section 8.1.3, such an extension increases significantly problem complexity and, thereby, computational solving time. Further research about the trade-off between model accuracy and problem complexity is suggested.

8.1.6.3 Discussion on the results of the proposed case study

The case study presented in the previous sections is structured in order to present the potentiality of the planning model. A network of limited size and a short planning period characterises the problem used as an example. Such decisions are due to the need to simplify the presentation of the problem and to make possible the representation of the results and their effective understanding. However, it is expected that its use in cases of study of standard size can be managed with an acceptable calculation time, e.g. a few hours for each Pareto solution. The application of the model on a real extended case study is recommended as final test for this research.

8.1.7 Conclusion

This study presents a MOMILP model that can be applied as a decision support system for the SCND of fruit and vegetables multi-packaging distribution systems. Aim of the model is the simultaneous optimisation of economic and environmental performances of the network, in agreement with the principles of GSCM. Output of model application is a set of Pareto solutions that can be considered optimal by the decision-maker. A small example of application of the model on a realistic case study is also presented. Output of the application is the Pareto frontier of optimal solutions. Results show that the mere consideration of economic costs as well as the concern alone of environmental issues leads to extremely different network configurations. This research suggests that, in fresh food SCND the decision-maker deals with the existence of significant trade-offs between economic and environmental objectives, as also shown in Chapter 6.1 (Accorsi et al., 2014) . Therefore, MOO can be profitably used as decision support system and MOMILP is an efficient methodology.

8.1.8 References

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9 CONCLUSION

The main purpose of this dissertation is to present the results of a research on innovative models and approaches for Green Supply Chain Management. Following this fundamental idea, several issues are debated and innovative methods are presented, as well as the results of their application on different case studies, from which intermediate and final conclusions are drawn.

As demonstrated by the surveys presented in Chapter 2 and Chapter 3, Green Supply Chain Management has a broad meaning and embraces a large number of topics related with the integration of the environmental concern in supply chain activities. According to the hot topics stated by several authors, this research has been focused on the analysis, adaptation, integration, development and application of decision-support methods for the environmental concerned design of products and services.

The first part of this thesis has the aim to highlight the meaning of sustainability and life cycle approach and to introduce the concept of Green Supply Chain Management. By presenting the results of a survey on recent literature, the main sub-topics of Green Supply Chain are classified in a structured hierarchy. According to the classification, two main issues are identified as the components of Green Supply Chain Management activities: Green Design and Green Operations.

In accordance with this distinction, a second stage survey focused on these two concepts is presented. As results of the survey, two research areas have been distinguished. The first embraces the research related to the environmental concerned design of products and is known in literature as Design for Environment, Ecodesign, Environmental Conscious Design, and other synonyms. The second area considers the environmental concerned design and planning of services, mostly logistics activities, among the supply chain, and is known in literature with synonyms such as Green Operations, Green Logistics, Green Supply Chain design and planning. It includes sub-topics like remanufacturing, refurbishment and Reuse, Reverse Logistics activities, Closed-Loop Supply Chain Management, design and planning of Green Supply Chain networks.

All the above mentioned research topics share the need of appropriate methodologies and approaches for life cycle economic and environmental impact assessment, uncertainty analysis, process and design optimisation, decision-making support. Therefore, Life Cycle Assessment, Life Cycle Costing, multi-scenario and sensitivity analysis, Mixed Integer Linear Programming and Multi-Objective Optimisation, are included in the methodological foundation of the research.

Such methodologies have been adapted and applied (in some cases used for the development of innovative models) for the solving of a large group of product and process design problems. In the case studies analysed, methodologies have often been integrated, taking advantage from their complementarity, in order to face multidisciplinary and multidimensional problems typical of Green Supply Chain Management.

The research activity has been articulated as follows:

- Assessment of the life cycle environmental impact of prototypical devices and mechanical plants by Life Cycle Assessment methodology (Chapter 5). This research has been designed according to the principles of Design for Environment, as a part of the cascade closed feedback cycle of product development process, which involves the alternation of phases of analysis of the environmental impact of product life cycle and stages of redesign/reconfiguration, with the final purpose of improving the environmental performance of the product. The activity has been articulated in the application of Life Cycle Assessment on a photovoltaic-thermal cogeneration system with Fresnel lenses and bi-axial tracking system, on a set of agricultural machinery for haymaking, and on commercial refrigeration walk-in systems for food preservation. In all cases, these analyses led to the identification of components and life stages crucial for the sustainability of machines and plants (design hotspots), to the evaluation of the benefit induced by certain alternative configurations or design choices, to the estimation of absolute environmental impact indices through the use of impact assessment methods, to the development of proposed improvement proposals aiming at the minimisation of the impact associated with the life cycle of the devices and their components.
- Environmental-economic combined analysis for the design and planning of a fresh food supply chain: disposable versus reusable containers (Chapter 6.1). In this research, the principles of eco-efficient design have been applied, not for the development of a product, but for the planning of a logistics system. Firstly, an analysis of the supply chain in which an organisation active in the supply, recovery and management of returnable plastic containers for fruit and vegetables distribution has been carried out. Then a comparative analysis between disposable packages and reusable plastic containers, and related logistics systems, has been performed. The analysis is characterised by the parallel use of Life Cycle Assessment and Life Cycle Costing, based on common inventory data, in order to obtain a comprehensive environmental-economic assessment. The application of a multi-scenario simulation, defined on the variation of parameters such as the lifespan and the washing frequency of reusable containers, the end-of-life treatment strategy, and the degree of the geographical extension of the distribution network and recovery, have provided the bases for a comprehensive comparison.
- Development of an optimisation model for the design and planning of a closed-loop supply chain in the automotive industry (Chapter 6.2). The activity led to the development of a mathematical model thought as a support to the strategic and tactical planning of a closed-loop supply chain, where the distribution of vehicles, the recovery of end-of-life vehicles (according to the specifications of the European Directive 2000/53), the replenishing of remanufactured components of end-of-life vehicle components in the manufacture of new vehicles and/or their reuse as spare parts are simultaneously optimised. This single-product, multi-period, multi-level, multi-component Mixed Integer Linear Programming model aims at resolving a location-allocation problem, according to an objective function of minimisation of the costs bearing on Original Equipment Manufacturers and customers. The objectives of the model are the

identification of the location of a set of nodes of the network in question and the assignment of flows of vehicles, components and materials among the network layers. The model has been applied to a case study and tested by an extensive sensitivity analysis on the main parameters of the problem.

- Development of an economic-environmental Multi-Objective optimisation model for the design and planning of fresh food supply chain with multi-packaging systems (Chapter 8). This activity integrates Life Cycle Assessment, Life Cycle Costing and Multi-Objective Mixed Integer Linear Programming, and its purpose is to combine knowledge and methodologies developed during the whole PhD programme. The model is designed as a support to the stakeholders, in particular to companies operating in large retail chains, in strategic and tactical planning of the distribution of fresh fruit and vegetables. In particular, it solves the problems of location of certain nodes of the network, selection of types of packaging (disposable/reusable), allocation and scheduling of flows between the different network layers, selection of the most suitable vehicle types, by means of the calculation of Pareto-optimal solutions obtained from the simultaneous minimisation of economic cost and environmental impact functions. Formally, the model is defined as a Multi-Objective Mixed Integer Linear Programming model for the solving of a multi-product, multi-period, multi-level, multi-packaging, and multi-modal location-allocation problem. Its solving involves the definition of a curve of optimal solutions, on the basis of which decision makers can orient their strategies. To each point of the curve corresponds a different physical configuration of the network and different packaging mix and transportation strategies. The model has been applied to a case study, where inputs coincide with the output of Life Cycle Assessment and Life Cycle Costing previously conducted.

From the presented research path clearly emerges the role of Life Cycle Assessment as methodological central thread. As a start, Life Cycle Assessment has been adopted as supporting tool in Design for Environment of products. Then, combined with Life Cycle Costing, as part of a comprehensive economic-environmental evaluation of multiple options in the logistics of the distribution of products. Finally, through the implementation in a Multi-objective optimisation model, Life Cycle Assessment has been included in a decision support tool for the optimal design and planning of a closed-loop supply chain. While in the first applications, Life Cycle Assessment has been used as evaluation instrument of certain design choices, in the last part of the research, Life Cycle Assessment metrics have been used for the definition of the model environmental objective function, and its results as model parameters. In summary, this research can be also understood as a path, in which Life Cycle Assessment has evolved from *ex post* assessment method, to *ex ante* optimisation tool.