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“Multi-objective Models and Methods for Design and Management of Sustainable Logistic Systems”

“Modelli e Metodi Multi-obiettvo per la Progettazione e Gestione di Sistemi Logistici Sostenibili”

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Multi-objective Models and Methods for Design and Management of Sustainable Logistic Systems

by

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Abstract

Logistics is typically defined as the design and operation of the physical, managerial and informational systems needed to allow goods to overcome space and time. Traditional models and methods for logistic system design and management focus on the optimization of the techno-economic performances. However, logistic activities are distinguished by a huge environmental impact. For instance, the final energy consumption for freight transportation reached in recent years the alarming value of 13% of the total end-use energy worldwide, equal to 40 EJ per year. Thus, innovative techniques for logistic system design and management have to guarantee these system overall sustainability not only from a technical and economic perspective but also from an environmental viewpoint. To this end, multi-objective optimization is of strong help. This is a mathematical programming technique to systematically and simultaneously optimize a collection of objective functions, often conflicting among them.

Considering this scenario, aim of this Ph.D. thesis is to develop, propose and validate innovative multi-objective models and methods for design and management of sustainable logistic systems simultaneously optimizing the system technical performance, economic profitability and environmental impact.

The developed models fully manage the material flow from suppliers to assembly or manufacturing areas and from these to final customers through the distribution, storage and retrieving activities among and within the logistic actors. An original decision support system is proposed to jointly minimize the operating cost, carbon footprint and delivery time in the design of multi-modal multi-level distribution networks considering the most relevant features of the delivered products. Concerning warehousing systems, both design and operation problems are tackled. A multi-objective optimization model is developed to determine the warehouse building configuration, namely length, width and height, which simultaneously minimizes travel time, total cost and carbon footprint objective functions. These two latter are estimated through a lifecycle approach. All the activities related to warehouse building installation and operating phases are evaluated both from an economic and an environmental perspective. Warehousing system operation is analyzed by means of storage assignment strategy. A time and energy based strategy is proposed to jointly minimize the travel time and the energy required by the material handling vehicles to store and retrieve the unit loads. Proper vehicle motion configuration and unit load features are considered to accurately model the objective functions. Finally, the presented models and methods are tested and validated against case studies from the food and beverage industry. The results demonstrate that a tremendous environmental impact reduction is possible at negligible technical and economic performance worsening.

Sommario

La logistica viene tipicamente definita come l'insieme di quelle attività di progettazione e gestione di sistemi fisici ed informativi necessari per consentire alle diverse tipologie di merci di superare lo spazio ed il tempo. I modelli ed i metodi tradizionali per la progettazione e gestione dei sistemi logistici si focalizzano sull'ottimizzazione delle prestazioni tecnico-economiche. Tuttavia, le attività logistiche si contraddistinguono per un elevato impatto ambientale. Solo per citare un esempio, il consumo di energia per il trasporto merci ha raggiunto negli ultimi anni il 13% dell'energia complessivamente utilizzata su scala mondiale, pari cioè a 40 EJ annui. Gli approcci innovativi per la progettazione e gestione di sistemi logistici devono necessariamente garantire la loro sostenibilità non solo da un punto di vista tecnico ed economico, ma anche da quello ambientale. A tal fine, l'ottimizzazione multi-obiettivo è di notevole aiuto. Questo metodo di programmazione matematica permette di ottimizzare sistematicamente e simultaneamente un insieme di funzioni obiettivo spesso contrastanti tra loro.

Alla luce di questo scenario, lo scopo di questa tesi di dottorato è quello di sviluppare, proporre e validare modelli e metodi multi-obiettivo innovativi per la progettazione e la gestione di sistemi logistici sostenibili ottimizzando contemporaneamente le loro prestazioni tecniche, economiche ed ambientali.

I modelli sviluppati permettono di gestire nella sua interezza il flusso di materiali dai fornitori ai reparti di fabbricazione o assemblaggio e da questi ai clienti finali attraverso le necessarie attività di distribuzione, stoccaggio e prelievo all'interno e tra gli attori della catena logistica. E' stato sviluppato un sistema per il supporto decisionale atto a minimizzare contemporaneamente il costo operativo, la carbon footprint ed il tempo di trasporto di reti distributive multi-livello e multi-modali prendendo in considerazione le più importanti caratteristiche dei prodotti trasportati. Per quanto riguarda i sistemi di immagazzinamento e stoccaggio, questa tesi affronta sia le tematiche di progettazione sia quelle operative. Un modello di ottimizzazione multi-obiettivo è proposto per definire la configurazione degli edifici atti allo stoccaggio merci, ovvero la loro lunghezza, larghezza ed altezza, al fine di minimizzare il tempo di prelievo, il costo totale e la carbon footprint. Queste ultime due funzioni obiettivo sono state valutate considerando l'intero ciclo di vita del magazzino. Tutte le attività relative alle fasi di installazione ed esercizio dell'edificio vengono contabilizzate sia da un punto di vista economico che ambientale. Per quanto concerne la gestione operativa di un sistema di immagazzinamento, questa tesi affrontata il problema dell'assegnazione dei prodotti ai vani di stoccaggio. Si è definito un modello di ottimizzazione multi-obiettivo per minimizzare contestualmente il tempo e l'energia necessari alle attività di prelievo e stoccaggio. Per modellare opportunamento le funzioni obiettivo temporali ed energetiche sono stati valutati accuratamente sia i profili di moto dei veicoli per lo stoccaggio merce sia le caratteristiche dei prodotti da immagazzinare. Per concludere, i modelli ed i metodi presentati sono stati validati e testati con casi studio provenienti dall’industria alimentare. I risultati ottenuti dimostrano come sia possibile ridurre drasticamente l’impatto ambientale di questi sistemi logistici a scapito di un trascurabile peggioramento delle prestazioni tecnico ed economiche.

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Thank you Giulia. Strong woman irreplaceable for me.

Francesco Pilati

“Don’t whine,
don’t complain,
don’t make excuses.”
John Robert Wooden

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Abbreviations

LS	Logistic system
DN	Distribution network
MH	Material handling
KPI	Key performance index
DC	Distribution center
NPV	Net present value
LCC	Life cycle costing
GDP	Gross domestic product
GWP	Global worming potential
DSS	Decision support system
I/O	Input/output
UL	Unit load
WH	Warehouse
AS/RS	Automated storage/retrieval system
SKU	Stock keeping unit
SLA	Storage assignment problem
WCED	World Commission on Environment and Development
UNSD	United Nation Sustainable Development
LCA	Life cycle assessment
CF	Carbon footprint
MO	Multi-objective optimization
WB	Warehouse building
S/R	Storage/retrieval

1. Introduction

Logistics is traditionally defined as the “design and operation of the physical, managerial and informational systems needed to allow goods to overcome space and time” (Daskin, 1985). According with the proposed definition, logistic purpose is the development of design criteria and management strategies for material handling and information sharing along the supply chain through proper systems.

Design criteria differ from management strategies due to the time horizon considered. The former define the long-term structure and configuration of logistic systems. These decisions can be rarely modified, have a terrific economic impact and often rely on forecasts and estimations. The latter manage the short-term aspects of logistic. The related decisions are frequently modified to consider the evolution of the reference environment over time.

Furthermore, logistic typically handle two goods, namely materials and information. The term materials generically stands for the flow of raw materials, components, and final produces through the supply chain. The products required by the customers are delivered, handled and manufactured from suppliers to retailers through manufactures, production plants and distribution centers. Along with materials, the corresponding information represent the second good shared among the supply chain actors. Information usually represent a precious source of feedbacks for each actor to assess its performances and to improve its efficiency and effectiveness.

Last, proper systems are designed to perform the different logistic functions. Distribution network purpose is to deliver the products required by the customers in the right quantity, at the right place and at the right time with the most efficient and effective supply configuration. Inventory management is the activity which organizes the availability of items along the supply chain coordinating the purchasing, manufacturing and distribution functions. Warehousing system purpose is buffering the material flows through the supply chain to accommodate variability caused by several factors. Material handling is the activity that manages and organizes the material flows within an industrial system. Finally, assembly lines are the flow-line mass production systems for the component assembly and the definition of the final product required by the customer.

This Ph.D. thesis focuses on two logistic systems, distribution networks and warehousing systems in particular. The material flow from suppliers to assembly or manufacturing areas and from these to the final customers is fully managed by these systems. Distribution networks define the optimal configuration to transport products from supplier facilities to production plants through distribution centers. When the products are delivered to the plants these have to be properly stored waiting the retrieving to feed the assembly lines or job shops. Once a product is assembled or manufactured it is usually stocked waiting to be delivered to the final customer with the most efficient and effective transportation configuration. Furthermore, the distribution centers that belong to a distribution network typically are warehousing systems themselves.

Purpose of distribution network planning is the definition of a set of features that univocally determine the network configuration. Three are the most commonly adopted configuration, namely producer storage with direct shipment, distribution storage with carrier delivery and producer or distribution storage with customer pick up. For each of these configurations design criteria and management strategies vary considering the planning horizon. Strategic design defines the overall network structure considering a long term horizon, tactical planning manages the material flow among the distribution network nodes in the mid-term horizon, whereas operational management deals with the short-term dynamic management of the network.

Concerning warehousing systems, the interrelated set of decisions that defines the warehouse configuration can be divided in design criteria and operation strategies. Warehouse design aims to define the overall structure that affects the material flow pattern, the building size and dimensions, the layout configuration within each storage department and the equipment selected for material handling. Warehouse operation focuses on the receiving and shipping activities for incoming and outgoing material flows, storage assignment strategy of the stock keeping units and picking of the items required by customer orders. While warehouse design concerns long-term planning decisions, warehouse operation deals with short-term management strategies. Furthermore, design and operation are sequential decisions. The former defines the warehousing system structure in which the latter manages the product storage activities.

Traditional indicators of logistic system performances typically focus on technical and economic performances. Travelled distance, throughput rate, cycle time for the former and net present value, total cost of ownership and life cycle costing for the latter are among the widest spread indices to assess a logistic system performances. However, recent trends suggest to include other dimensions for logistic system evaluation. Elkington first (1998) proposes a framework to measure the overall performances for companies and organizations. Traditional business accounting techniques commonly use the term “bottom line” to refer to the profit (or loss) of a company at the end of the year. Thus, this author proposes the term “triple bottom line” to suggest a triple accounting for firms that considers three business dimensions, namely economic, social and environmental, to achieve the overall sustainability. Thus, economy, society and environment are the three pillars of sustainability. Sustainable business activities, manufacturing processes or logistic services have to simultaneously focus on all the three sustainability pillars. Economic dimension represents the typical financial accounting that measures the economic performances of a company, manufacturing or logistic system. Social dimension measures the extent in which a companies use fair and beneficial practices for employees, local community, and social structures where they develop the business. The last sustainability dimension is the environmental one and it evaluates the impact of the business activities, manufacturing or logistic system to the environment. Including environmental impact in company and business key performance indices is of major importance since “in the last 60 years the atmospheric concentrations of carbon dioxide increased by 25%” and “it is extremely likely that human influence has been the dominant cause of this observed global warming” (IPCC, 2013). Several techniques and approaches can be adopted to estimate the environmental impact of a certain business activity, manufacturing process or logistic service. One of the most widely adopted is carbon footprint. “Carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity (or process) or is accumulated over the life stages of a product (or system)” (Wiedmann and Minx, 2007). Direct emissions are those that are directly produced during the progress of a process or the characteristic activities of a system. On the contrary, indirect emissions are the one produced far from the process or system site but required to guarantee the offered service or product. For carbon footprint calculating it is necessary to evaluate the amount of greenhouse gases emitted during the life cycle of the product, process or system. Life cycle includes all the stages of a product as its manufacturing right from bringing of raw materials to final packaging, distribution, consumption or use, and final disposal and/or recycling.

Considering the importance of sustainability issue in industrial activities, design criteria and management strategies for logistic systems have to simultaneously ensure the required technical performances, increase the economic profitability, limit the environmental impact and, if possible, foster the social wealth. However, traditional design models and management methods focus on only one key performance index, usually economic. Melo et al. (2009) in a detailed survey on current models and methods for logistic system design and management states that only 9% of the analyzed researches propose non-economic key performance indices. Instead, logistic activities are distinguished by a tremendous environmental impact. The final energy consumption for freight transportation reached the alarming value of 13% of the total end-use energy worldwide, equal to 40 EJ per year (IEA, 2012).

To overcome these limitations multi-objective optimization is of strong help. This is defined a mathematical programming technique to systematically and simultaneously optimize a collection of objective functions, often conflicting among them. Typically, there is no single global solution, and it is often necessary to determine a set of points that all fit a predetermined definition for an optimum. The predominant concept in defining an optimal solution is that of Pareto optimality. A solution of a multi-objective optimization problem is Pareto optimal if there is no other solution that improves at least one objective function without detriment to another function. The set of the optimal solutions of a multi-objective optimization problem is named Pareto frontier. To define the final configuration of a system, for instance a logistic one, a unique solution has to be selected among the ones that lay on the Pareto frontier. The solution selection is an arbitrary but necessary phase in every multi-objective optimization problem that deals with real world application. Typically, the selection of the final solution is subjective and it depends on the absolute or relative importance that the decision-maker confers to the objective functions to identify a trade-off among them.

Considering this presented reference framework, aim of this Ph.D. thesis is to develop and propose multi-objective models and methods for design and management of sustainable logistic systems. Two logistic systems are analyzed, namely distribution network and warehousing systems. The interaction of these two enable the material flow from suppliers to assembly or manufacturing areas and from these to the final customers through proper storage systems. A decision support system is proposed to ease the distribution network planning. The system allocates the customer demand to the suppliers, evaluates the adoption of intermediate distribution centers and defines the transport configuration in terms of number of network level, node infrastructure and transport modes adopted considering the features of the several shipped products.

The delivered products have to be stored in proper warehousing systems. Thus, this manuscript proposes models and methods to tackle both the warehouse design and operation problems. In particular, an innovative model is developed for warehouse building design, whereas a custom storage assignment strategy is presented to support the operation activities.

Purpose of warehouse building design is the definition of warehouse building configuration, represented by length, width and height, to maximize the warehousing system performances during its entire lifetime. Both installation and operating phases are considered. Building installation includes land purchase, building material and handling

vehicle manufacturing as well as building construction. Operating activities deal with the handling vehicle usage and the worker salary for storage and retrieving activities as well as building lighting and heating during winter season.
Warehouse storage assignment deals with the definition of effective strategies to organize items into industrial warehouses, i.e. which product stores in which location, to achieve high performances. The model presented in this Ph.D. thesis includes three relevant features of the considered system. First, the speed profile of the material handling vehicles is evaluated both on vertical and horizontal directions modelling proper motion configurations distinguished by acceleration and deceleration. Furthermore, the friction effect is considered to correctly estimate the handling vehicle motion. Last, relevant features of the products to be stored are included as demand frequency, storage required capacity and weight.

Aim of the proposed models and methods is to ensure the sustainability of the presented logistic systems. Thus, this manuscript adopts three indices to assess the system performances. Several indicators can be used to measure the technical performance of the different logistic systems. The effectiveness of distribution network planning is measured through the delivery time to transport products from suppliers to customers, while one of the most relevant warehouse technical indicator is the travel time to store or retrieve the products. Concerning the economic dimensions of sustainability, total cost approach is exploited. The proposed models and methods aims to minimize the sum of all the direct and indirect expenditures determined by the system considered. Finally, environmental impact is evaluated through the carbon footprint approach. Innovative design criteria and management strategies have to minimize the greenhouse gases produced during the entire logistic system lifecycle and emitted by all its related activities, as the extraction, manufacturing, transportation, installation, maintenance and disposal (or recycling) of each of its components.

For each logistic system considered, the previously described key performance indices are modeled to define a multi-objective optimization model as a support tool for design criteria and management strategies. Each objective function accurately estimates a key performance index, whereas the decision variables fully represent the logistic system configuration. To define the problem optimal solutions, namely the Pareto frontier, proper methods proposed by the reference literature are adopted. The decision maker has to select among these the final solution that represents the logistic system ultimate configuration. This manuscript proposes a practical rule of thumb to determine the final solution of a multi-objective optimization problem as the best trade-off among the objective functions.

Finally, the proposed multi-objective models and methods for design and management of sustainable logistic systems are validated and tested through real case studies from the food and beverage industry. Fresh food distribution network and warehousing system for beverage product storage represent the designed logistic systems.

1.1. Thesis outline

This Chapter presents the reference framework for the developed Ph.D. thesis. It highlights the traditional approaches for logistic system design and management. Their major drawbacks are analyzed considering the relevance that sustainability achieved in these last years. Multi-objective optimization is presented and as an effective and efficient technique to simultaneously consider more than one key performance index in design criteria and management strategies. Thus, aim of this Ph.D. thesis is to develop and propose multi-objective models and methods for design and management of sustainable logistic systems. According to this purpose, the remainder of this Ph.D. thesis is organized as follows and as illustrated in Figure 1.1.

- **Chapter 2** analyzes the traditional design criteria and management strategies proposed by the literature and adopted by the practitioners for logistic system planning. An overview and definition of the most relevant logistic systems is presented. Inventory management, material handling, assembly lines, distribution networks and warehousing systems are considered. The Chapter focuses, in particular, on these two latter. The most relevant distribution network features are described along with the configurations typically adopted. Each configuration is assessed through a set performance indices that can be divided in cost and service factors. Considering warehousing systems, the most relevant problems concerning their design and operation are analyzed. Warehouse design is the process of interrelated decisions that defines the long term structure of the warehousing system, namely its size and dimensions, the department layout and the equipment selected. Warehouse operation techniques are described as the one that defines the short term system management to enable the product flow across the warehouse, from receiving to shipping through storage and order picking.

- **Chapter 3** presents the concept of sustainability and its application to the industrial context. An overview on sustainable development is proposed, from its former definition in the 1987 Brundtland report to its latter contained in the United Nations Resolution A/RES/70/1, also known as “Sustainable Development Goals”, singed the 25th September 2015 by more than 190 countries. The sustainability concept is further developed analyzing its relevance and adoption in operations, supply chain and logistic system management. Considering the industrial context, this chapter presents the three pillars of sustainability along with quantitative models and method for their evaluation. Economic profitability is estimated through the net present value approach and similar techniques, as well as exploiting the more inclusive life cycle costing. Environmental impact is evaluated through the standardized carbon footprint and life cycle assessment techniques. Aim of these techniques is the impact evaluation of a product, process or system to the human health, the natural environment and its resources during the entire system lifetime, exploiting the so called “from cradle to grave” approach. Social wealth is evaluated to determine how the considered system impacts on the society. Over the last decades several organizations proposed different indices to measure the health, poverty and education of a specific group of people. Finally, a fourth sustainability pillar is proposed to measure the technical performance of the considered system. Despite this last key performance index could converted in economic expenditures, it represents a relevant aspect of logistic systems. Thus, it should be separately and independently evaluated.

- **Chapter 4** proposes a mathematical programming technique to define the optimal solution of a problem distinguished by more than one objective function. An overview of the multi-objective optimization concept is presented along with its formulation and the reason why it has a remarkable importance within this research. Furthermore, this Chapter describes the Pareto optimality, presenting its definition, formulation and the most important features. The different methods to solve a multi-objective optimization problem are presented and analyzed. Three are the possible approaches: a priori, a posteriori and no articulation of preferences. One of these methods is deeply investigated since relevant for the purpose of this research. Finally, the Chapter proposes a selection criteria to determine the final solution for a multi-objective optimization problem.

- **Chapter 5** presents a multi-objective optimizer Decision Support System (DSS) to minimize the operating cost, the carbon footprint and the delivery time in the design of multi-modal distribution networks. A multi-objective optimization model is presented to overcome the widely adopted methodologies focused on the cost minimization, only. The proposed approach simultaneously assesses three independent objective functions, evaluating the network costs, the carbon footprint (CO_2 emissions) and the shipping time from the producers to the final retailers. The DSS manages multimodal four-level (three-stage) distribution networks, best connecting the producers to the final retailers, through a set of distribution centers. It allows multiple transport modes and inter-modality options looking to the most effective distribution network configuration from the introduced multi-objective perspective. The three optimization criteria can be considered independently or solved simultaneously, through the so-called Pareto frontier approach. Finally, the proposed DSS is validated against a case study about the delivery of Italian fresh food to several European retailers.

- **Chapter 6** deal with warehouse building design, which purpose is to define the warehouse building configuration, represented by length, width and height, that optimizes a certain objective function. Two are the objective functions traditionally considered: travel time and operating cost. Only few contributions propose design methods that simultaneously consider more than one objective function. Among these functions environmental impact is typically ignored, despite the significant importance this achieved in recent years in logistic context. This Chapter proposes an innovative multi-objective optimization model to determine the warehouse building configuration that simultaneously minimizes travel time, total cost and carbon footprint objective functions. Travel time is defined as the average time to pick up or drop off a stock keeping unit from or to the warehousing system. Total cost and carbon footprint are estimated exploiting a life-cycle approach. All the activities related to the warehouse building installation and operating phases are evaluated from an economic and an environmental perspective. Finally, a case study of a warehouse to be built for an Italian beverage company is presented to validate the proposed model.

- **Chapter 7** focuses on the effectiveness in warehouse operations. This is crucial for the industrial companies to be competitive in the market arena by reducing the response time and inbound costs, increasing their global service level. Storage assignment deals with the definition of effective strategies to organize items into industrial warehouses to achieve high performances. This Chapter enhances the conventional approaches on storage assignment proposing a time and energy based strategy, for traditional warehouses served by forklifts, based on the joint minimization of the travel time and the energy required by the material handling vehicles to store and retrieve the unit-loads. The models to compute the expected single-command travel time and energy are integrated into a multi-objective model, optimizing the load assignment. An application, taken from the beverage industry, is, finally, discussed. The different perspectives of adopting time and energy to drive the load assignment are stressed proposing a practical best trade-off rule.

- **Chapter 8** concludes this Ph.D. thesis presenting final remarks about the developed research activities and suggesting future development for further improvements of approaches, methods and models.

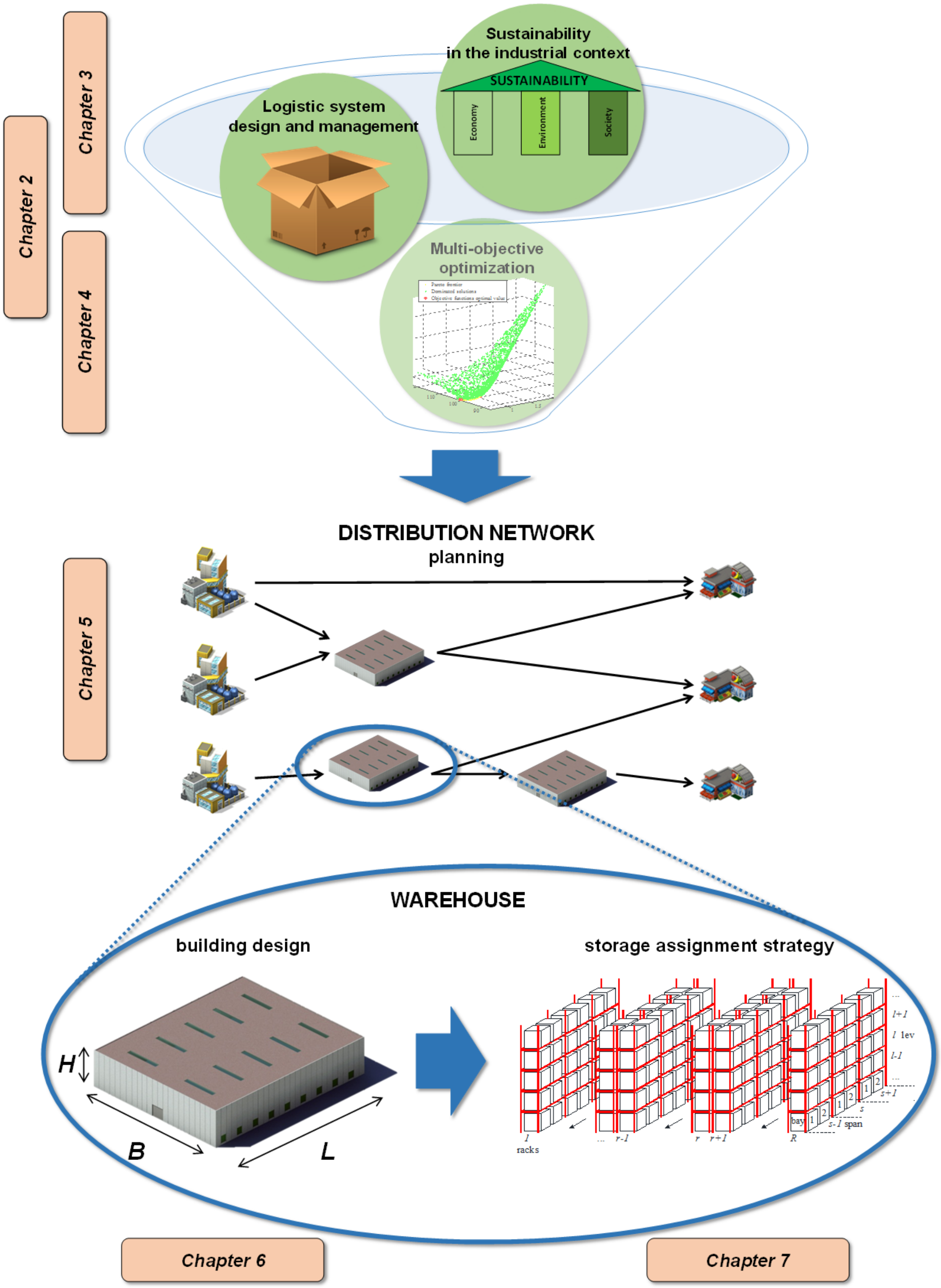


Figure 1.1. Ph.D. thesis outline.

2. Logistic system design and management

This Chapter analyzes the traditional design criteria and management strategies proposed by the literature and adopted by practitioners for logistic system planning. An overview and definition of the most relevant logistic systems is presented in Paragraph 2.1. Inventory management, material handling, assembly lines, distribution networks and warehousing systems are considered. Paragraph 2.2 and 2.3 focus, respectively, on these two latter. The most relevant distribution network features are described along with the configurations typically adopted. Each configuration is assessed through a set of performance indices that can be divided in cost and service factors. Considering warehousing systems, the most relevant problems concerning their design and operation are analyzed. Warehouse design is the process of interrelated decisions that defines the long term structure of the warehousing system, namely its size and dimensions, the department layout and the equipment selected. Warehouse operation techniques are described as the one that defines the short term system management to enable the product flow across the warehouse, from receiving to shipping through storage and order picking.

2.1 Logistic system definition and overview

Logistics is traditionally defined as the "*design and operation of the physical, managerial and informational systems needed to allow goods to overcome space and time*" (Daskin, 1985). This definition summarizes the most relevant features that distinguish logistics. First, both design and operation phases are considered. Design phase aims to define long-term structure and configuration of a logistic system (LS). The typical decisions involved are: the selection of the system location; the definition of its size and dimensions; the equipment installed and the worker employed; the throughput rate and the service capacity. Operation phase deals with LS mid and short-term management. The evolving environment in which the system operates heavily affects the decisions involved in this phase. Market demand, customer requirement, supplier capacity, equipment availability often change over time. Thus, appropriate management of LS operation defines and redefines strategies and procedures for each time horizon to include the dynamism that distinguished the operating environment.

Furthermore, LSs include both material and information flows. The former are the flows of goods from their sources to the customers through the necessary processes including manufacturing, assembly, storage, retrieval and delivery. The latter are the flows of information among the LS actors. Each actor shares the information about his supplier capacity and/or customer demand, product requirement as quantity, quality, cost or price, and the timing to enable an efficient and effective integration of the entire LS.

Lastly, LS purpose is to allow goods to overcome space and time. The products have to be physically delivered from the production sites to the demand points through the LS actors. Within each actor the possible activities of receiving, storing, retrieving, processing, sorting and shipping require in-house transportation and handling. Moreover, the goods have to be delivered on-time to each LS actor considering its own requirements.

An alternative definition of logistic is promulgated by Ballou (1992). "Logistic is the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of raw materials, in-process inventory, finished goods and related information from point of origin to point of consumption for the purpose of conforming to customer requirements."

This definition proposes two relevant LS features previously neglected, cost and customer requirements. Cost is one of the most relevant key performance indices (KPIs) for LSs. It should evaluates the expenditures determined by the system for its installation, during the operating activities and for its disposal. Cost is the KPI traditionally adopted to evaluate and compare LS design criteria and management strategies. Several other KPIs could be converted in cost to limit the LS evaluation to a unique unit of measure. However, this approach chance being considered inaccurate because of the assumption made for the unit of measure conversion. Concerning customer requirements, these define the characteristics of the shipped products in terms of quantity, quality, place, time and price.

Thus, aim of traditional design criteria and management strategies for LSs is to satisfy the customer requirements at the minimum possible cost.

The several logistic functions are performed by different LSs. Figure 2.1 presents the typical LSs that accomplish the aforepresented logistic goals along with their distinctive features.

1. Distribution network (DN) purpose is to deliver the products required by the customers in the right quantity, at the right place and at the right time with the most efficient and effective supply configuration. DN decisions deal with the location of new production plants and distribution centers, the allocation of the customer demands to the suppliers and the configuration of the transportation network (Manzini and Bindi, 2009). Considering time horizon, DN planning can be divided in strategic design, tactical planning or operational management respectively for long, mid and short term decisions (Jayaraman and Ross, 2003).
2. Inventory management is the activity which organizes the availability of items to the customers. It coordinates the purchasing, manufacturing and distribution functions to determine the level of inventory for raw materials, components, consumables, final products and spare parts necessary to achieve the desired level of customer service while considering the cost of performing the other logistic activities (Stock and Lambert, 2001 and Wild, 2007). Inventory management define when and how much to order for each stored product considering inventory holding, ordering and purchase cost.
3. Warehousing system purpose is buffering the material flow along the supply chain to accommodate variability caused by factors such as product seasonability and/or batching in production and transportation; consolidation of products from various suppliers for combined delivery to customers; value-added processing such as kitting, pricing and product customization (Gu et al, 2007). Gu et al. (2010) suggest to divide the warehouse (WH) related problem into design and operation. The formers deal with long-term decisions as the WH overall structure, its sizing and dimensioning, the department layout, the equipment selection and the operation strategy selection. The latters are short-term managed with receiving and shipping techniques, custom storage strategies and proper order picking.
4. Material handling (MH) is the activity that uses the right method to provide the right amount of the right material at the right place at the right time, in the right sequence, in the right position and at the right cost (Tompkins et al., 2010). Considering this definition, MH equipment can be classified into three groups based on their functions: equipment for movement, equipment for storage and equipment for positioning (Cho and Egbelu, 2005). Within each category the proper equipment has to be selected evaluating the required features for the handling activity.

5. Assembly line is a flow-line production system which consists of a number of stations arranged along a conveyor belt or a similar mechanical material handling equipment. The workpieces are consecutively launched down the conveyor belt and are steadily moved from station to station. At each station, a certain part of the total work, necessary to manufacture the product, is performed. The problems related to this LS deal with the balancing of the workload among the stations, the sequencing of the different products to be assembled on the same line, the selection of the proper equipment for the assembly operations and the feeding of components and materials required by the final product (Faccio et al., 2015).

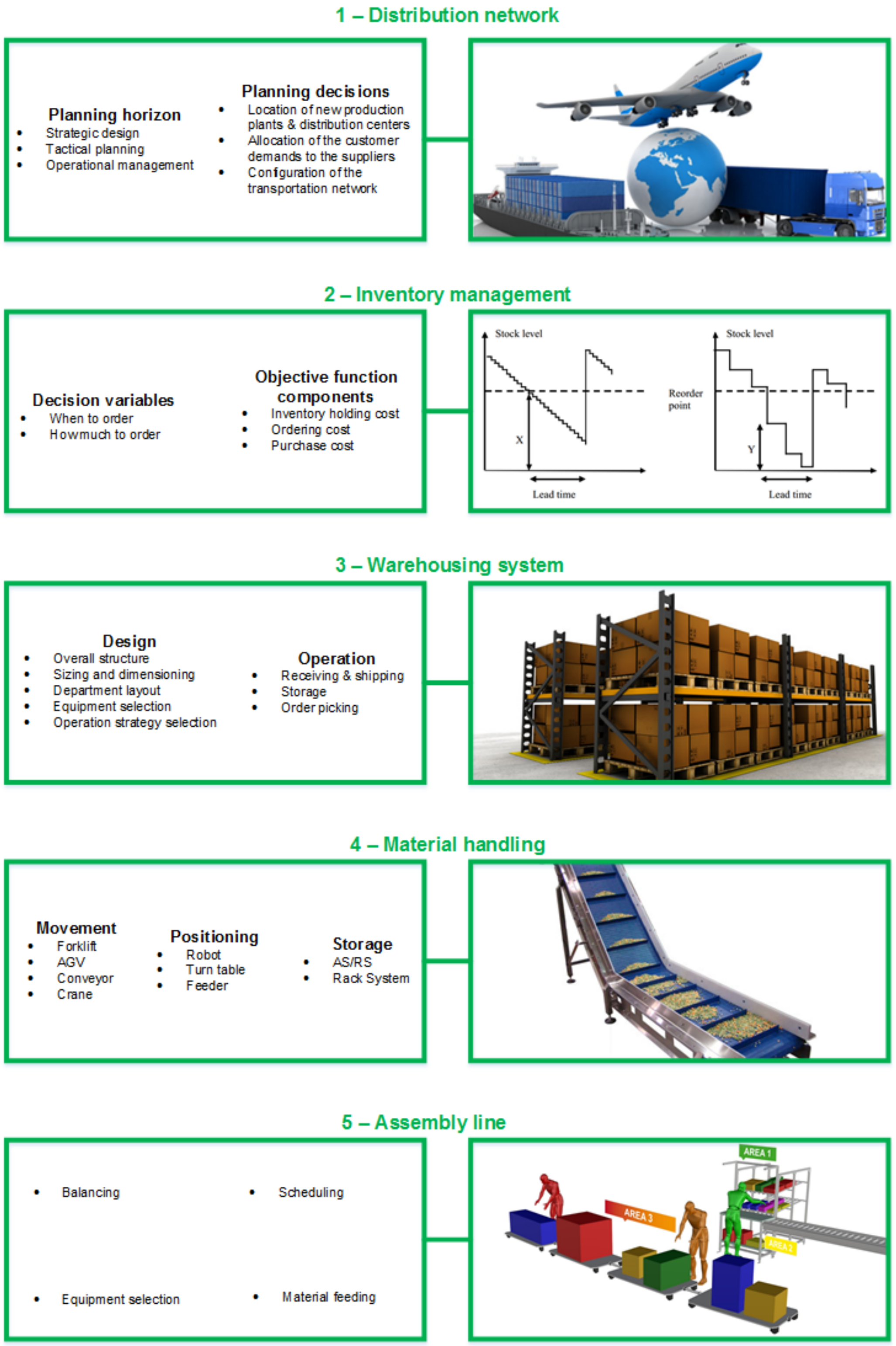


Figure 2.1 Traditional logistic systems of the logistic function.

The LSs presented are highly interconnected. For instance, the DN length (direct vs. two or more stage shipment) affects the inventory level of the delivered products. In turn, a certain stock level requires a specific storage capacity affecting the warehousing system design. The most efficient and effective MH equipment for WH storage and retrieving activities has to be selected considering all the aforementioned conditions. Last, even assembly line material feeding is affected by all the previous decisions.

Considering the extent of logistics field of research, this Ph.D. thesis focuses on two of the aforementioned LSs, namely DN and warehousing system. This research proposes innovative models and methods for design and management of these LSs to increase the efficiency and effectiveness of the material and information flows from supplier plants to the productions lines and from these to final customers. DNs are designed and managed to deliver raw materials and components from suppliers to producers and to ship final products from these to the customers. Warehousing system purpose is receiving and storing the incoming products from suppliers and the outgoing ones for customers. Furthermore, storage and retrieving activities aims at optimally feeding the production lines as well as stocking the manufactured products.

The following paragraphs 4.2 and 4.3 present for DN and warehousing system, respectively, traditional design criteria and management strategies along with the most commonly adopted KPIs.

2.2 Distribution network

DN aim is to transport products from production facilities to demand points ensuring the customer requirements of quantity, quality, time and place exploiting the most efficient and effective supply configuration.

2.2.1 Distribution network features

Each DN is distinguished by a set of features that univocally determine its configuration (Ambrosino and Scutella, 2005).

- Flow type: single vs. multi-product.
  Whereas the DN is designed to transport a specific or several product types. DN complexity is much greater for multi-product flows because the shipment configuration typically varies along the network. The shipload of a set of products delivered from a producer to a distribution center (DC) has to be sorted at the DC with other loads to guarantee the right product mix to be transported to the final customer.

- Problem dynamicity: single vs. multi-period.

  Single-period DN consider static information to design and manage the network, thus no input data varies over time. On the contrary, multi-period DN determines the optimal values of the network parameters for each time interval, e.g. month, week or day. For instance, the market demand of a certain customer could be fulfilled by distinct suppliers in different days.

- Level/stage number.

  A level is defined as a set of DN nodes distinguished by the same function (e.g. production plants). A stage is defined as the connection that links two levels. For instance, direct shipment is distinguished by the direct delivery of products from producers to final customers. One stage connects the two involved levels.

- Sourcing type: single vs. multi-sourcing.

  Single sourcing tremendously decreases the DN complexity. Each DN node can be served uniquely by one source, e.g. the demand of one customer can be fulfilled by only one DC. On the contrary, multi-sourcing enables the delivery of several nodes to a unique DN actor.

- Channel type: single vs. multi-channel.

  Single channel enables a unique transport mode from two nodes of different levels. On the contrary multi-channel frees the transport mode selection between each node couple. It is necessary to remark that this definition does not affect the DN mono/multi-modality. For instance, a single channel DN could exploit a certain transport mode from producers to DCs and a different one from these to customers.

- Node infrastructure.

  This feature defines with transportation infrastructure is available for each DN node. For instance, even if train is generally available for producers-DCs delivery some of these could not be closely located to railway stations.

2.2.2 Distribution network configuration

The combination of the aforepresented DN features identifies specific DN configurations. Each of these is typically adopted in a specific logistic environment. The selection of which configuration to adopt depends on which performances are relevant and/or required. Three are the most commonly adopted DN configurations. Considering where the products are stored and how these reach the final customers the DNs are distinguished in (Chopra, 2003):

- Producer storage with direct shipment.

  Products are directly shipped from the producers to the final customers bypassing the retailers which only receive the orders and initiates the delivery request. All inventories are centralized and stored at producers. These aggregate the demand and provide a high product availability with low inventory level. This DN configuration is typically adopted for a large variety of low and unpredictable demand of high value items where customers are willing to wait for delivery and accept several partial shipments. Furthermore, this configuration enables producers to postpone product customization.

- Distribution storage with carrier delivery.

  Inventory is held by DCs/retailers in intermediate WHs and carriers are used to transport products from the intermediate location to the final customers. This DN configuration is well suited for medium to fast moving items and when customers require faster delivery than producer storage configuration but not even immediate one. This DN configuration is able to handle lower product variety compared to the producer storage one.

- Producer or distribution storage with customer pick up.

  Inventory is stored at producer or DC WHs but customers place orders online and come to designate pickup points to collect the ordered products. This DN configuration enables to lower the delivery cost thus increasing the set of product sold and customer served. The greater handling cost at the pick-up points is overcame by the expenditure savings of using an existing infrastructure.

The following Table 2.1 proposes the DN configurations along with their features whereas Table 2.2 defines the performance characteristics for each of these. Furthermore, Figure 2.2 presents a graphical representation of the DN configurations highlighting the product and information flows. As shown in Table 2.2, DN performance characteristics can be grouped in cost and service factor. Cost factor includes all the expenditures determined by the product storage at certain DN node, transportation to the final customer, facility installation and on-site product handling as well as information sharing. Service factor represents the service level offered to the customer. It is determined by the response time, the product variety, the product availability, the customer experience, the order visibility and the returnability. Analyzing the DN economic performance, most of direct shipment DN cost is determined by transportation from producers straight to each customer and by the effort to collect and share the order information. Carrier delivery DN expenditures are equally partitioned among the cost factors, whereas customer pick up DN is remarkably affected by the inventory cost to hold and store a great product variety at the pick-up sites. Concerning service factor, direct shipment DN greatest effort is focused on products, thus this DN benefits from a wide product variety and a great product availability. On the contrary, carrier delivery DN aim is to ensure a great customer satisfaction. Response time and customer experience are the main strengths of this DN. At last, customer pick-up service level is a mix of the previous two, distinguished by a great product availability as well as a tremendous customer experience.

Table 2.1. Distinctive features for each distribution network configuration.

DN feature	**Producer storage with direct shipment**	**Distribution storage with carrier delivery**	**Producer/distribution storage with customer pick up**
Flow type	Both single and multi-product	Both single and multi-product	Both single and multi-product
Problem dynamicity	Both single and multi-period	Both single and multi-period	Both single and multi-period
Level/stage number	2 levels, 1 stage	3 levels, 2 stages	4 levels, 3 stages
Sourcing type	Multi-sourcing	Single-sourcing	Single-sourcing
Channel type	Multi-channel	Multi-channel	Multi-channel
Node infrastructure	Function of the transport modes	Function of the transport modes	Function of the transport modes

Table 2.2. Performance characteristics for each distribution network configuration (adapted from Chopra, 2003). The arrows represent the qualitative evaluation of the performances. Very high ↑↑, high ↑, intermediate ↑↓, low ↓, very low ↓↓.

	Performance characteristic	**Producer storage with direct shipment**	**Distribution storage with carrier delivery**	**Producer/distribution storage with customer pick up**
Cost factor	Inventory	↑↓	↑↑	↑
	Transportation	↑	↑↑	↑↓
	Facilities and handling	↓	↑	↑↓
	Information	↑	↑↓	↑↓
Service factor	Response time	↑	↓	↑↑
	Product variety	↑	↓	↑↓
	Product availability	↑	↑↑	↑↓
	Customer experience	↑↓	↑↑	↑
	Order visibility	↓	↑	↑↓
	Returnability	↓	↑	↑↓

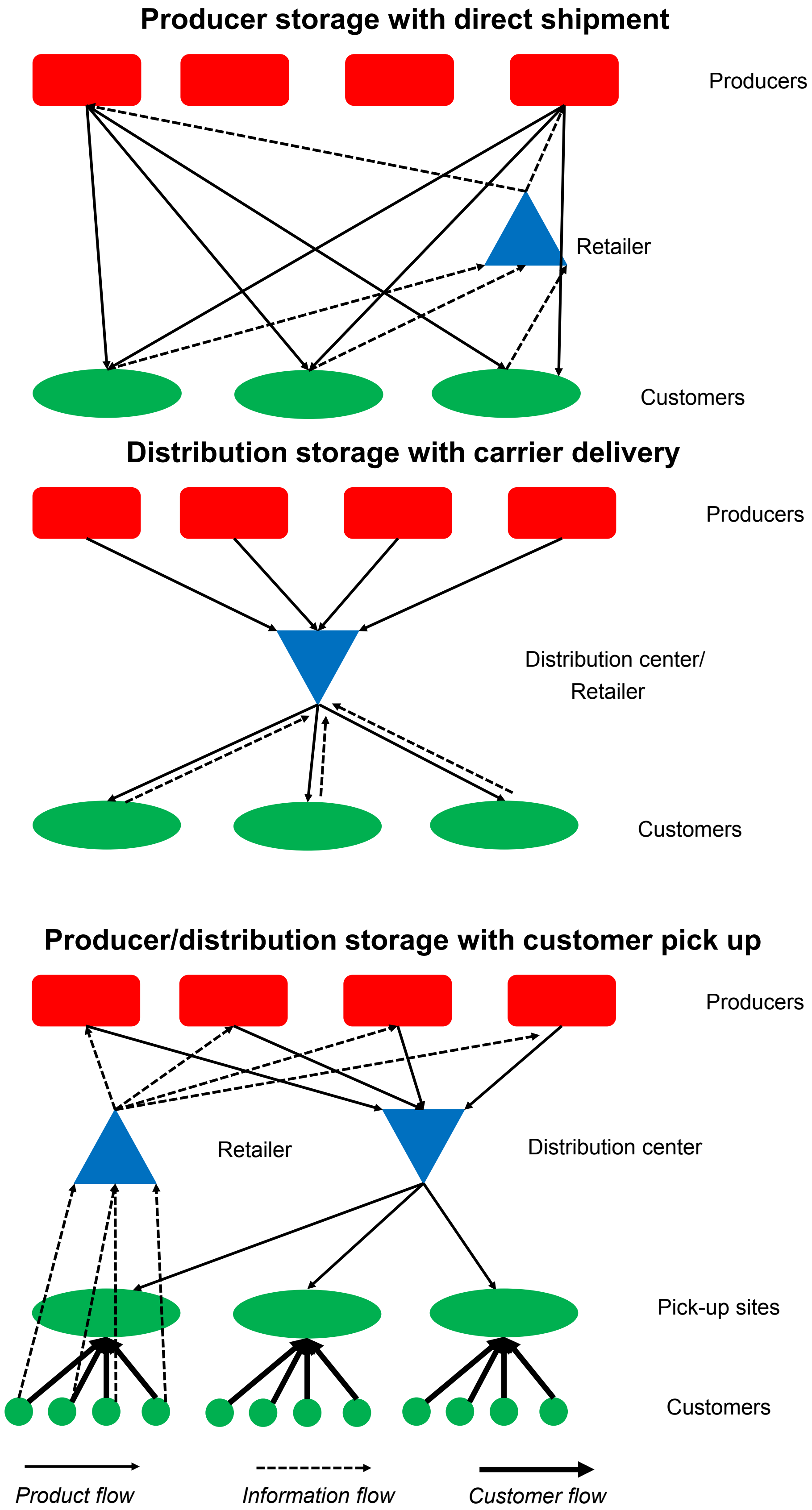


Figure 2.2. Product (solid line) and information (dashed line) flows for each distribution network configuration (from Chopra, 2003). Red, blue and green figures respectively for producers, DCs/retailers and customers.

2.2.3 Distribution network planning horizon

A further approach to classify DNs is considering their planning horizon (Table 2.3). Design criteria and management strategies varies considering long, mid or short term decisions. For each of these time horizons a specific planning approach is suggested (Manzini et al., 2008).

- Strategic design
  Strategic design defines the overall DN structure considering a long term horizon (3-5 years). Typical decisions deal with how many facility of each type (producer, DC, retailer) to install and open, their location into the network, the production/distribution/storage capacity as well as the customer demand allocation to the other DN nodes. Aim of this approach is to minimize the DN cost (or maximize its profit) for a single planning period without considering the interaction between these. Lastly, this problem type is typically classified as location-allocation and network location problem.

- Tactical planning
  Tactical planning manages the material flow among the DN nodes in the mid-term horizon (1 year - 6 months) considering the interaction of the decision variables over several operating periods. Lead time, service level, stock level and safety stock are defined for each analyzed period simulating the system dynamicity. Aim of this planning approach is to define the fulfillment policies, to manage the material flows and to control the bullwhip effect for the multi-echelon inventory distribution fulfillment system considered.

- Operational management
  Operational management deals with the day by day (or week by week) dynamic management of the DN. This short term, multi-period planning approach allocates the customer (retailer) demand to the retailers (DCs/productions plants) to define the logistic requirement planning. Aim of this approach is to define the vehicle routing for product delivery, maximize their saturation and reorder the right quantity to the DN upper levels.

Table 2.3. DN planning approaches for different time horizons (adapted from Manzini et al., 2008).

	Strategic design	**Tactical planning**	**Operational management**
Planning horizon	Long term	Mid term	Short term
Problem type	Location-allocation problem & network location problem	Multi-echelon inventory distribution fulfillment system	Dynamic location-allocation problem
Problem dynamicity	Single-period (3-5 years)	Multi-period (1 year-6 months)	Multi-period (weeks-days)
Planning approach	Static design	Dynamic design and management	Dynamic management
Decisions	Facility number, location, storage/production capacity and demand allocation	Lead time, service level, stock level, safety stock	Allocation of customer (retailer) demand to retailers (DCs/prod.plants)
Objectives	Cost minimization/profit maximization	Fulfillment policies, material flow management ,bull-whip effect control	Logistic requirement planning

As it is possible to notice from the DN framework presented in this paragraph, traditional design criteria and management strategies purpose is to define the DN features to maximize its profitability and/or the service level. Both installation and operating revenues and costs are included in the presented approaches to evaluate the DN overall profitability. Technical performances as lead time, stock-out, delivered product quality are suggested to evaluate the DN service level. However, traditional literature is typically limited to the evaluation of these DN KPI, neglecting the integration of these with other relevant DN performances.

2.3 Warehousing system

Two are the most relevant purposes of warehousing systems (Bartholdi and Hackman, 2011): to match the supplier capacity with customer demand and to consolidate the final products (Figure 2.3).

The former purpose is required by the variability of supplier capacity and customer demand both in term of quantity and time. Product seasonality could be better managed by producers by mean of WHs storing final products in low-demand period and retrieving these in peak one. Unreliable transport delivers final products in the wrong quantity and/or time. Exploit a WH located closed to the customer enables the producers to face this problem category.

The latter purpose of warehousing system is consolidating the final products to optimize transportation and to increase customer service. Transport optimization aims to maximize the container or load saturation. The products delivered from different producers and addressed to one customer are unpacked, sorted and repacked (thus, consolidated) to decrease the shipment number with a benefit for all the DN actors. Lower transportation cost for producers, higher vehicle saturation for carriers and fewer receives for customers. Furthermore, product consolidation enables to increase customer service level. Small manufacturing activities and assembly operations can be handled in WHs. Thus, storing identical products of the same family ready to be completed increases the product variety and decreases the lead time for customers, while decreases the producer inventory levels.

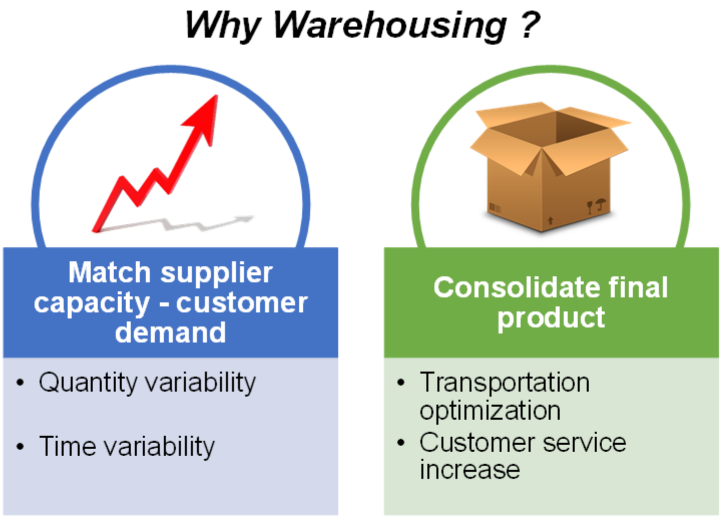


Figure 2.3. Purposes of warehousing systems.

Design and management of a warehousing system is an interrelated set of decisions which purpose is to define the WH optimal configuration and the best operating strategies to maximize the storing system performances. WH problems can be divided in design and operation (Rouwenhorst et al., 2000) (Figure 2.4). WH design aims to define the WH overall structure that affects the material flow pattern, the building and the department size and dimensions, the layout configuration within each department, the equipment selected for material handling and the operation storage strategy to adopt (Gu et. al, 2010). WH operation planning focuses on the receiving and shipping activities for incoming and outgoing material flows, in-house storage of the stock keeping units (SKUs) and picking of the items required by the customer orders (Gu et al., 2007). These last two WH activities requires respectively the following decisions. The former specifies for each incoming SKU in which storage location of which zone of which department it has to be stored. The latter divides the picking orders into batches of items to be independently picked, determines the best sequence and route of picking locations and defines if the picked items have to be sorted in order during or after the picking process.

The following paragraph 4.3.1 analyzes the traditional WH design problems whereas the operation ones are investigated in paragraph 4.3.2. As previously mentioned, design and operation planning are highly connected. Operational performances are significantly affected by the decisions taken in the design phase. The former are long-term decisions almost impossible (or with tremendous expenditures) to be changed when the WH building is set-up. Operation planning deals with daily, weekly or monthly short-term decisions that can change over time and permanently constrained by WH design. Finally, aim of these design criteria and management strategies is the maximization of the most relevant WH performances, typically considered as total cost, throughput rate, cycle time and space utilization.

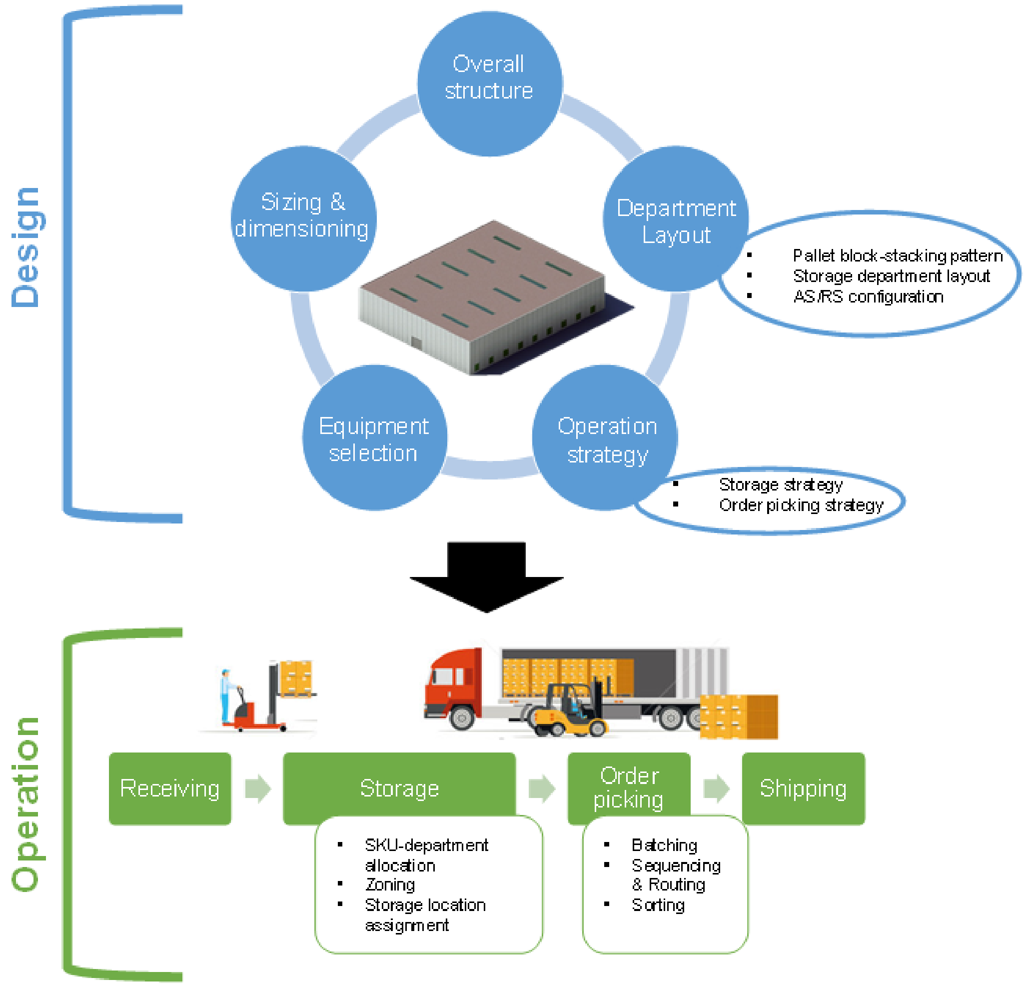


Figure 2.4. Framework for WH design and operation problems (from Gu et al., 2007).

2.3.1 Warehouse design

As suggested by Gu et al. (2010), five are the most relevant problems concerning WH design, namely overall structure, sizing and dimensioning, department layout, equipment selection and operation strategy.

- Overall structure
  This design phase defines how many storage departments to include in the WH, which technologies to adopt and how picking orders are handled to meet the storage and throughput requirements at minimum cost.

- Sizing and dimensioning
  - Sizing
    WH sizing determines the WH storage capacity. Two are the types of WH sizing problem. The former considers the WH inventory level as an external requirement that has to be satisfied both in term of quantity and time. The latter confers the WH the direct control on inventory policy.

  Considering the former problem, White and Francis (1971) first propose a cost minimization linear programming model to determine the optimal WH storage capacity to satisfy a stochastic demand of storage space. The considered costs estimate the building construction, the product storage and the unsatisfied storage demand. Concerning the latter problem, Levy (1974) model includes not only the WH construction cost but even the expenditures related with inventory holding and replenishment procedures (Gu et al., 2010).

  - Dimensioning

    Purpose of this WH problem is the definition of the WH building dimensions, namely length, width and height, to ensure the required size determined in the previous phase. Dimensioning objective function is determined by the sum of construction and operating costs (Francis, 1967).

    Finally, latest research suggests to consider the different WH departments in sizing and dimensioning problems (Heragu et. al, 2005). These models and methods define the WH total size and its allocation to departments and determine the WH dimensions along with the department one.

- <u>Department layout</u>

  Three are the layout problems within a warehouse department (Gu et. al, 2010): pallet block-stacking pattern, storage department layout and automated storage/retrieval system (AS/RS) configuration.

  - Pallet block-stacking pattern.

    Aim of this problem is to determine the storage lane depth, the number of lanes, the stack height, the pallet placement angle with the aisle, the clearance between the stored pallets and the aisle length and width. The definition of the lane depth has to balance the tradeoff between space utilization and ease of storage and retrieval operations. Indeed, deep lanes decrease the aisle number, thus increase the space utilization. On the other hand, this lane configuration worsens the accessibility of the bottom storage locations.

  - Storage department layout.

    This problem defines the structure of aisles for a WH department to both minimize the construction and material handling cost. Traditional decisions deal with the aisle number, orientation, length and width supposing certain storage and picking policies (e.g. random storage and single-command order picking).

  - AS/RS configuration.

    For WHs equipped with AS/RSs for storage and retrieval activities it is necessary to determine the number of cranes and aisles as well as the storage rack dimensions to minimize the installation and operating cost and/or maximize the equipment utilization.

- <u>Equipment selection</u>
  A further relevant problem of WH design deals with the level of automation to select and consequently the type of material handling equipment to adopt for storage and retrieval activities. These decisions remarkably affect other WH design problems as well as several operating decisions. Furthermore, equipment selection has a great impact both on WH installation and performance.

- <u>Operation strategy</u>
  In the design phase the strategies that regulate the WH operation are selected. These strategies have a remarkable importance since they have a great impact on the WH performance and they are not likely to be often changed. Two are the major operation strategies: storage and order picking ones.
  - Storage strategy.
    This problem deals with the selection of which strategy to adopt to select in which storage location to stock the WH products. Three are the most frequently used storage strategies. Random storage enable to stock the incoming products in any empty storage location, typically the closest to the input/output (I/O) point. Dedicated storage suggests to define a single or a set of possible storage locations for each product type considering the distinctive product features. Class-based storage is a hybrid of the former two and proposes to group the storage locations in classes (typically by proximity to the I/O point), assigning each product type to a class and randomly storeing the products within each class.
  - Order picking strategy.
    Order picking is the process of retrieving products from storage in response to specific customer orders. To maximize this added-value activity, order picking has to be performed following one of the most common strategies (Gu et. al, 2010). Wave picking groups the orders that have to be shipped together and suggests to pick them during the same day/shift fraction. Batch picking assigns a certain group of orders to a picker to be simultaneously picked in one trip. Zone picking divides the storage spaces into picking zones for each of which one or more picker perform the activities uniquely within the assigned picking zone.

Outcome of the WH design is a set of decisions that have to be taken for each WH design problem as presented by Table 2.4. In the end, WH design is univocally determined by the sum of the taken decisions.

Table 2.4. Warehouse design problems and related decisions (from Gu et al., 2007).

WH design problem	Decisions
Overall structure	• Material flow • Department identification • Relative location of departments
Sizing & dimensioning	• Size of the warehouse • Size and dimension of departments
Department layout	• Pallet block-stacking pattern • Aisle orientation • Number, length, and width of aisles • Door locations
Equipment selection	• Level of automation • Storage equipment selection • Material handling equipment selection
Operation strategy	• Storage strategy selection • Order picking method selection

2.3.2 Warehouse operation

WH operation concerns the management of the material flow incoming and outgoing the WH as well as within the WH building. Incoming shipments are delivered into the warehouse and unloaded at the receiving docks. Then the received products are stored in the WH through proper strategies to achieve high space utilization and facilitate efficient material handling. When customers require certain products to be delivered an order is placed and picking process is designed to efficiently and effectively retrieve the desire products and to prepare the orders. Finally, the required ordered are shipped to the customers through shipping docks. Gu et al. (2007) divide the described process in three sequential phases, namely receiving and shipping, storage and order picking.

- Receiving and shipping

  These activities manage the products arrival to WH, their unloading at receiving docks as well as the later loading into carriers and WH leaving through shipping docks. To proper manage these presented activities a set of required information is needed. The time and quantity of the incoming shipments, the content and due date of the customer orders and the WH dock layout as well as MH equipment availability. Aim of this phase is to assign the inbound and outbound carriers to docks, schedule their service and allocate the MH resources. Finally, efficiency and effectiveness of receiving and shipment activities is seriously affected by the knowledge level of the incoming and outgoing shipments, namely no, partial statistical or perfect knowledge of arriving and departing processes.

- Storage

  Storage phase aim is to define for each SKU in which department, zone and storage location it has to be stocked and held. These decisions are fully analyzed in the following.
  - SKU-department allocation

    Concerning WH department, for each SKU it has to be defined in which department and in what quantity it has to be stored along with its inter-departmental moves. One of the most relevant and common problem that belongs to this category is the forward-reverse one. A separate and compact forward area is designed for picking high-demand, fast-moving products. This technique decreases the order-picking cost but it requires additional MH to restock the forward area from a reserve one (Gu et al., 2007).
  - Zoning

    Aim of this problem is the definition of specific zones within each department and the assignment of SKUs to these zones. One of the most relevant zoning advantage is to fully exploit zone picking strategy (see Paragraph 2.3.1). This picking techniques strengths are the limited space the picker has to cover to pick an order and the great familiarity a picker obtains with the subset of picked SKUs.
  - Storage location assignment

    This problem purpose is to assign the incoming products to storage locations to minimize the MH cost and/or maximize the space utilization. Required information are the storage location availability, physical dimension and layout location along with physical features, demand quantity, arrival and departure time of the SKUs to store.

    Storage location assignment (SLA) problem varies considering the amount of information available for the incoming SKUs.

    Item information provides complete information about the arrival and departure time of each single item (e.g. unit load or pallet). Thus, SLA problem can benefit from these facts and defines dynamic storage location that varies over time (Goetschalckx, 1998). Product information are the features that distinguish the SKU of the same type. Required storage location, demand frequency, physical dimensions and weight enable to group SKUs in classes and assign these to storage location. Traditional SLA strategies adopted for this category are random, dedicated and class-based storage. This latter typically exploit common product indices as popularity, maximum inventory and cube-per-order-index. Finally, if no information about the SKUs are available simple SLA strategies are used, as closest-open-location and random ones.

- Order picking

  Order picking process organizes the received customer orders and manage the MH activities to efficiently and effectively retrieve the products from their respective storage locations and sort them for the shipment to the customer (Frazelle, 2002). Order picking is typically organized in the following sequential steps.

  - Batching

    Given a set of customer orders, this step divides the set into batches. Each batch is picked and accumulated for packing and shipping by a certain picker during a specific time window, also known as “pick wave” (Gu et al., 2007).
  - Sequencing and routing

    This phase defines the best sequence and route of locations for picking a certain set of products. Typically, the purpose is the travelled distance minimization. Traversal and return are two of most widely adopted routing polices. The former requires the picker to cross through the whole aisle distinguished by at least one product to pick. The latter suggests the picker to always enter and exit at the same aisle side (Hall, 1993). Advanced approaches should exploit simulation techniques to consider congestion when multiple picking tours are simultaneously executed.
  - Sorting

    When two or more orders are picked together it is necessary to sort during or after the picking process. Each of these approaches is distinguished by its specific advantages and disadvantages.

Outcome of the WH operation planning is a set of decisions that have to be taken for each WH operation problem as presented by Table 2.5. In the end, WH operation activity is univocally determined by the sum of the taken decisions.

Table 2.5. Warehouse operation problems and related decisions (from Gu et al., 2007).

WH operation problem		Decisions
Receiving and shipping		• Truck-dock assignment • Order-truck assignment • Truck dispatch schedule
Storage	SKU-department assignment	• SKUs assignment to WH departments • Space allocation
	Zoning	• SKUs assignment to zones • Pickers assignment to zones
	Storage location assignment	• Storage location assignment • Storage classes definition (eventually)
Order picking	Batching	• Batch size • Orders assignment to batches
	Sequencing and routing	• Sequencing of picker tours • Routing of picker tours
	Sorting	• Order assignment to lanes

3. Sustainability in the industrial context

This Chapter presents the concept of sustainability and its application to the industrial context. An overview on sustainable development is proposed, from its former definition in the 1987 Brundtland report to its latter contained in the United Nations Resolution A/RES/70/1, also known as “Sustainable Development Goals”, singed the 25th September 2015 by more than 190 countries. The sustainability concept is further developed analyzing its relevance and adoption in operations, supply chain and logistic system management. Considering the industrial context, this chapter presents the three pillars of sustainability along with quantitative models and method for their evaluation. Economic profitability is estimated through the net present value approach and similar techniques, as well as exploiting the more inclusive life cycle costing. Environmental impact is evaluated through the standardized carbon footprint and life cycle assessment. Aim of these techniques is the impact evaluation of a product, process or system to the human health, the natural environment and its resources during the entire system lifetime, exploiting the so called “from cradle to grave” approach. Social wealth is evaluated to determine how a specific system impacts on the society. Over the last decades several organizations proposed different indices to measure the health, poverty and education of a specific group of people. Finally, a fourth sustainability pillar is proposed to measure the technical performance of the system analyzed. Despite this last key performance index could be converted in economic expenditures, it represents a relevant logistic system aspect, thus it should be separately and independently evaluated.

3.1 Sustainability definition and overview

Industrial development after the Second World War determined radical changes to the earth. Economic models uniquely based on profit maximization severely affected the society and the environment.

3.1.1 Sustainability ground

Child labor, unfair working conditions, inadequate health assistance, insufficient education level and discrimination based on gender, race and age are the most serious consequences of modern development for the society. Considering environment, the Intergovernmental Panel on Climate Change in their Fifth Assessment Report on climate change (IPCC, 2013) states that "in the last 60 years the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years". Carbon dioxide concentration increased by 40% since pre-industrial times and by 25% in the last 6 decades (Figure 3.1). Furthermore, IPCC states that "it is extremely likely that human influence has been the dominant cause of the observed global warming since the mid-20th century" IPCC, 2013).

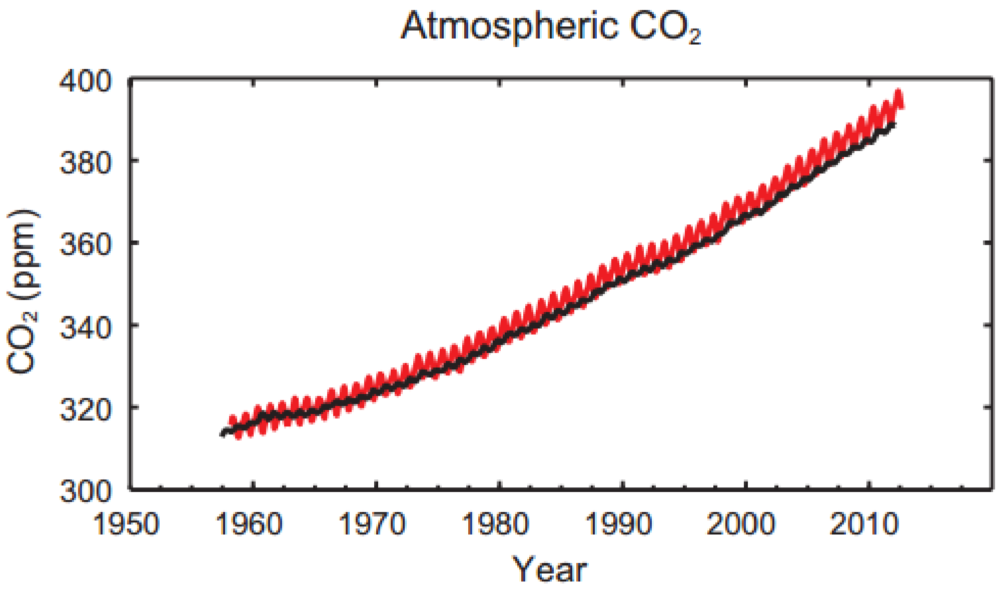


Figure 3.1. Atmospheric concentrations of carbon dioxide (CO2) from Mauna Loa (19°32'N, 155°34'W – red) and South Pole (89°59'S, 24°48'W – black) since 1958 (from IPCC, 2013).

Considering the consequences that a development uniquely based on economic parameters had both on society and environment, in the last decades several organizations, panels, commissions and think-tanks defined and proposed alternative models and scenarios for a sustainable development. The first formulation is provided by the WCED almost 30 years ago. “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). Aim of this definition is to remark that the current exploitation of natural resources for today economic purposes should not compromise the future generations to have the chance to do the same. Several other definitions are proposed to define sustainable development and sustainability in general.

“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, together with the importance of linking our social, financial, and environmental wellbeing". (Sustainable Seattle, n.d.).

"Sustainable development involves the simultaneous pursuit of economic prosperity, environmental quality and social equity” (World Business Council on Sustainable Development, n.d.).

3.1.2 Sustainability pillars

All these presented definitions suggest that three are the sustainability dimensions or pillars, namely economy, environment and society (Figure 3.2).

- Economy.

  Economic dimension includes the monetary aspect of the development as the company profit, the industry productivity and the business competitiveness. Furthermore, aspects that deal with the life of single individuals are included as income or living standards.

- Environment.

  Environmental pillar estimates if and in which extent the development is compatible with the natural resources preservation, the prevention of greenhouse gas (GHG) emissions, the protection of safe and healthy air and water quality and the recycling and disposal of the produced waste flows. Moreover, energy utilization is evaluated through the sources selected, the production efficiency and the demand satisfaction.

- Society.
  The last sustainability pillar represents the social dimension of the development. Sustainable development has to guarantee appropriate health assistance and service, affordable and accessible education of each level and long-lasting peace. Furthermore, it should avoid poverty and hunger to each extent.

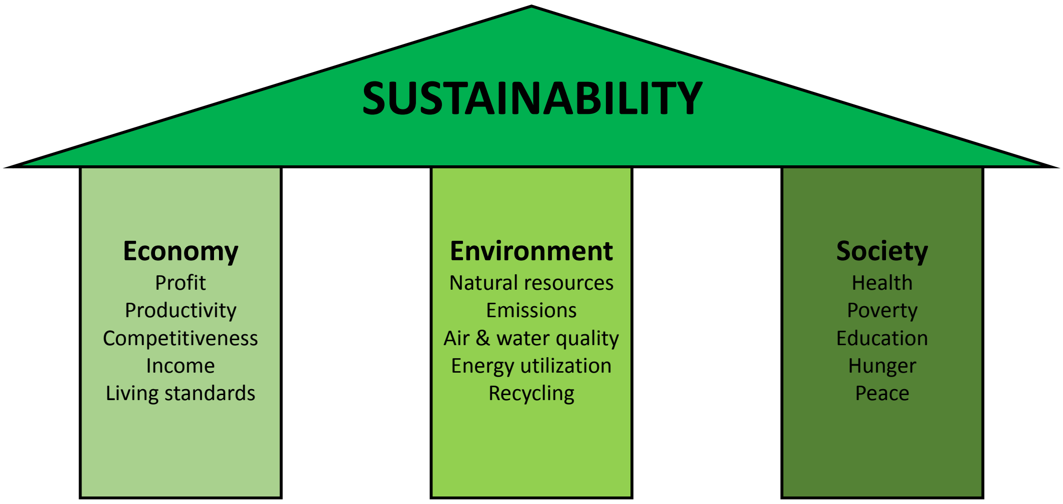


Figure 3.2. Sustainability pillars (adapted from Rosen and Kishawy, 2012).

The greatest difference between sustainability and traditional development indicators development is the simultaneous and joint consideration of its pillars, their interaction and how they affect each other. For instance (Rosen and Kishawy, 2012):

- the natural resource base provides the materials for production on which jobs and profits depend;
- employment affects wealth creation, living standards and poverty rates;
- poverty relates to crime and social unrest and instability;
- resource, air and water quality affect health;
- resources used for production affect profits.

On the contrary, many traditional development indicators are not holistic, like gross domestic product (GDP), which is a monetary measure of the value of all final goods and services produced in a period of time in a certain geographical region. GDP is generally regarded as a measure of a country economic well-being, under the presumption that the more money spent, the higher the index and the better the economic well-being. Although, this indicator reflects only the amount of economic activity, regardless of how that activity affects the community social and environmental welfare (Rosen and Kishawy, 2012).

3.1.3 Pillar intersections

Sustainability is the result of the simultaneous existence of all the pillars previously described. However, even the interaction and intersection of just a couple of these dimensions can be classified as a distinctive feature (Hauschild et al., 2005) (Figure 3.3).

- Eco-efficiency.
  This intersection represents the ratio between a certain economic performance and a relevant environmental indicator. Graedel and Allenby (2009) suggest to measure eco-efficiency as the ratio between the GDP and the environmental impact determined by the economic activities considered in the GDP. This indicator measures the ability to obtain an identical economic wealth at a lower environmental impact, or to increase the GDP exploiting an equal amount of natural resources.

- Environmental justification.
  This feature is determined by the intersection between society and environment. It represents the environmental justification to a certain product, process, service or even system (Elkington, 1995). A product, for instance, should provide the customer a service relevant enough to justify the emissions determined by its manufacturing. Furthermore, it is necessary to determine whereas the society really needs the product or not, as well if there are any alternative products that could fulfill the same function at a lower environmental impact.

- Company ethics.
  This intersection represents the way in which an organization behaves towards the people that interact with it. The traditional shareholder perspective should be broadened to consider all the organization stakeholders, from suppliers to customers, from employees to neighbors (Dreyer et al., 2006). Company ethics is closely related to the concept of corporate social responsibility, proposed in the seventies by Heald (1970). Corporate social responsibility purpose is to self-regulate the business model to guarantee the compliance with ethical standards beyond the short-term economic interests and the current regulations to include the social dimension in the organization business models.

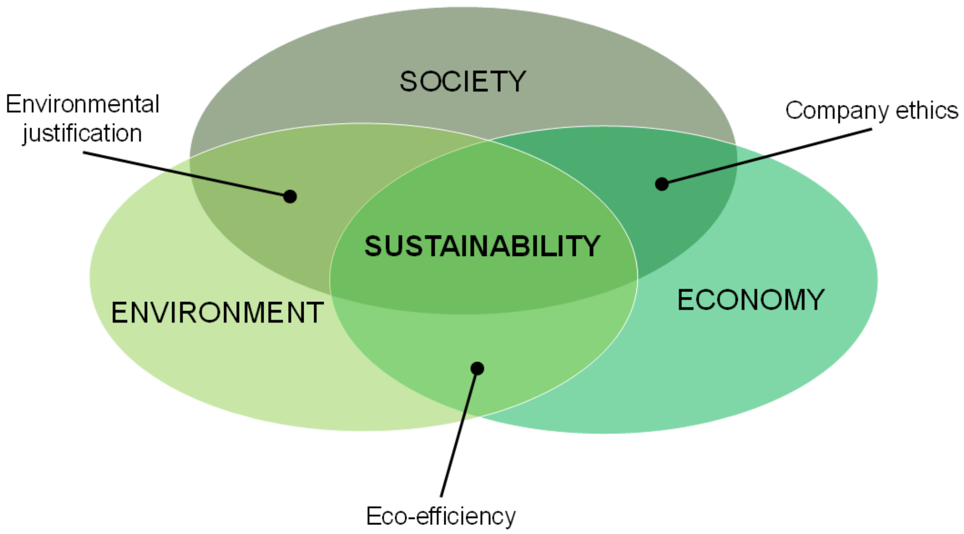


Figure 3.3 Possible intersection among the sustainability pillars (from Hauschild et al., 2005).

3.1.4 Sustainability in the 21st century

To conclude this paragraph it is necessary to underline today relevance of sustainable development despites its first definition is proposed in the Brundtland report (WCED, 1987) almost 30 years ago. The 25th September 2015 more than 190 countries singed the United Nations Resolution A/RES/70/1, also known as “Sustainable Development Goals” (UNSD, 2015). Aim of this resolution is to define the agenda for the next 15 years of sustainable development all around the world. The three sustainability dimensions are distinguished by 17 goals for a total of 169 targets. The goals are listed in the following.

1. No poverty
2. Zero hunger
3. Good health and well-being
4. Quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation and infrastructure
10. Reduced inequalities
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action

14. Life below water
15. Life on land
16. Peach, justice and strong institutions
17. Partnerships for the goals

3.2 Sustainable industrial development

Sustainability in the industrial context achieved a remarkable relevance in the last twenty years. Elkington first (1998) proposes a framework to measure the sustainability for companies and organizations. Traditional business accounting techniques commonly use the term “bottom line” to refer to the profit (or loss) of a company at the end of the year. This information is typically recorded at the bottom line on a statement of revenue and expenses. Thus, the author proposes the term “triple bottom line” to suggest a triple accounting for firms that consider three business dimensions.

- Profit

  The first bottom line proposed is called “profit” and it represents the typical financial accounting that measures the economic performances of the company.

- Planet

  The second is called “planet” and it evaluates the impact of the business activities to the environment. Therefore, it is necessary to evaluate the sources of energy used by the business processes, whether these are renewable or not and so on. Furthermore, the waste flows have to be monitored to reuse them as much as possible or to treat them properly for disposal purposes.

- People

  The latter bottom line proposed is called “people” and it measures the extent in which the companies use fair and beneficial practices for employees, local community, and social structures where they develop their business.

The aforepresented three bottom lines are clearly equivalent to the sustainability pillars proposed in the previous paragraph. Original of this framework is the definition and the analysis of sustainability components in the industrial field, where the companies are established. The triple bottom line represents a quantitative technique to evaluate in which extent the business products, processes and systems are sustainable. Purpose of the triple bottom line is to underline the relevant components of a long-term succeeding business model. Even the social and the environmental components have a long-term effect on the business profitability. The employee loyalty, the customer satisfaction, the local institution goodwill, the avoided ecological disaster, the lower energy consumed and all the other positive consequences of the triple bottom line approach enable the company to eliminate future, hidden, indirect and usually high costs.

Nowadays operations and supply chain management researchers and practitioners face new challenges to integrate sustainability issues in their traditional area of interests. During the last twenty years a growing pressure on businesses forces these people to pay more attention to the environmental and social consequences of products, processes and systems. Accordingly to Kleindorfer et al. (2005) this scenario is mainly determined by three trends.

1. The cost of materials and energy will continue to grow as rapidly industrializing countries, as China and India, make strong demands on these resources.
2. Public pressure for environmental, health and safety performance is likely to remain strong or even be strengthened by additional regulations.
3. Increasing awareness of consumers on sustainable business practices and their demands for products made by companies adopting triple bottom line approach.

Considering logistic systems, product distribution and warehousing represent two remarkable opportunities to achieve sustainability in logistic field (Hassini et al., 2005). For instance, transport mode selection has a tremendous impact both on social and environmental dimensions of sustainability. Avoiding truck delivery and exploiting train as transport mode enables to significantly decrease the GHGs emissions per ton of product shipped. Furthermore, the selection of this transport mode decreases the number of vehicles on roads, both reducing the traffic congestion and increasing the road safety.

3.3 Economic profitability

The economic dimension of sustainability requires appropriate models and techniques to evaluate and measure the profitability of a certain product, process or system (entity). Several techniques can be exploited for this purpose. The most widespread approach to evaluate the profitability of a certain business investment is the net present value (NVP) (Fisher, 1907). Another relevant technique is Life cycle costing (Sherif and Kolarik, 1981). Its aim is the evaluation of all the costs related to a certain entity during its entire lifetime considering the installation, operating and disposal/recycle phases.

3.3.1 Net present value

The NPV is probably the most widely adopted methodology for the economic evaluation of an investment. The considered investment can represent the launch of a product in the market, the adoption of a manufacturing, production or logistic process or the installation of a system, plant, or building to fulfill a certain business function. NPV is a technique to evaluate as accurately as possible all the cash flows related to a certain investment during its entire lifetime (Bortolini et al., 2014). Fundamental for this technique is the concept of discounted cash flow. This concept states that the value of 1 € today is not equal to its value in the past or in the future. Inflation and most of all the possibility of money investment suggest that the value of 1 € today is greater than the value of 1 € in the future. Thus, this monetary flow can be invested today and increase its value over time.

Eqs. 3.1-3.4 propose the NPV formulation and each of their component is fully analyzed in the following bullet point. Furthermore, Figure 3.4 presents a NPV graphical representation.

$$NPV = -C_0 + \sum_{j=1}^{n} \frac{R_j - C_j}{(1 + OCC)^{\,j}} \tag{3.1}$$

$$C_0 = C_P + C_T + C_I \tag{3.2}$$

$$C_j = C_{O_j} + C_{M_j} + C_{D_j} + C_{T_j} \tag{3.3}$$

$$C_{D_j} = r \cdot [\varphi C_0 - \sum_{k=1}^{k<j} (s \cdot \varphi C_0 - C_{D_k})] \tag{3.4}$$

- Initial investment C_0

  The initial investment represents the financial cash outflow at the beginning of the initiatives to enable the product to be manufactured, the process to be activated or the system to be operative. As it is possible to notice, NPV assumes that this outflow affects only the first year of the initiatives. However, some investment categories, as infrastructures, buildings and power plants, are distinguished by a initial investment that covers more than one year. A possible technique is to discount these monetary flows and refer them to the year 0 of the investment.

  Three are the most common outflows for initial investment.

  - Purchase C_P

    Purchase represents the expenditure to buy the system components.
  - Transportation C_T

    The components have to be delivered to the installation site. For building and plant in particular, this outflow could represent a relevant portion of the initial investment.
  - Installation C_I

    Installation represents the required activities to enable the system to be operative. Labor cost as well as equipment rental should be considered.

- Revenues R_j

  Revenues are the uniquely source of financial inflows included in the NPV. This typically represents the quantity of products sold or service offered times its price.

- Operative costs C_j

  Operative costs represent the financial outflows that distinguish each year j of the investment lifetime. Four are the typical components of this cost.

  - Operation C_{O_j}

    Operation costs deal with the typical activity of the investment. Considering the NPV of a new product to be launched in the market, this outflow estimate the direct cost for its manufacturing, packaging and delivery as well as the indirect one determined by the purchase, marketing and customer assistance activities.

  - Maintenance C_{M_j}

    This financial outflow deals with the maintenance activities that occur to guarantee the market demand satisfaction, the production capacity or the service level for which the product, process or system is designed.

  - Financing C_{D_j}

    This is the outflow due to the interest paid for financing the initial investment at year 0 (equal to 0 if the whole investment is paid through equity). It expresses the interest that each year the investors have to pay for the loan obtained to finance, entirely or partially, the investment. The Eq. (3.4) allows to calculate the annual value of C_{D_j} where r is the interest rate on debts, assumed constant and equal over the years, φ is the percentage of the initial investment financed through loan, i.e. financial leverage and s is the amortization coefficient of the investment.

  - Tax C_{T_j}

    This cost is the annual tax outflow and it is usually evaluated adopting the Earning Before Tax approach and considering the specific tax rates imposed to the corporate gross income in the country of the investment.

- Opportunity cost of capital OCC

  This parameter has a tremendous relevance for a correct estimation of the investment NPV. Exploiting the discount cash flow approach, it determine the present value of future cash flows. OCC should represent the risk of the investment. In other terms, it should be equal to the interest that remunerates an investment distinguished by the same risk level. A correct OCC evaluation should include the effect of inflation on the discount rate (OCC).

- Lifetime n
  Number of weeks, months or year in which the product is on the market, the process offers its services or the system is operative.

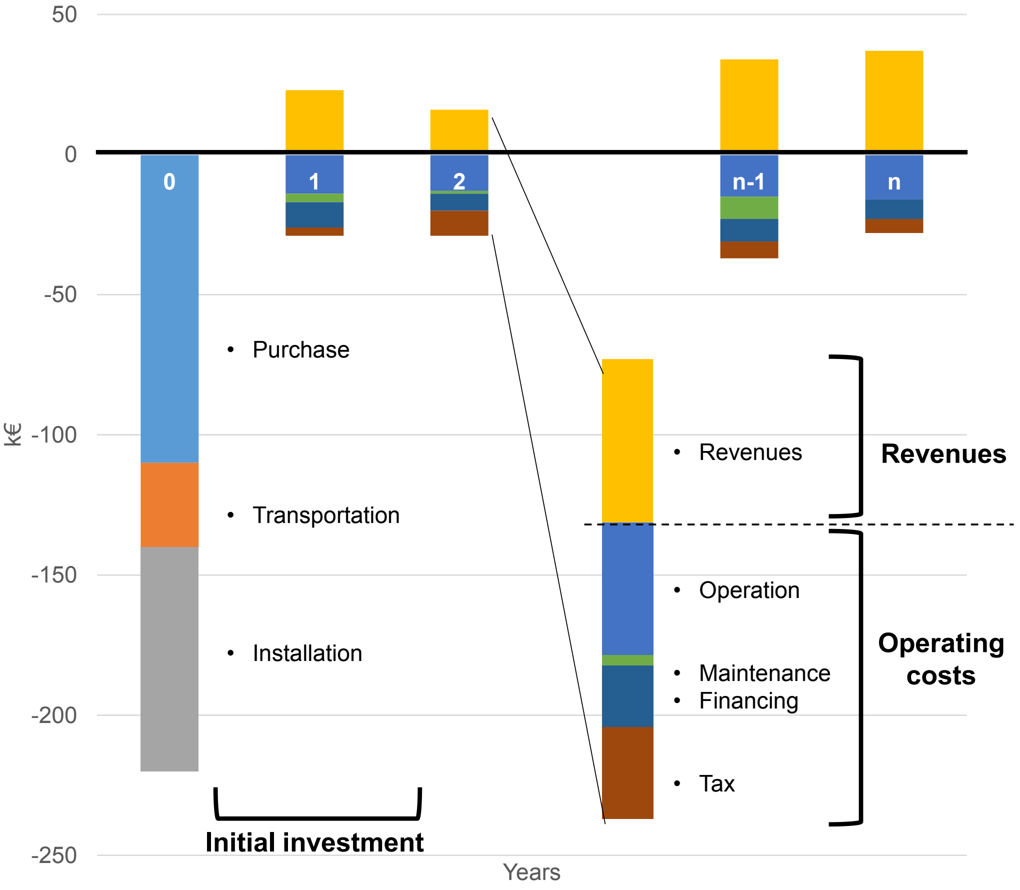


Figure 3.4. NPV graphical representation.

3.3.2 Life cycle costing

Purpose of LCC is to evaluate all costs related to a product, process or system (entity) over its entire lifetime, from production to use considering its maintenance and disposal (UNEP, 2009). LCC is first developed by the U.S. military in the 1960's for tanks and tractors cost evaluation and it is further developed and adopted by several researchers and practitioners in the following years. The main advantage of this approach, even compared to NPV, is its focus on all the direct and indirect costs that can occur during the entire lifetime of a system, considering both installation and disposal phases. As suggested by Woodward (1998), disposal cost should include the cost of demolition, scrapping or selling the system, adjusted for any tax allowance or charge upon resale. This cost has be deducted from the residual value of the system at the end of its lifetime.

Hunkeler et al. (2008) define LCC as "the assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or End of Life actor) with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future". According to this definition a further aspect that distinguishes LCC is the inclusion of several actor of the product supply chain as relevant shareholders. LCC has to include in its comprehensive approach all the costs covered by these actors related to the entity analyzed.

To determine the value of the LCC of a certain entity a procedure has to be followed. Harvey (1976) first proposed a general procedure for LCC analysis made of four sequential phases.

I. <u>Define the cost elements of interest.</u>

The cost elements of interests are all the cash flows considered relevant that occur during the system lifetime.

II. <u>Define the cost structure to be used.</u>

Grouping cost to identify potential trade-offs and achieve the minimum LCC. The cost structure depends on the depth and width that the LCC should achieve. White and Osvald (1976) divide the cost in three categories with well-defined patterns over time (Figure 3.5). The proposed cost categories are engineering and development, production and implementation, and operating.

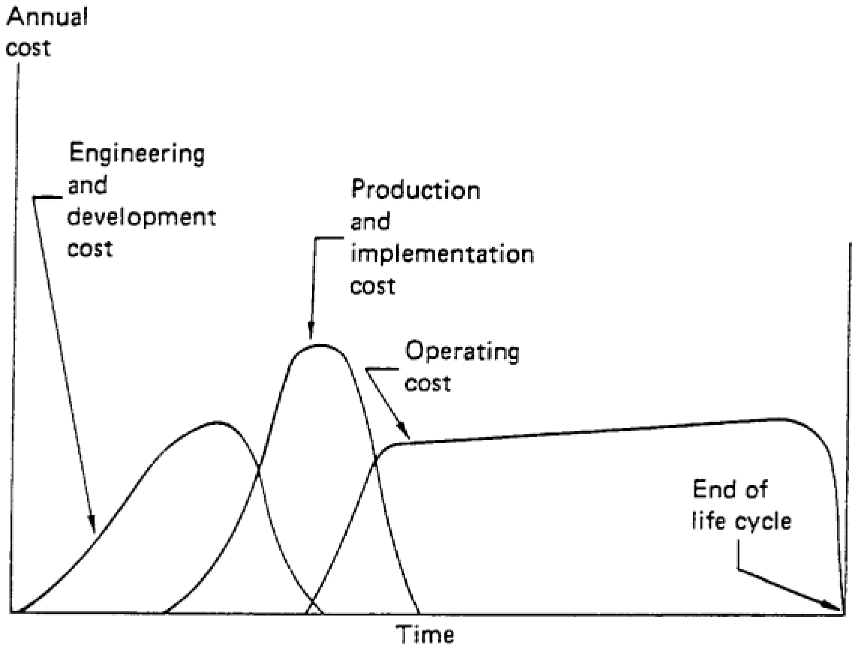


Figure 3.5. Structure of LCC over time (from White and Osvald, 1976).

III. <u>Establish the cost estimating relationships</u>

Define a mathematical function (linear, parabolic, hyperbolic, etc.) to estimates the cost of an item or an activity of the considered system as a function of one or more independent variables (Woodward, 1998).

IV. Establish the method of LCC formulation

Chose an appropriate methodology to evaluate the LCC of the system considered. Kaufman (1970) proposes an eight steps formulation for LCC estimation that stood the test of time.

1. establish the operating profile;
2. establish the utilization factors;
3. identify all the cost elements;
4. determine the critical cost parameters;
5. calculate all costs at current prices;
6. escalate current costs at assumed inflation rates;
7. discount all costs to the base period;
8. sum discounted costs to establish the net present value.

3.4 Environmental impact

The second pillar of sustainability is the environment. Sustainable industrial activities and logistic systems have also to minimize the environmental impact related to their products and processes. Considering the principle that “only measurable is manageable”, several techniques and methods can be used to evaluate the environmental impact in the industrial context. This paragraph presents two of the most widely adopted approaches: carbon footprint (CF) and life cycle assessment (LCA).

3.4.1 Carbon footprint

IPCC in its fourth assessment report has strongly recommended to limit the increase in global temperature below 2°C as compared to preindustrial level to avoid serious ecological and economic threats. A rise in temperature by 0.7°C has already been recorded and hence climate scientists are focusing on an urgent action to limit global warming (IPCC 2007; Kerr 2007). The rise in global temperature is due to the enhanced greenhouse effect determined by human release of GHGs into the atmosphere. Not all GHGs have equal capacity to cause warming and their strengths depend on radiative forcing it causes and the average time for which that gas molecule stays in the atmosphere. Considering these, the average warming a GHG can cause over a specific time interval (typically 100 years) is known as global warming potential (GWP) and it is calculated and expressed relative to that of carbon

dioxide (CO_2). Therefore, unit of GWP is carbon dioxide equivalent (CO_2 eq.) (Pandey et al., 2011).
According to this concept, Wiedmann and Minx (2007) defined that:

“Carbon footprint (CF) is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity (or process) or is accumulated over the life stages of a product (or system)”.

Direct emissions are those that are directly produced during the progress of a process or the characteristic activities of a system. On the contrary, indirect emissions are the one produced far from the process or system site but required to guarantee the offered service or product. For instance, CF of a drug is distinguished by the GHGs emitted during the product production (direct emissions) and the one determined by the electricity generation to power the equipment as well by the gasoline combustion for the drug delivery to the clients.

For CF calculating it is necessary to evaluate the amount of GHGs emitted during the life cycle of the product, process or system (entity). Life cycle includes all the stages of a product as its manufacturing right from bringing of raw materials to final packaging, distribution, consumption or use, and to the final disposal and/or recycling (Bortolini et al., 2015c). Two are the approaches to evaluate the GHG emissions during the entire product or system lifetime.

- Bottom up or process analysis.
  The emission sources are divided into different categories to ease the quantification. This method is more accurate for small products or systems but too complex for large ones (Lenzen, 2001)

- Top down or input-output analysis.
  This approach uses the concept of economic input–output (EIO) model to perform and evaluate operations on environmental variables for CF calculation. Inputs represent the requirements for product production whereas products themselves are distinguished as outputs (Miller and Blair 1985).

To evaluate the emissions during the entity life cycle, the following structured framework is suggested by the World Business Council for Sustainable Development and World Resource Institute (WRI/WBCSD 2004)

1. Selection of GHGs
   Selection of the GHG set covered in calculation depends on the guideline followed, on the need of CF calculation, and on the activity type for which CF is being done.

However, Kyoto protocol suggests six GHGs to monitor and measure: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

2. Setting boundary

   Boundary refers to an imaginary line drawn around the activities that will be used for calculating CF. It depends on the objective of footprinting and characteristics of the entity for which footprinting is done.

   To facilitate accounting, Carbon Trust (2007b) suggests three type of CF.

   - Minimum CF

     It consider uniquely the direct emissions, i.e. onsite emissions.
   - Basic CF

     It evaluates direct emissions and the one embodied in purchased energy.
   - Full CF

     It includes all direct and indirect emissions, as those associated with transport of purchased goods, sold products, business travels, energy activities and disposal of products.

3. Collection of GHG emission data

   Two are the alternatives to collect GHG data. The former is through direct onsite real-time measurements, the latter exploits estimations based on emission factors and models. The choice of the appropriate method depends on the objective, feasibility, cost and capacity considerations that deal with CF. Emission factors and models are typically adopted using data on consumption of fuels, energy, and other inputs leading to emissions. Furthermore, emission factors are available for a wide range of industrial processes in several GHG protocols (IPCC, 2006).

4. Footprint calculation

   Finally, the GHG data are translated into CO_2 eq. using conversion factors provided by different sources (IPCC, 2007).

3.4.2 Life cycle assessment

Life Cycle Assessment (LCA) is a technique developed to evaluate the environmental impacts associated with the life cycle of products, processes and systems (entities). The life cycle of an entity includes its development, manufacturing, assembly, distribution, use, and end of life. Furthermore, it also considers the extraction of raw materials, their transformation in feedstock, the maintenance of the entity, the eventual recovery after its end of life and all the activities that allow the entity components and materials to start a new life cycle. The entity life cycle also includes the production of the energy used for its manufacturing, assembly and use as well as the extraction of feedstock for the generation of this energy. The same considerations hold for transportation activities, the consumption of tools and instruments for product manufacturing and the construction of infrastructures required by the entity activities (Cascini, 2015). All these activities could be included in the entity LCA because they have a direct or indirect impact on the environment. However, limits of the LCA technique have to be defined. LCA *boundaries* determine which activities are included in the environmental impact evaluation and which not. A further relevant approach that distinguishes LCA is the *cradle-to-grave* one. This term suggests that the entity environmental impact should be evaluated considering all the activities related with the entity before its manufacturing and until its end of life. Raw material extraction, purchase and transformation as well as entity delivery to the final customer, entity usage and recycling/disposal are all within the cradle-to-grave approach.

Considering the normative and regulatory framework, the International Standards Organization (ISO) define a global standardization process for LCA. Four standards were originally developed for LCA and its main phases and these are issued in the ISO 14000 series of standards for Environmental Management (Cascini, 2015).

- 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 – replaces since 2006 the four aforementioned standards.

The LCA phases defined by the ISO regulations are proposed in the following paragraphs 3.4.2.1 - 3.4.2.4 (Hauschild et al., 2005).

3.4.2.1 Goal and scope definition

In this first phase, the goal of LCA is defined along with the scope in terms of boundaries of the entity for which the environmental impact is estimated, the temporal and technological purpose of the entity analyzed, and the definition of the parameters to consider in the analysis. The function provided by the entity is deeply described in qualitative terms and quantified in the *functional unit*. This represents a relevant element of the LCA technique. It defines the reference flow of products for the LCA, i.e. the number of product units for which the collection of data has to be done. The functional unit definition is of major importance for LCA. Indeed, purpose of this technique is to evaluate and compare the environmental impact of similar entitys which provide the same function to the user.

3.4.2.2 Life cycle inventory

Inventory analysis collects information on the input and output for all the processes within the boundaries of the entity for which it is necessary to estimate the LCA. For each process within the system boundaries it is necessary to evaluate the inflow and outflow of resources, material, energy, waste, emissions and products referred to the defined functional unit. The data are usually presented in an aggregated form for the entire system. For instance, the total emissions of a certain element or the total use of a certain resource are accounted per functional unit.

3.4.2.3 Life cycle impact assessment

Purpose of the life cycle impact assessment phase is the interpretation of the results from the inventory phase to define their potential impacts on the so-called *areas of protection* of the LCA, i.e. the systems that the LCA usage should protect.

According to Hauschild et al. (2005) four are the areas of protection: human health, natural environment, natural resources, man-made environment.

Life cycle impact assessment evaluate the environmental impact with a holistic perspective. Its purpose is to model any impact of the entity considered that could potentially damage one or more areas of protection. One of the greatest difference between CF and LCA is that this latter does not only consider the impact of GHG emissions into atmosphere but also the impact of waterborne pollutants as well as different forms of land use and loss of renewable and non-renewable resources. Additionally, some life cycle impact assessment methods also include the impact on human health from occupational exposure due to the operating processes in the life cycle.

If the life cycle impact assessment analysis for the product system has been thorough, the inventory will contain a multitude of substance emissions and input of different resources.

One of the greatest strength of LCA technique is the environmental impact evaluation for every substance emitted or resource consumed considering its relevance. While some of these are environmentally significant even in small amounts, other could have no significant even in large quantities. For the environmental exchanges, life cycle impact assessment translates 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 on the environment. For GHGs, the earliest impact in the causality chain is the increment in the atmosphere ability to absorb infrared radiation. For the consumption of resources, the severity applied in the impact assessment is determined by the scarcity of the resource itself.

The life cycle impact assessment proceeds through four steps (ISO 14044).

1. Selection of impact categories and classification

   This step defines the categories of environmental impacts relevant for the LCA. To each of the substance emission identified in the inventory phase, this step assigns an impact category according to its ability to contribute to different environmental problems. ReCiPe 2008 method (Goedkoop et al., 2009) is one of the most comprehensive impact assessment method and it considers: 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 (Cascini, 2015).

2. Characterization

   The impact of each emissions is measured with an impact score in a unit common to all contributions within the impact category. For instance, kg CO_2 eq. for all GHGs. Then, the contributions from different substance emissions are summed within each impact category and the inventory data translated into a profile of environmental impact scores and resource consumptions.

3. Normalization

   Impact scores and resource consumptions from the characterization step are related to a common reference to facilitate comparisons across impact categories, for instance to evaluate whereas or not improvements in one impact category are obtained at the expense of another. Thus, normalization expresses the magnitude of the impact scores on a scale common to all impact categories.

4. Evaluation

   This steps is required to give to the different environmental impact categories the relative importance assigned by the specific LCA exploiting a weighting approach. Furthermore, while normalization estimates the relative magnitudes of the impact scores and resource consumptions, evaluation expresses their relative significance considering the goal of the specific LCA and defines trade-off scenarios.

3.4.2.4 Interpretation

Purpose of this phase is to interpret the other phase results according to the goal of study. Typical studies performed at the interpretation phase are sensitivity and uncertainty analyses. Outcome of the interpretation could be a conclusion exploited as a recommendation for decision makers, who typically consider the environmental impact along with the other sustainability pillars, namely economic profitability and social wealth.

The interpretation phase may also suggests of a further LCA iteration, reviewing and revising the study scope, the data collection for the inventory or the impact assessment.

3.5 Social wealth

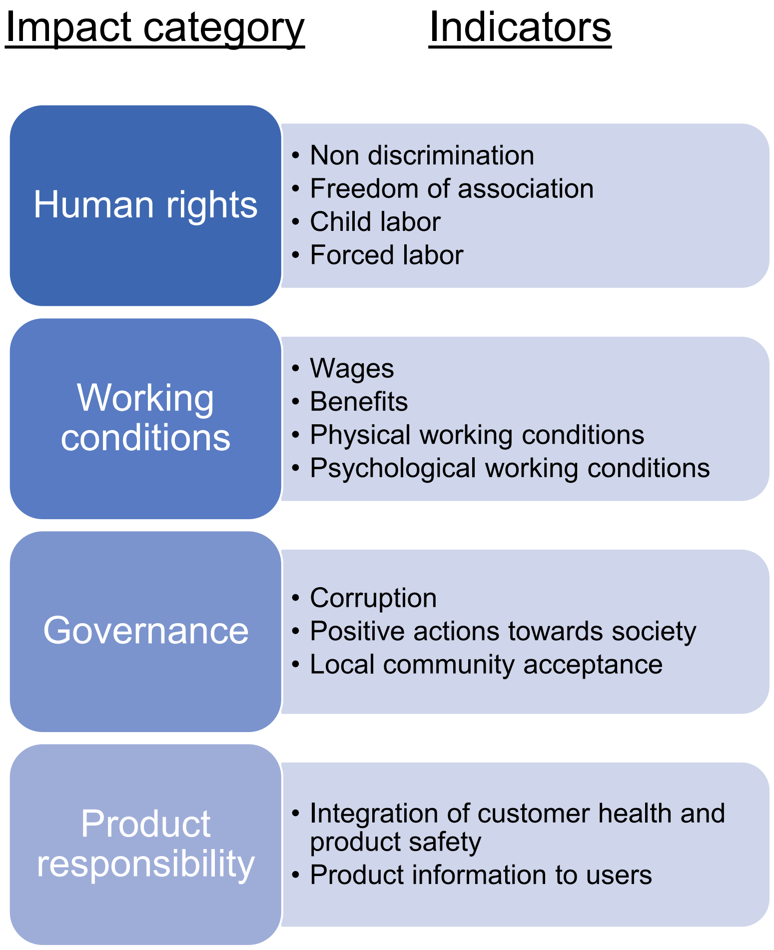
The social dimension of sustainability measures how and in which extent the product, process or system (entity) analyzed affects the different society dimensions. For instance, how the development and commercialization of a new service of car-sharing influence the people health, the citizen life quality and the job market? The answer to these questions represents the social dimension of the sustainability for a certain entity.

However, it is extremely difficult to estimate the impact that a system has on the different society aspects considering its different stakeholders at local, national and global levels. Thus, several indicators propose a measure of social wealth at regional or national level.

The first of these indices to be proposed is the well-known Gini coefficient developed at the beginning of the 20th century (Gini, 1912). This coefficient intends to represent the income distribution of the residents of a certain nation as measure of inequality. In the following decades several other indicators are proposed to measure the social wealth at national level. The Human Development Index (UNDP, 2015) is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. The Human Development Index is the geometric mean of normalized indices for each of the three dimensions. The health dimension is assessed by life expectancy at birth, the education dimension is measured by mean of years of schooling for adults aged 25 years and more and expected years of schooling for children of school entering age. The standard of living dimension is measured by gross national income per capita. The Human Development Index uses the logarithm of income, to reflect the diminishing importance of income with increasing gross national income per capita. Drawback of this indicator is that it does not reflect on inequalities, poverty, human security, empowerment and freedom. Thus, several other indices are developed to specifically measure a certain aspect of the social wealth of a nation. For instance, the Human Freedom Index (Vasquez and Porcnik, 2015) is a holistic indicator used to evaluate the personal, civil, and economic freedom of a country. Human freedom is presented to be a social concept that recognizes the dignity of individuals and it is defined by the index as negative liberty or the absence of coercive constraint.

In the last years several authors and organizations proposed innovative techniques to account the social impact of products, processes, or systems. The most promising one is defined Social LCA. This technique exploits the approach, framework and structure of the well-known LCA to estimate the impact that an entity has on the society (Dreyer et al., 2006 and Norris, 2006).

One of the most relevant issue dealing with social LCA is the definition of the impact categories and the respective indicators. A comprehensive review of the few techniques currently available enables Finkbeiner et al. (2010) to propose the most significant impact categories and indicators for social LCA (Figure 3.6). Human rights are evaluated trough non-discrimination, freedom of association, child labor and forced labor. Workings conditions are determined by wages, benefits, physical and psychological working conditions. Governance impact category is represented by the corruption of the institutions and organizations, the positive actions towards society and the acceptance of local communities. Furthermore, social LCA of a product includes the product responsibility. This impact category measures the degree in which the interaction between the product and the users is considered. The information provided to the customer and its health and safety are the indicators for this impact category.



Impact category	Indicators
Human rights	• Non discrimination • Freedom of association • Child labor • Forced labor
Working conditions	• Wages • Benefits • Physical working conditions • Psychological working conditions
Governance	• Corruption • Positive actions towards society • Local community acceptance
Product responsibility	• Integration of customer health and product safety • Product information to users

Figure 3.6. Impact categories and indicators for social life cycle assessment (adapted from Finkbeiner et al., 2010).

The most relevant single contribution presented so far for social LCA is the technical framework proposed by the UNEP (2009). This framework presents a method similar to the LCA to determine the social impact of a product.

However, despite the research done in this field, none method, procedure or tool to determine the social impact of the manufactured products, the proposed processes or the operating systems is nowadays widely adopted. The biggest weakness of these methods is the difficulty to evaluate the relation between a certain activities of the product considered with the level of the social impact indicator determined. For instance, how and in which extent the extraction of the raw materials to manufacture a plastic or a glass bottle impacts on the wages of the company workers and on the corruption of the local organizations?

3.6 Technical performance

Technical performance is not one of the sustainability pillars. However, it represents one of the most relevant KPI for companies and organizations operating in the industrial context. Usually, technical performances are included in the economic profitability KPI. The throughput rate of an assembly line, the travel time in a warehouse and the due dates in a distribution network can be converted in costs or revenues and thus added to the economic performance of a logistic system. However, the same approach can be used even for environmental impact. Indeed, carbon market enables to determine a price (or cost) for the GHGs emitted. Considering this approach, even the worker satisfaction, the customer loyalty and the goodwill of the local institutions have an impact (probably in the long-term) on the company economic performance. Nevertheless, the conversion in euros (or dollars) of the unit of measures that evaluate the different sustainability pillars is subject to strong limitations. It is extremely difficult to estimate the cost of a lost customer for late product delivery or the effect on the company profit of a more efficient warehouse. Likewise, it is inaccurate to determine for a company the cost of using scarce and nonrenewable energy sources, or emitting pollutants in the atmosphere of the local community where it is established.

The most accurate techniques for sustainability assessment should separately evaluate the three pillars and the so-called fourth one. This approach enables the most precise evaluation of the economic profitability, environmental impact, social wealth and even technical performance. However, an ex-post procedure is required to determine the trade-off configuration of the product, process or system considered that best satisfies the designer or manager preferences among the sustainability pillars considered.

4. Multi-objective optimization

This Chapter presents a mathematical programming technique to define the optimal solution of a problem distinguished by more than one objective function. Paragraph 4.1 proposes an overview of the multi-objective optimization concept, its formulation and the reason why it has a remarkable importance within this research. Paragraph 4.2 describes the concept of Pareto optimality, presenting its definition, formulation and most important features. Aim of Paragraph 4.3 is to present and analyze the different methods to solve a multi-objective optimization problem. Three are the possible approaches: a priori, a posteriori and no articulation of preferences. One of these methods is deeply investigated in Paragraph 4.4 since relevant for the purpose of this research. Finally, Paragraph 4.5 proposes a selection criterion to determine the final solution of a multi-objective optimization problem.

4.1 Overview and definition

Chapter 2 and 3 of this Ph.D. thesis respectively present the key features for design and management of logistic systems and the sustainability concept in the industrial field. Indeed, aim of this research is to propose innovative models and method for design and management of sustainable logistic systems. However, as previously described, sustainability is a concept made of three pillars: economic profitability, environmental impact and social wealth (with technical performance as supplementary). The design and management of a sustainable logistic system necessarily requires a trade-off among the system economic, environmental and social (or technical) performances. For instance considering DN, to minimize the product delivery time to a costumer is necessary to exploit a fast shipment configuration, as truck direct shipment. However, this configuration is distinguished by high GHG emissions per ton transported and km travelled. Beyond logistics, MO is of strong help for every decisional problem in which the system configuration has to be defined considering more than one conflicting design objectives. A specific system configuration that optimizes one objective function worsens the value of the remaining ones, and vice versa.

Multi-objective optimization (MO) is defined as a mathematical programming technique to systematically and simultaneously optimize a collection of objective functions.

The generic multi-objective minimization problem states as follows (Eqs. 4.1-4.2) (Gamberi et al., 2015):

$$\min_{x \in S} \{f_1(x), f_2(x), \dots, f_n(x)\} \tag{4.1}$$

$$S = \{x \in R^m : h(x) = 0, \qquad g(x) \leq 0\} \tag{4.2}$$

n objective functions $(f_1(x), f_2(x), \dots, f_n(x))$ are to be minimized (with $n > 1$) subject to a set of constraints of equality $(h(x) = 0)$ and inequality $(g(x) \leq 0)$ defining the m-dimension admissible region S (also called objective space) for the MO problem decision variable x. The image of the objective space is the n-dimension region C, univocally defined through the so-called attained set. Formally (Eq. 4.3):

$$C = \{y \in R^n : y = f(x), x \in S\} \tag{4.3}$$

The solution of a MO problem can be determined through the following procedure presented in Figure 4.1. The first procedure step is the definition of the MO problem by mean of the aforepresented Eqs. 4.1-4.2. Then, a method to determine the problem solutions has to be selected. Three are the possible method categories: a priori (Paragraph 4.3.1), a posteriori (Paragraph 4.3.2) or no articulation (Paragraph 4.3.3) of preferences.

The difference among methods consist in the phase in which the decision-maker expresses his/her preferences for the objective functions. Respectively, before, after the problem solving or never. Despite the chosen method, it is always possible to obtain a set of points, called Pareto frontier, that represent the MO solutions. Thus, a further step is required (Paragraph 4.5) to select the final solution among the proposed ones.

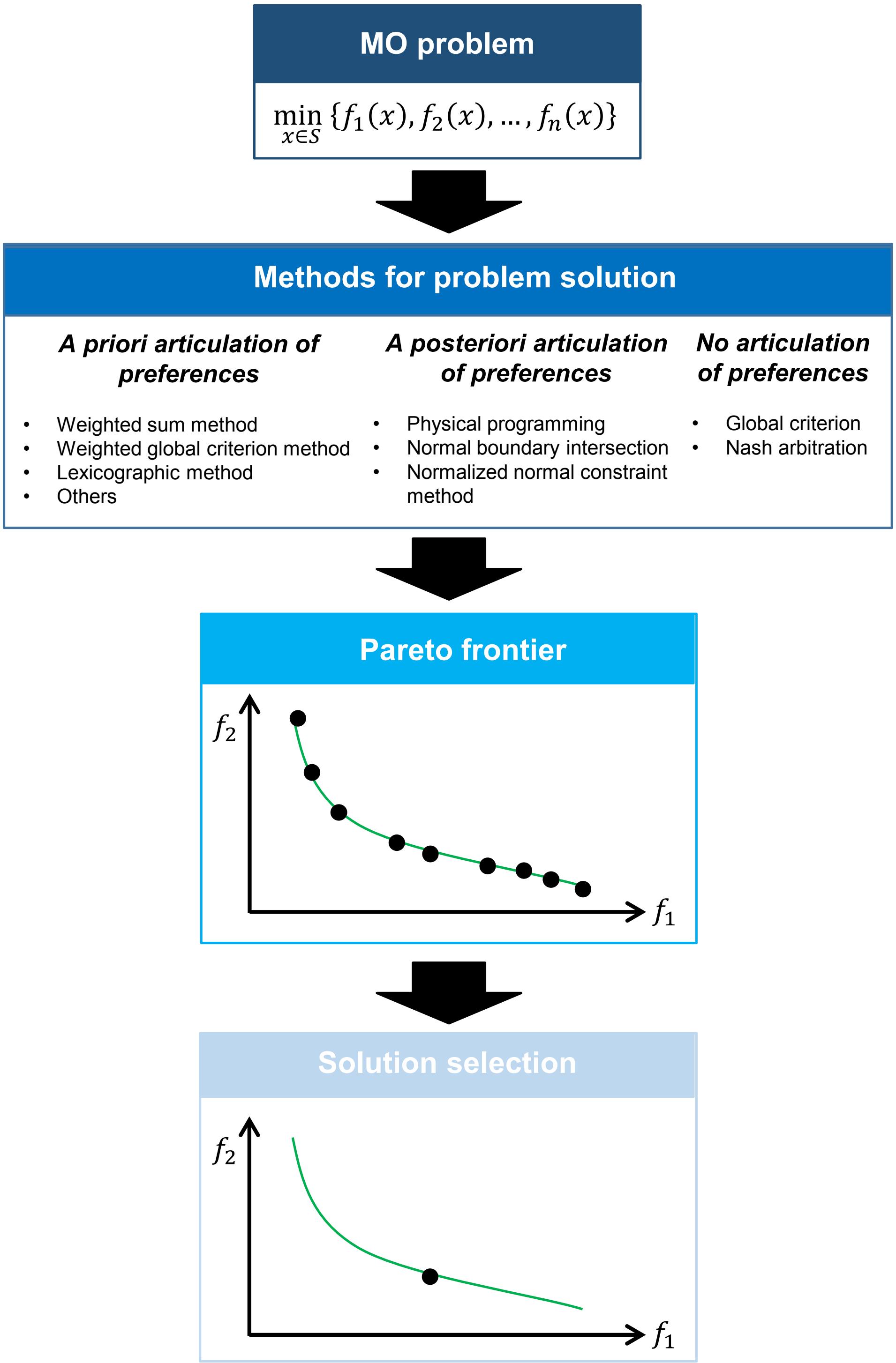


Figure 4.1. Stepwise procedure to solve a MO problem.

4.2 Pareto optimality

For the single-objective scalar space, the concept of optimality is univocal. In the case of minimization problems, $x^* \in S \subseteq R^m$ is the minimum of the scalar objective function $y = f(x) \in C \subseteq R$ if $\forall x \in S: f(x) \geq f(x^*)$. Such a concept does not apply directly to the multi-objective setting. Typically, there is no single global solution, and it is often necessary to determine a set of points that all fit a predetermined definition for an optimum. The predominant concept in defining an optimal point is that of Pareto optimality (Pareto, 1906).

Pareto optimality

A vector $x^* \in S$ is a Pareto optimal for the MO (Eqs. 4.1-4.2) if all other vectors, $x \in S$, have a higher value for at least one of the objective functions f_i (Eq. 4.1), with $i = 1, \dots, n$ or they have the same value for all the objective functions.

The definition of Pareto optimality requires the distinction of these solutions in weak and strict. More properly, a vector $x^* \in S$ is said to be a *weak Pareto optimum* or a *weak* efficient solution of the multi-objective problem iff (if and only if) there is no other $x \in S$ such that $f_i(x) < f_i(x^*)$ for all $i = 1, \dots, n$. Furthermore, a vector $x^* \in S$ is said to be a *strict* Pareto optimum or a *strict* efficient solution of the multi-objective problem iff there is no other $x \in S$ such that $f_i(x) \leq f_i(x^*)$ for all $i = 1, \dots, n$, with at least one strict inequality. In other words, a point is weakly Pareto optimal if there is no other point that improves all of the objective functions simultaneously. In contrast, a point is Pareto optimal if there is no other point that improves at least one objective function without detriment to another function. Pareto optimal points are weakly Pareto optimal, but weakly Pareto optimal points are not Pareto optimal (Marler and Arora, 2004). Finally, local Pareto-optimal points are defined as above, except for the attention restriction to a feasible neighborhood of x^*.

Pareto frontier

The image of the efficient set, i.e. the image of all the efficient solutions, is called Pareto frontier, curve, surface or optimal set.

Its shape indicates the nature of the best trade-off among the different objective functions. The point of the Pareto frontier are called non-dominated points or, shortly, Pareto points. Steuer (1989) provides the following definition for non-dominated and dominated points.

Non-Dominated and Dominated Points

A vector, $x^* \in S$, is non-dominated iff there does not exist another vector, $x \in S$, such that $f_i(x) \leq f_i(x^*)$ for all $i = 1, \dots, n$ with at least one $f_i(x) < f_i(x^*)$ for a certain i-th objective function. Otherwise, x^* is dominated.

Utopia and anchor points

Further required definitions for MO optimization are utopia and anchor points. A subset of the Pareto points is made of the so-called anchor points. Given a multi-objective problem with n objective functions, n anchor points exist. The i-th anchor point comes from the solution of the following single-objective model.

$$\min_{x \in S} f_i(x) \tag{4.4}$$

$$S = \{x \in R^m : h(x) = 0, g(x) \le 0\} \tag{4.5}$$

Given the optimal solution $\tilde{x}_i$ of Eqs. 4.4-4.5 the related anchor point coordinates in the C space are $A_i\big(f_1(\tilde{x}_i), f_2(\tilde{x}_i), \dots, f_n(\tilde{x}_i)\big)$. $\tilde{x}_i$ minimizes $f_i(x)$ so that all the other admissible solutions for the multi-objective problem are with $f_i(x) \ge f_i(\tilde{x}_i)$. As a consequence, each anchor point A_i is the best solution looking at the correspondent objective function, $f_i(x)$. The point $U\big(f_1(\tilde{x}_1), f_2(\tilde{x}_2), \dots, f_n(\tilde{x}_n)\big)$ is the so called utopia point, representing the *virtual* desirable solution for the multi-objective problem. Generally, $U \notin C$ so that $\nexists x \in S: f(x) = \big(f_1(\tilde{x}_1), f_2(\tilde{x}_2), \dots, f_n(\tilde{x}_n)\big)$. On the contrary, the Pareto frontier is the *locus of points* admissible for the multi-objective problem and most desirable given the n objective functions.

The following Figure 4.2 presents all the aforedescribed relevant MO elements for a bi-objective minimization problem.

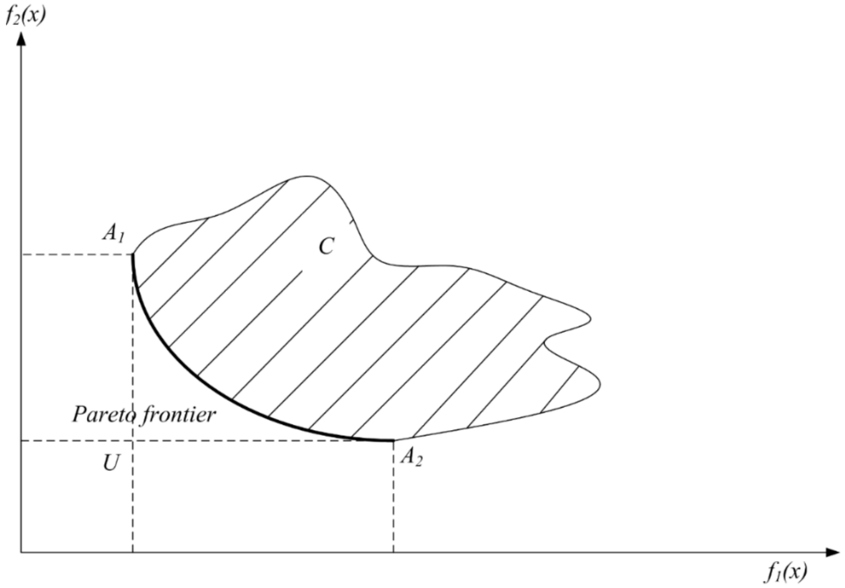


Figure 4.2. Relevant MO elements for a bi-objective minimization problem (from Gamberi et. al, 2015).

4.3 Methods for problem solution

It is important to notice that for any given MO problem, there may be an infinite number of Pareto optimal points constituting the Pareto frontier. Therefore, as investigated by Marler and Arora (2004), one must distinguish between methods that provide the Pareto frontier or some portion of this, and methods that actually seek a single final point as solution of the MO problem.

4.3.1 A priori articulation of preferences

Distinctive feature of this method category is that the decision-maker of the MO problem can specify his/her preferences in terms of goals or relative importance of different objective functions. Most of these methods incorporate parameters, which are coefficients, exponents, constraints, etc. that can either be set to reflect decision-maker preferences and obtain a single solution for the MO problem, or be continuously altered in an effort to represent the complete Pareto frontier (Marler and Arora, 2004). Preferences dictated by the decision-maker provide constraints. The most common approach to imposing such constraints is to develop a utility function (UF). Utility function represents decision-maker satisfaction. The utility function is defined as an amalgamation of the single objective and it is a mathematical expression that attempts to model the decision-maker preferences. The following methods proposed in this Paragraph are based on different utility functions.

- Weighted sum method

  The most common a priori approach to MO is the weighted sum method:

  $$UF = \sum_{i=1}^{n} w_i f_i(x) \tag{4.5}$$

  If all of the weights w_i are positive, the minimum of Eq. 4.5 is Pareto optimal (Zadeh, 1963). Thus, minimizing Eq. 4.5 is sufficient for Pareto optimality. However, the formulation does not provide a necessary condition for Pareto optimality (Zionts, 1988). Misinterpretation of the theoretical and practical meaning of the weights can make the process of intuitively selecting non-arbitrary weights an inefficient chore. Consequently, many authors developed systematic approaches for weights selection. Ranking, categorizing, rating, eigenvalue and ratio questioning are some of the most widespread methods. However, weighted sum method is even distinguished by drawbacks. First, despite the many methods for determining weights, a satisfactory, a priori selection of weights does not necessarily guarantee that the final solution will be acceptable. Thus, one may have to resolve the problem with new weights. Second, it is impossible to obtain points on non-convex portions of Pareto frontier in the criterion space. Last, varying the weights consistently and continuously may not necessarily result in an even distribution of Pareto optimal points and an accurate, complete representation of the Pareto frontier.

- Weighted global criterion method

  One of the most general utility functions for this method is expressed in its simplest form as the weighted exponential sum (Eqs. 4.6-4.7).

$$UF = \sum_{i=1}^{n} w_i [f_i(x)]^p, \quad f_i(x) > 0 \; \forall i \tag{4.6}$$

or

$$UF = \sum_{i=1}^{n} [w_i f_i(x)]^p, \quad f_i(x) > 0 \; \forall i \tag{4.7}$$

Here, the weights w_i should satisfy the following conditions: their sum has to be equal to 1 and each of them has to be greater than 0. Generally, the relative value of the weights reflects the relative importance of the objectives for the decision-maker.

One of the major advantages of this method is that minimizing Eq. 4.7, in particular, is necessary for Pareto optimality (Athan and Papalambros, 1996). However, this is not a practical approach for depicting the complete Pareto frontier.

- Lexicographic method

  With the lexicographic method, the objective functions are arranged in order of importance. Then, the following optimization problems are solved one at a time:

$$\min_{x \in S} f_i(x) \tag{4.8}$$

Subject to $f_j(x) \leq f_j(\tilde{x}_j), \;\; j = 1,2,\dots,i-1, \;\; i > 1, \;\; i = 1,2,\dots,n.$

Here, i represents a function position in the preferred sequence and $f_j(\tilde{x}_j)$ represents the optimum of the j-th objective function, found in the j-th iteration. After the first iteration ($j = 1$), $f_j(\tilde{x}_j)$ is not necessarily the same as the independent minimum of $f_j(x)$ because new constraints have been introduced.

- Others

  Other methods for a priori articulation of preferences that deserve to be mentioned are the weighted min-max method, the exponential weighted criterion, the weighted product method, the goal programming methods, the bounded objective function method and the physical programming. Description of these method is not part of this research.

4.3.2 A posteriori articulation of preferences

In some cases, it is difficult for a decision-maker to express an explicit approximation of the utility function to quantify its preferences. Therefore, it can be effective to allow the decision-maker to choose from a palette of solutions. These methods all depend on the solution of multiple sequential optimization problems with a consistent variation in method parameters. This method category is developed to overcome the disadvantages of a priori articulation of preferences. First, repeatedly solving the a priori methods can be ineffective in providing an even spread of points that accurately represents the complete Pareto frontier. In addition, although a formulation theoretically provides a necessary condition, it may not be clear how to set method parameters to capture only Pareto optimal points. Consequently, some algorithms are specifically designed to produce a set of Pareto optimal points that accurately represents the complete Pareto frontier (Marler and Arora, 2004).

- Physical programming
  Although it was initially developed for a priori articulation of preferences, physical programming can be effective in providing Pareto optimal points that accurately represent the complete Pareto frontier, even when the Pareto optimal surface is non-convex (Martinez et al. 2001). Messac and Mattson (2002) provide a detailed algorithm for systematically modifying the method constants as a mathematical tool rather than an indication of preferences. As the constants are shifted, contours of the utility function traverse the criterion space, capturing different Pareto optimal points.

- Normal boundary intersection
  In response to deficiencies in the weighted sum approach, Das (1999) and Das and Dennis (1998) present the normal boundary intersection method. This method provides a means for obtaining an even distribution of Pareto optimal points for a consistent variation in the decision maker-supplied parameters, $\boldsymbol{w_i}$, even with a nonconvex Pareto optimal set. Drawback of this method is that it may also yield non-Pareto optimal points. Thus, it does not provide a sufficient condition for Pareto optimality.

- Normalized normal constraint method
  The normalized normal constraint method is an alternative to the normal boundary intersection method with some improvements. Using normalized objective functions and a Pareto filter which eliminates non-Pareto optimal solutions, this

approach provides a set of evenly spaced Pareto optimal points in the criterion space. In fact, it always yields Pareto optimal solutions. In addition, its performance is independent of design objective scales. Considering all these strengths and its applicability for this research purposes, this method is deeply analyzed and described in Paragraph 4.4.

4.3.3 No articulation of preferences

Often the decision-maker cannot concretely define his/her preferences. Thus, some authors proposed methods that do not require any articulation of preferences. Most of the methods are simplifications of the “a priori” methods, usually excluding the definition of method parameters.

- Global criterion
  This method can be summarized with its fundamental idea: the use of an exponential sum to determine the Pareto optimal set.

- Nash arbitration
  The Nash arbitration scheme is an approach that is derived from the game theory. Based on predetermined axioms of fairness, Nash (1950) suggests that the solution to an arbitration problem is the maximum of the product of the player utilities. In this case, the utility functions always have non-negative values and it is distinguished by a value of zero in the absence of cooperation, thus no reached agreement. For sake of MO, individual objective functions have to be minimized and the method purpose is maximizing the following global criterion (Straffin 1993) (Eq. 4.9).

$$UF = \prod_{i=1}^{n} [s_i - f_i(x)] \tag{4.9}$$

Where $s_i \geq f_i(x)$ and s_i represents an upper limit on each function. This ensures to obtain a Pareto optimal point, considering that if any component of the product in Eq. 4.9 becomes negative, the result can be a non-Pareto optimal solution. The solution to this method depends on the value of s_i because Eq. 4.9 tends to improve most significantly those objective functions that are farthest away from s_i (Davis 1983).

4.3.4 Heuristic algorithms

The MO methods analyzed in the previous paragraphs involved unique formulations that are solved using standard optimization techniques, namely single-objective optimization methods. However, other approaches can be tailored to directly solve MO problems. Because genetic algorithms do not require gradient information, they can be effective regardless of the nature of the objective functions and constraints. They combine the use of random numbers and information from previous iterations to evaluate and improve a certain population of points, namely a group of potential solutions, rather than a single point at a time.

The specific mechanics of genetic algorithms involve the language of microbiology and, in developing new potential solutions, mimic genetic operations. A population represents a group of potential solution points. A generation represents an algorithmic iteration. A chromosome is comparable to a design point, and a gene is comparable to a component of the design vector (Marler and Arora, 2004).

The definition of a proper Pareto frontier depends on the adopted method features. As already mentioned, even a priori methods (Paragraph 4.3.1) can be used by a decision-maker to obtain a set of Pareto points. Each set of method parameters identify a Pareto point. Varying the parameters several Pareto points can be determined. Messac et al. (2003) suggest a set of attributes to assess the methods presented in this Paragraph.

- Spread Pareto points
  The method should generate an even set of Pareto points in the design space and not neglect any region. All regions of the design space should be adequately represented in the generated sampling.

- All Pareto points
  The method should have the ability to generate all available Pareto solutions. In cases where the desired Pareto optimal solution cannot be generated because of structural deficiencies of the method, the process fails in a fundamental way.

- Only Pareto points
  The method should generate only Pareto solutions. Indeed, weather a method generates also non-Pareto solutions, one should use these with extreme caution. A non-Pareto solution implies that it is possible to find a better solution that entails no tradeoff.

- Easy to apply
  The method should be relatively easy to apply and implement in standard and automatic software procedures.

The more of these attributes distinguish a method, the greater its value is. Methods distinguished by all of these attributes are the best to adopt.

4.4 An example: the normalized normal constraint method

Among the presented methods, normalized normal constraint one deserves to be further described and analyzed considering the purpose of this Ph.D. thesis. First, it is distinguished by all the four relevant attributes proposed by Messac et al. (2003). Indeed, this easy to apply method offers a spread set of all and only Pareto points. Furthermore, it belongs to the a posteriori method category. This feature is extremely relevant because does not require the decision-maker to express an a priori preference among the objective functions. Thus, the user is enabled to select the system configuration which prefer analyzing the Pareto frontier trend and assessing possible trade-off considerations among the objective functions. In the following, the method process to obtain the Pareto frontier is presented and described (Messac et al., 2003 and Gamberi et al., 2015). Eqs. 4.10-4.17 propose the mathematical formulation for a MO problem distinguished by n functions, whereas, for sake of clarity, Figures 4.3-4.5 represent the related bi-objective configuration.

Starting from the multi-objective minimization problem in Eqs. 4.1-4.2, the n anchor points, A_i, and the utopia point, U, the normalized normal constraint method firstly normalizes the R^n dimensions through the following metrics (Figure 4.3). Each dimension $f_i(x)$ is scaled as follows:

$$\varphi_i(x) = \frac{f_i(x) - f_i(\tilde{x}_i)}{\max_j\{f_i(\tilde{x}_j)\} - f_i(\tilde{x}_i)} \tag{4.10}$$

$\varphi_i(x)$ ranges in $[0,1]$.

In the normalized objective space, all anchor points are one unit away from the Utopia point, and the Utopia point is at the origin, by definition.

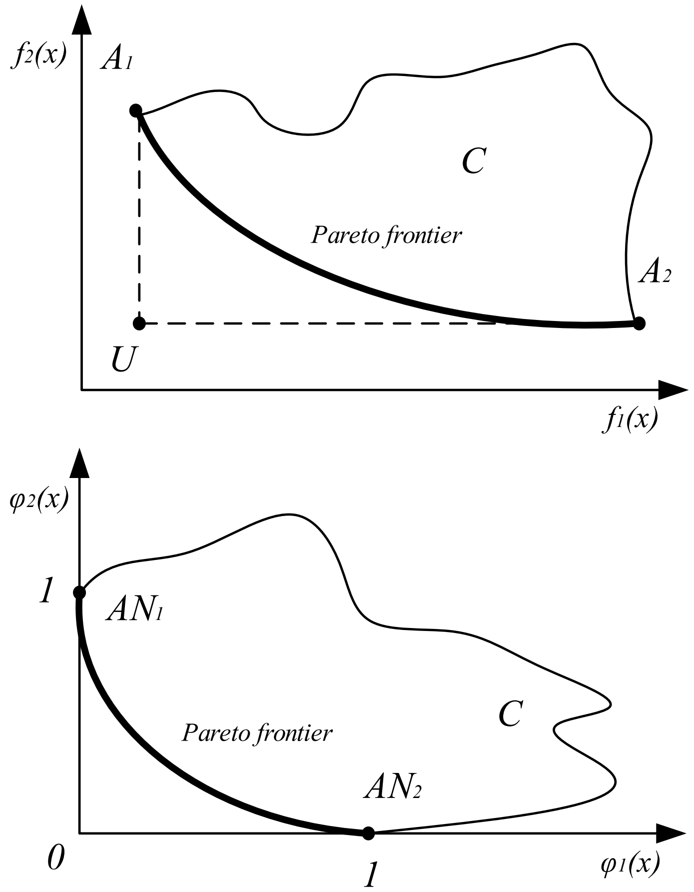


Figure 4.3 Non-normalized (top) and normalized (bottom) objective space.

In the normalized R^n hyper-space, the so-called utopia hyper-plane is defined (called utopia line in bi-objective optimization and utopia plane in tri-objective optimization). All the anchor points belong to this hyper-plane and its directions along the axes are univocally identified by $n-1$ vectors. For the k-th direction ($k=1,\dots n-1$) such vector is (Eq. 4.11):

$$N_k = \varphi(\tilde{x}_n) - \varphi(\tilde{x}_k) \tag{4.11}$$

Furthermore, the Pareto frontier is approximated through a set of Pareto points. To get each of them, the introduced utopia hyper-plane is evenly sampled along each of its directions moving stepwise with a normalized constant increment δ_k so that m_k samples are obtained per each direction (Figure 4.4). Follows that (Eq. 4.12):

$$\delta_k = \frac{1}{m_k - 1} \qquad , k = 1, \dots n-1 \tag{4.12}$$

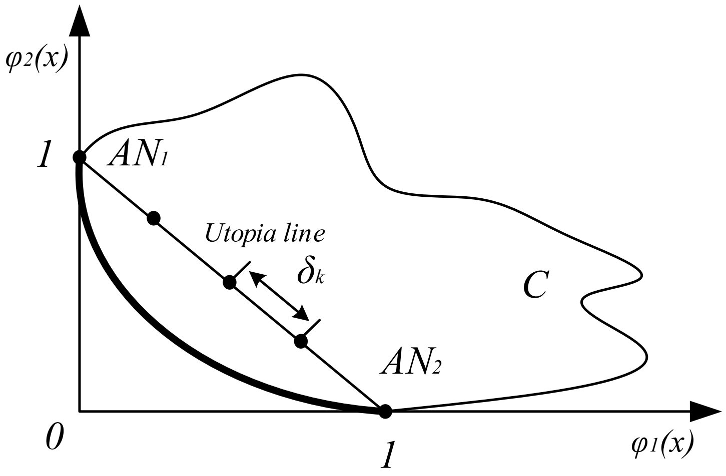


Figure 4.4 Utopia line and normalized constant increment.

Each sample corresponds to a point of the utopia hyper-plane, called utopia point, X_j, univocally identified by its n coordinates respecting the following equation (Eq. 4.13).

$$X_j = \sum_{k=1}^{n} \alpha_{kj} \cdot \varphi(\tilde{x}_k) \tag{4.13}$$

where $0 \leq \alpha_{kj} \leq 1$ and $\sum_{k=1}^{n} \alpha_{kj} = 1$.

For each utopia point the correspondent Pareto point in the normalized hyper-space comes by solving the following auxiliary single-objective model (Eqs. 4.14-4.17).

$$\min_{x \in S} \varphi_n(x) \tag{4.14}$$

$$S = \{x \in R^m : h(x) = 0, g(x) \leq 0\} \tag{4.15}$$

$$N_k\left(\varphi(x) - X_j\right)^T \leq 0 \qquad , k = 1, \ldots, n-1 \tag{4.16}$$

$$\varphi(x) = \{\varphi_1(x), \varphi_2(x), \ldots, \varphi_n(x)\} \tag{4.17}$$

The model minimizes the n-th normalized objective function, $\varphi_n(x)$, (4.14), considering the objective space, S, (4.15). The $n-1$ vectorial constraints in (4.16) limit the image of the objective space, C, through a same number of hyper-planes orthogonal to the utopia hyper-plane and including the utopia point, X_j. Figure 4.5 graphically exemplifies such concepts for the bi-objective and tri-objective cases.

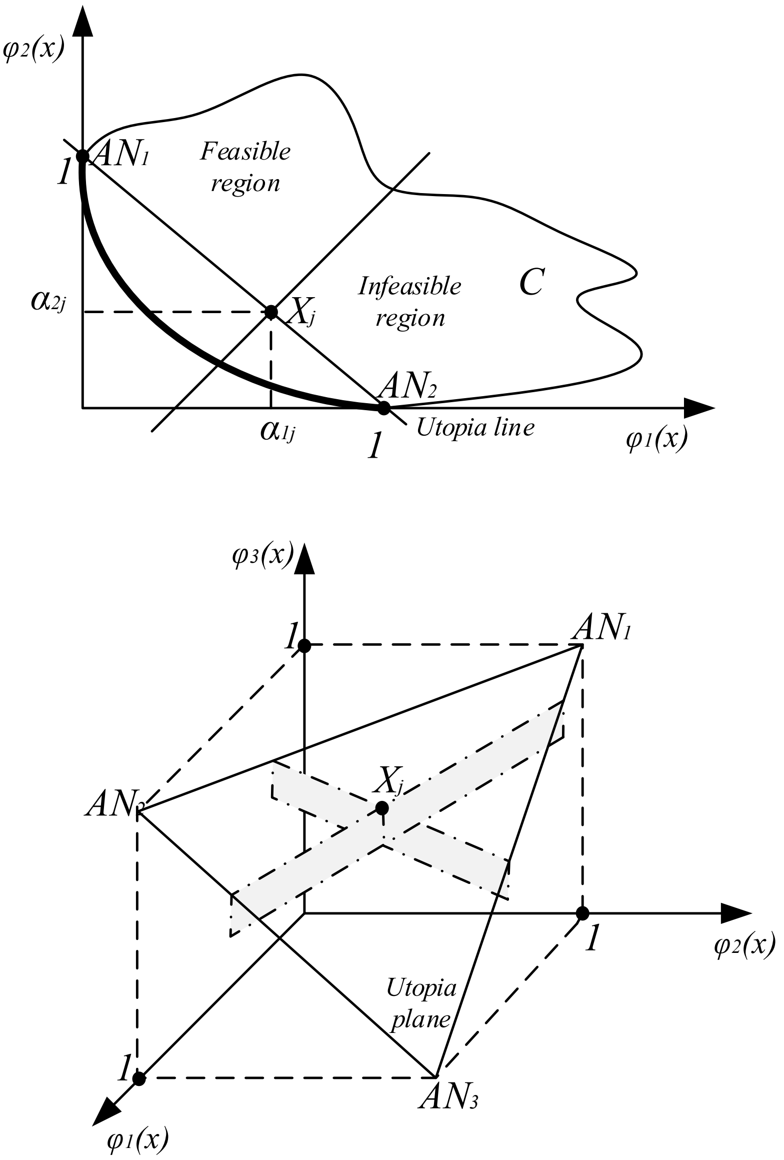


Figure 4.5 Graphical representation of the auxiliary single-objective model for bi-objective (top) and tri-objective (bottom) cases.

Given the j-th solution, x_j^*, of the model in Eqs. 4.14-4.17 and the optimal value $\varphi_n(x_j^*)$ of the n-th objective function in the normalized hyper-space the correspondent Pareto point x_j^* (also called pp^j) is $\left(\varphi_1(x_j^*), \varphi_2(x_j^*), \dots, \varphi_n(x_j^*)\right)$ in the normalized hyper-space and $\left(f_1(x_j^*), f_2(x_j^*), \dots, f_n(x_j^*)\right)$ in the R^n original hyper-space. The metric in Eq. 4.10 allows the switch between the two coordinate systems. It is important to notice that the generation of the Pareto point set is performed in the normalized objective space, which results in critically beneficial scaling properties.

Finally, the introduced normalized normal constraint method for generating the Pareto frontier guarantees that the obtained Pareto points are local Pareto-optimal points, pp^j. All the anchor points belong to this set. The final check of each local Pareto-optimal point against the previous notion of Pareto global optimality allows to discharge the so-called dominated points, i.e. non Pareto global optimal points, fixing the Pareto frontier uniquely made of global Pareto points, gpp^j. Such a last checking step is, also, called, Pareto filtering procedure proposed by Messac et al. (2003) (Figure 4.6). A Pareto filter is an algorithm that, given a set of design points in objective space, returns a set of design points that are all Pareto solutions (at least with respect to the original set provided). That is, the filter eliminates all dominated points from the given set. Effectively, the filter works by comparing a point on the Pareto frontier with every other generated point. If a point is not globally Pareto, it is eliminated.

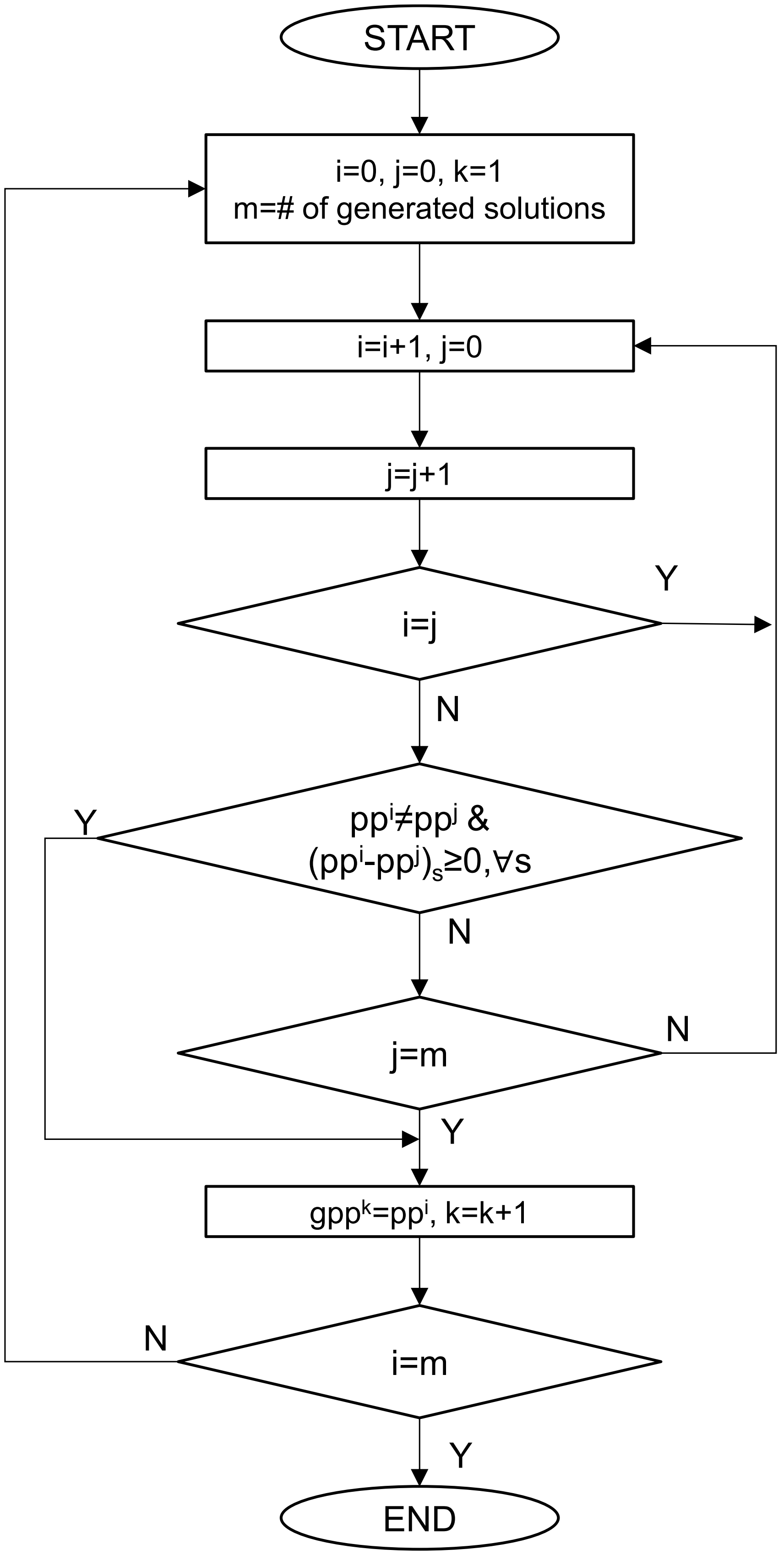


Figure 4.6. Flow diagram of Pareto filter (from Messac et al., 2003).

4.5 Solution selection

The Pareto frontier represents the set of the MO optimal solutions. However, a final solution has to be selected among the ones that lay on the Pareto frontier. The solution selection is an arbitrary but necessary phase in every MO problem that deal with real world application. For instance, consider a tri-objective optimization problem for the joint minimization of cost, emissions and delivery time of a distribution network. Each MO problem solution identified by a Pareto point is a feasible distribution network configuration distinguished by a compromise among the objective functions. However, a final configuration of this system has to be defined univocally to determine which production plant satisfies which customer demand, where and how many distribution centers it is necessary to install as well as which paths and transport modes are used for product delivery. Typically, the selection of the final (or trade-off) solution of a MO problem is subjective and it depends on the absolute or relative importance that the decision-maker confers to the objective functions. Several qualitative and quantitative criteria and approaches can be used for this purpose. This research suggests a practical rule of thumb to determine the final MO problem solution as the best trade-off among the objective functions (Eq. 4.18).

$$\min_{j=1,..,m} G_j, \quad G_j = \prod_{i=1}^{n} \frac{f_i(x_j^*)}{f_i(\tilde{x}_i)} \tag{4.18}$$

The MO trade-off solution is the one distinguished by the minimum value of the global function G_j, among the m Pareto points obtained. For each j-th Pareto point x_j^*, the global function value is calculated as the product of the ratio $\frac{f_i(x_j^*)}{f_i(\tilde{x}_i)}$ for all the n objective functions. The denominator represents the i-th objective function optimal value, thus calculated in $\tilde{x}_i$. The numerator evaluates the i-th objective function value determined by the j-th Pareto point x_j^*.

The greatest strength of the proposed criterion is its objectivity. No articulation of decision-maker preferences is considered. The relative and absolute importance is equal among all the objective functions. The final (trade-off) solution is selected as the one that minimizes the product of the objective function increment compared to their minimum. For sake of exemplification, the next Figure 4.7 proposes the Pareto frontier of a bi-objective optimization problem, whereas Figure 4.8 proposes the objective function increments (green and blue lines) and the global function value (red line) for every Pareto solution. The final trade-off configuration is the one that minimizes the global function and it is represented by a black dot.

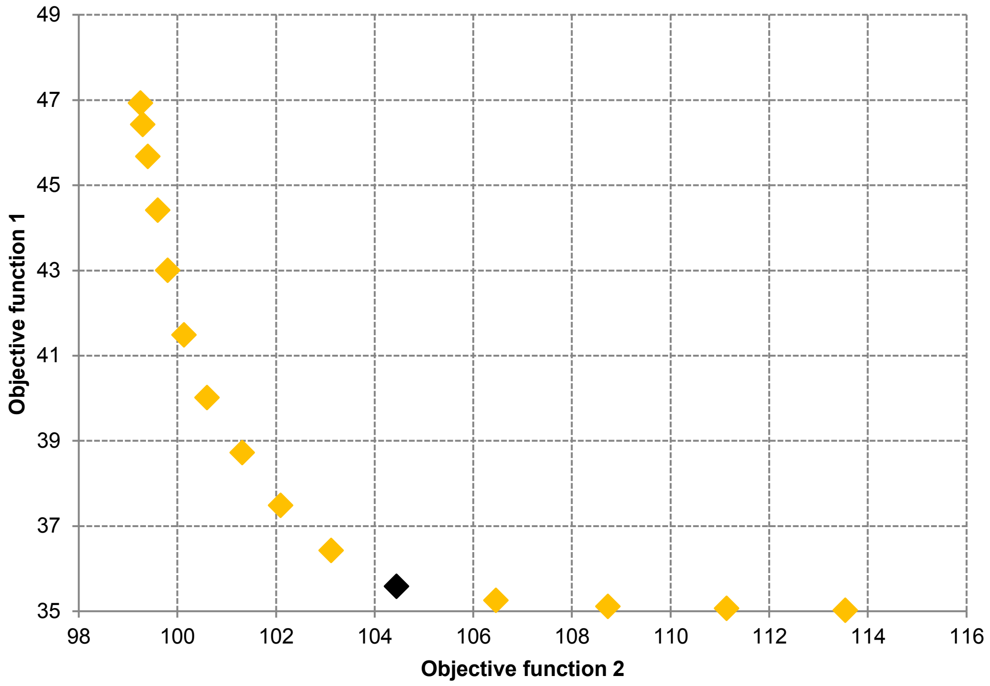


Figure 4.7. Bi-objective optimization problem Pareto frontier.

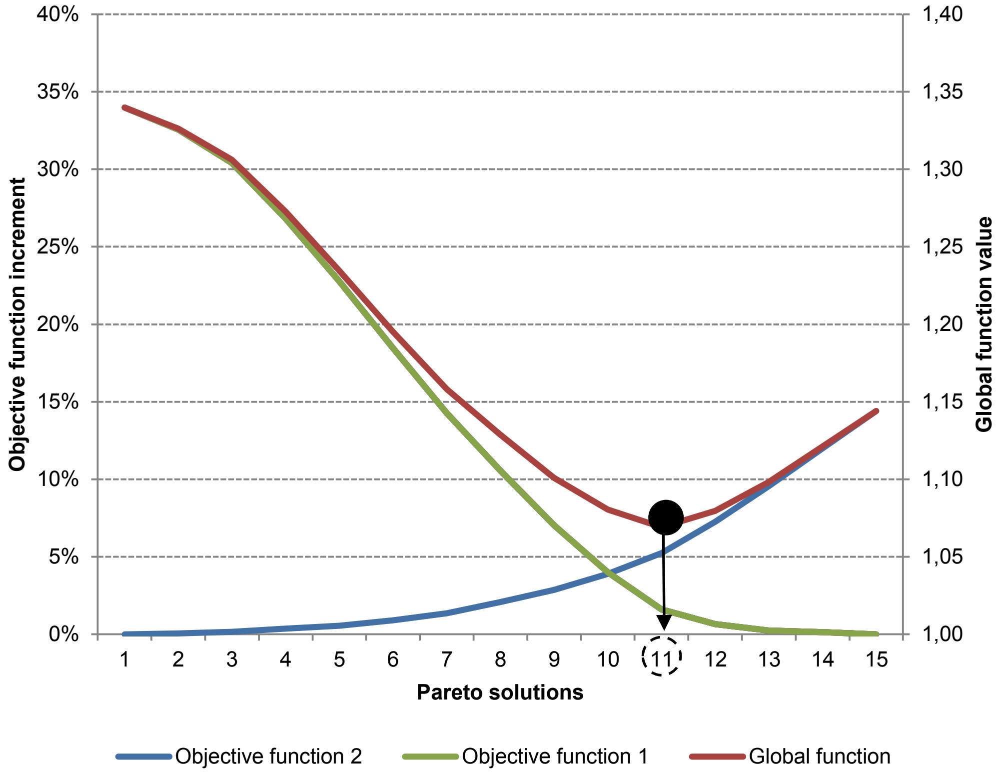


Figure 4.8. Objective function increment (green and blue lines) and the global function value (red line) for every Pareto solution.

Please note that the proposed selection criterion is for minimizing MO problem distinguished by $f_i(\tilde{x}_i) > 0, \quad \forall\, i$.

4.6 Notations

x	decision variable
$f_i(x)$	i-th objective function
n	number of objective functions
S	admissible region
$h(x) = 0$	equality constraint
$g(x) \leq 0$	inequality constraint
C	objective space
x^*	Pareto point or optimum
A_i	anchor point of the i-th objective function
U	utopia point $\tilde{x}_i$
$\tilde{x}_i$	optimal solution of the i-th objective function
UF	utility function
w_i	weight of the i-th objective function
AN_i	normalized anchor point of the i-th objective function
pp^i	i-th Pareto point
gpp^i	i-th global Pareto point

5. Distribution network planning

This Chapter presents a decision support system to minimize the operating cost, the carbon footprint and the delivery time in the design of multi-modal distribution networks. A multi-objective optimization model is proposed to overcome the widely adopted methodologies focused on cost minimization, only. The developed approach simultaneously assesses three independent objective functions, evaluating the network costs, the carbon footprint (measured in CO_2 emissions) and the shipping time from the producers to the final retailers. The decision support system manages multimodal four-level (three-stage) distribution networks, best connecting the producers to the final retailers, through a set of distribution centers. It allows multiple transport modes and inter-modality options looking to the most effective distribution network configuration from the introduced multi-objective perspective. The three optimization criteria can be considered independently or solved simultaneously, through the so-called Pareto frontier approach. Finally, the proposed decision support system is validated against a case study about the delivery of Italian fresh food to several European retailers.

5.1 Background and introduction

The aim of distribution network (DN) design and management is to study the most effective ways to ship products from the production centers to the end-users facing the related decisions (Manzini et al., 2007b), e.g. the allocation of the market demand to the producers considering their capacity and peculiarities (Apaiah and Hendrix, 2005), the shipment mode choice (Eskigun et al., 2005), the distribution center (DC) inclusion (Cheng and Tsai, 2009; Ioannou, 2005), etc. According to this definition, the following Paragraphs 5.1.1-5.1.4 present the most relevant DN design and management methodologies, the most commonly adopted KPIs, the current DN MO trends, and the goals and an overview on this Chapter.

5.1.1 Design and management methodologies

A deep review of the DN design decisions is in Klibi et al. (2010) pointing out a set of strategic questions to be addressed: "Which markets should we target? What delivery time should we provide in different product markets and at what price? How many production and DCs should be implemented? Where should they be located? Which activities should be externalized? Which partners should we select? What production, storage and handling technologies should we adopt and how much capacity should we have? Which products should be produced/stocked in each location? Which factory/DC/demand zones should be supplied by each supplier/factory/DC? What means of transportation should be used?" Answering to all questions with a unique approach and methodology is almost impossible in practice especially if more than one decisional criterion is adopted. The current literature agrees to split the problem into multiple parts proposing dedicated methodologies for each of them. Useful approaches already presented in Paragraph 2.2.3 are in Manzini et al. (2014), presenting strategic, tactical and operational DN design and management horizons to focus on the long-term, mid-term and short-term network design separately. Mehrjerdi (2009) classifies the DN components and the related separate management actions. Furthermore, he introduces temporal and functional classifications of the problem. Beamon (1998) reviews the existing models and methods for DN design and management proposing a reference classification against the following categories:

- Deterministic analytical models;
- Stochastic analytical models;
- Economic analytical models;
- Simulation models.

Such categories cross with two other basic methods to tackle the problem:

- Optimal models;
- Heuristics.

According to the definition proposed in Paragraph 2.2.1, deterministic analytical models are based on fix input data. No data variability is modeled differently from the stochastic analytical models in which some of the variables are stochastically distributed, e.g. the expected end-user future demand levels. Economic analytical models are considered separately due to their importance and high adoption. The economic perspective is frequently the unique considered decisional criterion. Finally, simulation models refer to a different approach respect to analytical models. The former builds models reproducing the DN behavior to infer ex-post general trends, while the latter builds conceptual mathematical models to predict ex-ante the best values for the decisional variables. Finally, optimal models look for the optimization of the considered objective functions and are, generally, based on linear programming models, while heuristics propose good solutions and practical rules-of-thumb to face the considered DN design and management issues. Almost all the existing methodologies for the DN design and management may be grouped according to the previous drivers. The extensive review proposed by Soni & Kodali (2012), considering 619 empirical studies on DNs, follows such categories. Similarly, Appelqvist et al. (2004) follow similar criteria in their 83 article review with the, further, inclusion of the industrial sector the studies refer to. Such contribution highlights the range of applicability of the design methodologies as another relevant issue to consider.

5.1.2 Concurrent key performance indices

The effective DN design and management deals with and integrated set of actions looking for the whole system optimum. Manzini et al. (2007b) highlight the trend of the literature about the importance of adopting an integrated approach not focused on a single element of the DN and based on coordination and information sharing. Among the issues to be considered in the DN design and management, a basic one is the perspective to be adopted and the targets to look for (Ramaa et al., 2009). Three main perspectives can be followed.

- Single-objective, single-criterion perspective;
- Multi-objective, single-criterion perspective;
- Multi-objective, multi-criteria perspective.

In single-objective, single-criterion DN design and management perspective a sole driver is considered and, consequently, a unique function is managed and optimized. Standard approaches based on such a perspective look at the minimization of the DN length or shipping time, the unitary equivalent cost reduction, etc. No trade-off among different criteria is done. On the contrary, multi-objective approaches are based on the inclusion of more than one KPI. Typically, KPIs with divergent trends are considered, e.g. shipping time vs. shipping cost, DN cost vs. DN environmental impact, etc., looking for intermediate trade-off configurations. As presented in Paragraph 4.3, there are basically two ways in which two or more objectives can be dealt with, simultaneously. The former involves transforming the multi-objective problem into a single-objective problem that aggregates all the objectives through a procedure in which every objective is conditioned by a weighting factor and the objective function is calculated considering all the weighted objectives, i.e. multi-objective, single-criterion perspective. This requires the *a-priori* knowledge of the relative importance of the different KPIs. An alternative method is to accept several objectives simultaneously and determine a non-dominated set of alternatives. This set is a collection of alternative solutions that represent potential trade-offs among objectives, i.e. multi-objective, multi-criteria perspective (Moncayo-Martínez & Zhang, 2011).

Both the literature and the standard practice convey to identify the following criteria driving the DN design, management and optimization:

- Distance

  The purpose is to minimize the total travelled distance between the suppliers and the end-users, avoiding long routes, un-useful trips, partial load shipments, etc. Grouping strategies to supply more than one customer within the same trip are implemented. Typical objective functions are expressed in travelled kilometers/miles per year;

- Time

  The purpose is to minimize the total or average shipping time to supply the end-users. Respect to the distance criterion, the inclusion of the vehicle average commercial speed, the load/unload times, the route congestions, etc., is done. Typical objective functions are expressed in hours per supplied costumer;

- Cost

  The purpose is to minimize the annual equivalent cost for the DN activities. The boundary limits to define the cost drivers to be included generally vary among the approaches and models and they are generally classified between fix and variable costs, level and stage costs, operational and investment costs. Typical objective functions are expressed in euro/dollars per year or shipped product;

- Service level

  Differently from cost based DN design, in the case of the service level the target is the minimization of the gap between the end-user expectations and the experienced logistic service, trying to match them. Typical objective functions are expressed in percentage of satisfaction respect to predefined assessment metrics;

- Environmental impact
  A different and emerging perspective is about the direct and indirect impact on the environment of the DNs. The environmental burdens of production, shipment and storage processes for products and services are minimized. Behind such a criterion the concept of Green Supply Chain (GSC) and Sustainable Supply Chain (SSC) are spread (Seuring, 2013). Typical objective functions refer to the emitted pollutant quantities, e.g. CO_2, particulate, GHGs, etc., or to standard environmental assessment metrics, e.g. CO_2 equivalent, indicators from the standardized life cycle assessment (LCA) methodology, etc.

5.1.3 DN multi-objective optimization trends

As presented in Chapter 4, MO follows the basic idea of matching multiple criteria in the DN design (Deb, 2011). The recent literature on DN stresses the importance of adopting multiple criteria discussing about its superiority toward single-objective approaches (Harris et al., 2009). Nevertheless, the most of the existing design methods still considers a single objective function, typically related to the DN total annual cost. Melo et al. (2009) estimate that, approximately, 75% of the articles published on this topic in the last decade focuses on cost minimization, 16% on profit maximization and 9%, only, adopts a multi-objective perspective. A gap between the current research state of the art and the expectations exists and needs to be filled.

According to the procedure proposed in Paragraph 4.1, a stepwise approach has to be followed to determine the solution of a DN design and management MO problem. Starting from the model formulation and the choice of the optimization criterion two sequential and separate phases occur. The former deals with the multi-objective model optimization. Such phase does not univocally identify a unique solution, i.e. DN structure, but it is able to calculate a set of optimal trade-off solutions among the considered design criteria. The choice of the final solution is done in the latter phase by the panel of the decision makers. Despite the trade-off solution finding its objective and based on operation research algorithms, the final choice among such solutions is not univocal and depends on the personal preferences of the decision makers.

The recent literature facing the DN design through MO follows such a procedure. The basic difference among contributions is due to the considered decisional criterion to optimize. A first set of models focuses on logistic cost and delivery performance bi-objective optimization. Pokharel (2008) presents a two-objective model for decision making in DN based on cost minimization and delivery reliability maximization, while Xu et al. (2008) focus on fix and variable logistic costs and delivery time. Furthermore, Rajabalipour et al.

(2011) stress that time and cost are familiar criteria for every logistic provider and propose a three-level DN design bi-objective model based on the joint optimization of response time to consumers, transportation and facility costs. Similarly, Olivares-Benitez et al. (2013) focus on the same criterion presenting a mathematical model for DN design and a metaheuristic algorithm for its solution. Concerning the service level experienced by the end-users, Franca et al. (2010) propose a bi-objective model for the DN profit and quality level maximization, while Pishvaee et al. (2010) look for the total cost minimization and the maximization of the responsiveness of the network. The difficulties in expressing through a quantitative function the end-user experienced service level make such models almost qualitative or focused on partial aspects of this issue, e.g. the incidence of faulties on the total delivered products.

The increasing interest on environmental sustainability and low carbon patterns influence the DN design and management introducing the aforementioned concepts of green supply chain and sustainable supply chain. The recent literature investigated such aspects through reviews and reference frameworks (Seuring & Müller, 2008; Ageron et al., 2012; Dekker et al., 2012; Hassini et al., 2012; Rizet et al., 2012; Dasaklis & Pappis, 2013; Seuring, 2013). Following such trend, multi-objective DN design and management models including the environmental criterion, recently appear on the literature. Frota Neto et al. (2008) develop a bi-objective model for paper industry DN design including production and logistic costs together with the correspondent environmental impacts. Ramudhin et al. (2009) look for the best trade-off between logistic costs and GHG emissions, while Chaabane et al. (2011) present a bi-objective model for sustainable supply chain design considering costs and emissions during the production, storage and shipment phases. Similarly, Bouzembrak et al. (2011) present a conceptual model for the green supply chain design with the aim of capturing good compromises between the total cost and the DN environmental influence.

The proposed analysis of the recent literature about multi-objective network design points out the following research trends (Battini et al., 2013):

- The DN economic perspective, i.e. cost minimization or profit maximization, is essential and it must not be neglected;
- Promising optimization criteria to look for are about the delivery time and the network environmental impact;
- The service level is difficult to quantify and it is generally included among the model constraints;
- The most of the multi-objective models include two functions, i.e. bi-objective optimization, even if among the encouraged further developments several authors state about the inclusion of a third criterion.

Pioneering tri-objective contributions are outlined by Altiparmak et al. (2006) considering cost, customer service and vehicle capacity utilization joint optimization, Harris et al. (2009), considering cost, environmental impact and uncovered demand functions and, recently, Xifeng et al. (2013), considering cost, service reliability and carbon dioxide emissions. All authors recommend further studies in such a direction.

5.1.4 Research goals and overview

According to the introduced topic this chapter faces the optimal design and management of forward DNs. A set of fixed end-users with their own demands for a mix of physical products is considered best-building the static, multi-stage and multi-modal network to supply them. The intermediate level by-pass is, further, allowed making the DN flexible. The DN planning follows a multi-objective, multi-criteria perspective considering three drivers. The network operating unitary cost function looks for an efficient DN, not to heavily affect the delivered product full cost and market price, the carbon footprint function looks for a DN reducing the emitted pollutants. Finally, the delivery time function looks for a quick and safe supply of the end-user demand. Such three drivers are jointly considered through the Pareto frontier multi-criteria approach (Chapter 4) to identify effective trade-off DN configurations. The whole approach is based on a linear programming model and it is developed through a multi-objective optimizer Decision Support System (DSS) assisting the logistic designers and managers (Gamberi et al., 2015).
In the following paragraphs are introduced the model formulation and the DSS features and interface. A consistent case study taken from the fresh food European Union (EU) supply chain is, then, discussed to present a full application of the whole approach and tool. Further research directions and final remarks conclude this chapter.

5.2 Multi-objective optimization model formulation and decision support system

Starting from the problem statement to define the overall DN structure and allowed product flows, the present paragraph firstly introduces the multi-objective model formulation and, then, presents the DSS features and interfaces. The model formulation discussion is divided between the feasibility constraints, making the so-called *feasibility problem* and the three objective functions about operative cost, carbon footprint and delivery time minimization. Two different formulations of the MO problem are discussed. The former comes from the literature but presents a lack of applicability, the latter overcomes such a weakness. The DSS follows the model formulations and the required input parameters supporting the logistic planner in consolidating the input database, solving the model in accordance with the Pareto optimality concepts and, finally, saving and managing the output to draw useful conclusions about the most effective DN structure and management.

5.2.1 Problem statement and network configuration

The reference network structure consists of a multi-modal four-level (three-stage) forward DN (see Figure 5.1).

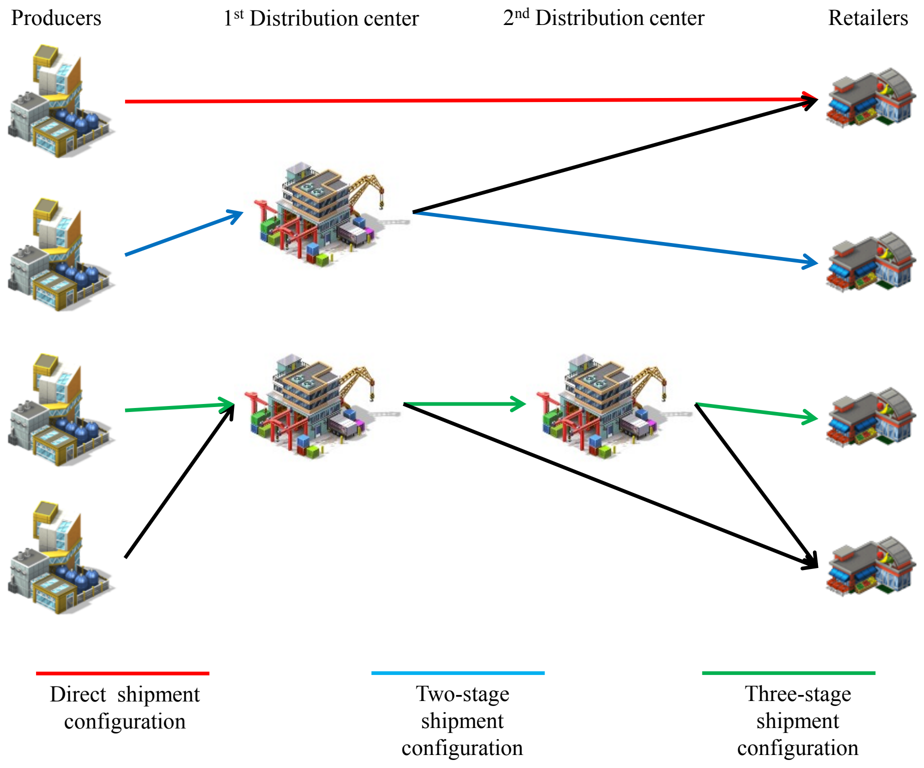


Figure 5.1. Distribution network reference structure.

The DN levels include:

- <u>Producers</u>
  This level deals with the product, i.e. goods with possible auxiliary services, manufacturing and assembly making it ready for the market. All the production processes are supposed to be concentrated at this level and performed by a production company leading the production process. Outsourcing and part supply are not included in the model focusing on the distribution phase;

- Central distributors
  This level, called 1st distribution center in Figure 5.1, is used in the case of indirect distribution channels to collect the producer output, sorting and delivery the loads to save shipping time and costs and eventually changing the shipping mode (i.e. intermodality concept). In dynamic models the central distributors may be, also, temporary storage centers. Central distributors are generally large logistic platforms, close to the production districts and with high level facilities and available services, e.g. railway, air and/or naval terminals, custom, high handling capacity, etc.;

- Regional distributors
  This level, called 2nd distribution center in Figure 5.1, is used in the case of long channels to further handle the products before the final consumption level. Regional distributors are closer to the end-users and represents the terminal for the so-called *last-mile shipment*. In the case of multi-modal shipments, these distributors frequently allow the further shipping mode change;

- Retailers
  In this context, the retailers are the DN end-users, having their demand profile to be supplied. The retailers may be large consumers or local vendors selling products to the single end-users and families. They represent the destination of the logistic fluxes.

In this network, there are three possible distribution configurations. Direct shipment (red arrow in Figure 5.1) links the retailers to the producers, two-stage shipment (blue arrow in Figure 5.1) considers a short indirect distribution channel with central distributors between producers and retailers. Finally, the three-stage shipment (green arrow in Figure 5.1) further includes regional distributors. Such distribution configurations define the correspondent network stages and introduce the distributor by-pass option making the DN more flexible.

Furthermore, the problem allows to consider a generic number of shipping modes and delivered products. The intermodality concept is included through the possibility of changing the shipping mode in the indirect channels thanks to the available facilities at the distributor sites. As example a load can be shipped by truck from the producer to the central distributors, by train from the central to the regional distributor and, finally, by truck between the regional distributor and the retailer. All combinations are admissible limited by the infrastructures available at each level. Finally, for the sake of simplicity and to face the problem from a long-term strategic view-point, the problem and DSS adopt a static perspective. Expected extensions of the problem statement need to include the suppliers as a further level before the producers and the dynamic DN modeling.

5.2.2 Feasibility model analytic formulation

Aim of the feasibility model is to define the aforementioned MO problem objective space (see paragraph 4.1), $\boldsymbol{S}$, in which the admissible solutions lie. In this model, the objective functions are not included and they are detailed, separately, in the following to build the full model formulation, i.e. objective functions and feasibility model. Two analytic formulations of the feasibility model are given starting from the literature and overcoming one of its major lack. Some common notations are, preliminarily, introduced.

Indices

c	product index, $c = 1,\dots,C$;
e	central distributor index, $e = 1,\dots,E$;
h	regional distributor index, $h = 1,\dots,H$;
u	shipping mode index, $u = 1,\dots,U$;
p	producer index, $p = 1,\dots,P$;
r	retailer/end-user index, $r = 1,\dots,R$.

Parameters

hcc_{ec}	handling capacity of central distributor *e* for product *c* [units/period];
hcr_{hc}	handling capacity of regional distributor *h* for product *c* [units/period];
pcp_{pc}	production capacity of producer *p* for product *c* [units/period];
dem_{rc}	market demand of retailer/end-user *r* for product *c* [units/period].

5.2.2.1 Feasibility model formulation #1

The feasibility model formulation #1 is based on the so-called location allocation problem (LAP) widely discussed by the literature (Manzini, 2012; Manzini et al., 2014). The goals are to define the logistic nodes to activate, the origin, path and destination of the product flows through the DN. The following decisional variables are necessary.

x_{pecu}	product *c* flow from producer *p* to central distributor *e* with mode *u* [units/period];
x_{phcu}	product *c* flow from producer *p* to regional distributor *h* with mode *u* [units/period];
x_{prcu}	product *c* flow from producer *p* to retailer/end-user *r* with mode *u* [units/period];
x_{ehcu}	product *c* flow from central distributor *e* to regional distributor *h* with mode *u* [units/period];
x_{ercu}	product *c* flow from central distributor *e* to retailer/end-user *r* with mode *u* [units/period];
x_{hrcu}	product *c* flow from regional distributor *h* to retailer/end-user *r* with mode *u* [units/period];

The feasibility model formulation, making the DN consistent, is in the following.

$$\sum_{p=1}^{P}\sum_{u=1}^{U}x_{prcu}+\sum_{e=1}^{E}\sum_{u=1}^{U}x_{ercu}+\sum_{h=1}^{H}\sum_{u=1}^{U}x_{hrcu}=dem_{rc}\ \forall r,c \tag{5.1}$$

$$\sum_{e=1}^{E}\sum_{u=1}^{U}x_{pecu}+\sum_{h=1}^{H}\sum_{u=1}^{U}x_{phcu}+\sum_{r=1}^{R}\sum_{u=1}^{U}x_{prcu}\le pcp_{pc}\ \forall p,c \tag{5.2}$$

$$\sum_{h=1}^{H}\sum_{u=1}^{U}x_{ehcu}+\sum_{r=1}^{R}\sum_{u=1}^{U}x_{ercu}\le hcc_{ec}\quad \forall e,c \tag{5.3}$$

$$\sum_{r=1}^{R}\sum_{u=1}^{U}x_{hrcu}\le hcr_{hc}\quad \forall h,c \tag{5.4}$$

$$\sum_{p=1}^{P}\sum_{u=1}^{U}x_{pecu}\ge\sum_{h=1}^{H}\sum_{u=1}^{U}x_{ehcu}+\sum_{r=1}^{R}\sum_{u=1}^{U}x_{ercu}\quad \forall e,c \tag{5.5}$$

$$\sum_{p=1}^{P}\sum_{u=1}^{U}x_{phcu}+\sum_{e=1}^{E}\sum_{u=1}^{U}x_{ehcu}\ge\sum_{r=1}^{R}\sum_{u=1}^{U}x_{hrcu}\quad \forall h,c \tag{5.6}$$

$$x_{pecu},x_{phcu},x_{prcu},x_{ehcu},x_{ercu},x_{hrcu}\ \ge 0\quad \forall p,e,h,r,c,u \tag{5.7}$$

Equation (5.1) guarantees the retailer/end-user demand is fully satisfied. In (5.2) the producer capacity per each product is not exceeded, while the central and regional distributor handling capacity constraints are in (5.3)-(5.4). Equations (5.5)-(5.6) balance the entry and exit flows at the distribution levels so that all the shipped products are, also, received. Finally, equation (5.7) give consistence to the decisional variables. The feasibility model includes $C\cdot(R+P+2E+2H)$ constraints (excluding the variable consistence definition), while the decisional variables are $C\cdot U\cdot(PE+PH+PR+EH+ER+HR)$.

The proposed formulation of the feasibility model allows to know the aggregate quantities of product flowing through the DN from the producers to the retailers/end-users. The nodes to activate are, consequently, defined. The key lack of the proposed model formulation is the impossibility to track the flow of each single product unit, especially in the case of indirect distribution channels. This is due to the presence of the distributors, acting as decoupling entities, so that, given the values of the flow variables, it is not possible to retrace the *journey* of each product unit, e.g. unit-load, container, etc. In the recent past, traceability rises as a key factor to consider in the DN design (Bevilacqua et al., 2009; Cheng & Tsai, 2009; Mehrjerdi, 2009). Such an issue is particularly relevant for high value products, with safety and quality properties rapidly decreasing within the lifetime. A brightly example is from the food sector. Nowadays, food traceability is mandatory to get high quality standards and to abide by the regulations actually in force. Both hardware solutions, protocols and reference frameworks to face the food traceability topic are introduced by the recent literature (Regattieri et al., 2007; Grunow & Piramuthu, 2013; Manzini & Accorsi, 2013; Storøy et al., 2013). The following alternative feasibility model formulation allows product traceability and it is suitable for applications in high value and critic sectors such as the food DNs.

5.2.2.2 Feasibility model formulation #2

The model goal is the same as before. This formulation is based on the concept of *path*. A path univocally connects a producer to a retailer/end-user through a shipment configuration. It is identified by its origin and destination, the intermediate distributors (if an indirect channel is used) and the shipping mode used between each couple of consecutive logistic nodes. Each unit of product flows the DN through one and only one path. Data about each path are known in advance so that traceability is ensured. According to the path concept, the model decisional variable become the following:

w_{zc} product *c* flow through path *z* [units/period];

where $z = 1, \ldots, Z$ is the index for the paths. Given a DN, a possible way to define the set of the available paths is to enumerate them starting from the permutations of all the DN entities and discarding those which are infeasible e.g. a combination of shipping mode and logistic node do not match with the available facilities.

The feasibility model formulation, making the DN consistent, is in the following. The operator $a \rhd z$ is used to indicate if the entity *a* belongs to the path *z*.

$$\sum_{z:r \rhd z} w_{zc} = dem_{rc} \quad \forall r, c \tag{5.8}$$

$$\sum_{z:p \rhd z} w_{zc} \leq pcp_{pc} \quad \forall p, c \tag{5.9}$$

$$\sum_{z:e \rhd z} w_{zc} \leq hcc_{ec} \quad \forall e, c \tag{5.10}$$

$$\sum_{z:h \rhd z} w_{zc} \leq hcr_{hc} \quad \forall h, c \tag{5.11}$$

$$w_{zc} \geq 0 \quad \forall z, c \tag{5.12}$$

Equation (5.8) fully satisfies the demand, while the node capacity constraints are in (5.9)-(5.11). Finally, the variables are defined in (5.12).

The feasibility model includes $C \cdot (R + P + E + H)$ constraints (excluding the variable consistence definition), while the decisional variables are $C \cdot Z$.

Similarities between the two feasibility model formulations are evident. In the latter formulation the constraints about flow balances at the nodes (see (5.6)-(5.7)) are unnecessary and already integrated within the path concept.

5.2.3 Tri-objective function formulation

The proposed multi-objective model is based on three functions to minimize. The operating cost function looks for the most effective DN configuration, leading to the lowest global cost of the network. The carbon footprint function aims at minimizing the CO_2 equivalent emissions from the shipments and inbound activities. Finally, the delivery time function forces the DN to be fast with short transit times. The analytic formulation for such objective functions is provided in the following sub-sections.

5.2.3.1 Operating cost objective function

The following drivers of cost are introduced.

hoc_{ec}	inbound handling cost of central distributor *e* for product *c* [€/unit];
hor_{hc}	inbound handling cost of regional distributor *h* for product *c* [€/unit];
pop_{pc}	inbound production cost of producer *p* for product *c* [€/unit];
so_{pecu}	shipping cost from producer *p* to central distributor *e* for product *c* and mode *u* [€/unit];
so_{phcu}	shipping cost from producer *p* to regional distributor *h* for product *c* and mode *u* [€/unit];
so_{prcu}	shipping cost from producer *p* to retailer/end-user *r* for product *c* and mode *u* [€/unit];
so_{ehcu}	shipping cost from central distributor *e* to regional distributor *h* for product *c* and mode *u* [€/unit];
so_{ercu}	shipping cost from central distributor *e* to retailer/end-user *r* for product *c* and mode *u* [€/unit];
so_{hrcu}	shipping cost from regional distributor *h* to retailer/end-user *r* for product *c* and mode *u* [€/unit];
s	discount function for transport economy of scale enabled by the DCs.

According to the previous formulation #1 of the feasibility model the operating cost objective function is expressed as:

$$OC^{I} = \sum_{p=1}^{P}\sum_{c=1}^{C} pop_{pc}\cdot\left(\sum_{e=1}^{E}\sum_{u=1}^{U} x_{pecu} + \sum_{h=1}^{H}\sum_{u=1}^{U} x_{phcu} + \sum_{r=1}^{R}\sum_{u=1}^{U} x_{prcu}\right) + \tag{5.13}$$

$$\sum_{e=1}^{E}\sum_{c=1}^{C} hoc_{ec}\cdot\left(\sum_{h=1}^{H}\sum_{u=1}^{U} x_{ehcu} + \sum_{r=1}^{R}\sum_{u=1}^{U} x_{ercu}\right) + \tag{5.14}$$

$$\sum_{h=1}^{H}\sum_{c=1}^{C} hor_{hc}\cdot\sum_{r=1}^{R}\sum_{u=1}^{U} x_{hrcu} + \tag{5.15}$$

$$\sum_{c=1}^{C}\sum_{u=1}^{U}\sum_{p=1}^{P}\left(\sum_{e=1}^{E} so_{pecu}\cdot x_{pecu} + \sum_{h=1}^{H} so_{phcu}\cdot x_{phcu} + \sum_{r=1}^{R} so_{prcu}\cdot x_{prcu}\right) + \tag{5.16}$$

$$\sum_{c=1}^{C}\sum_{u=1}^{U}\sum_{e=1}^{E}\left(\sum_{h=1}^{H} so_{ehcu}\cdot x_{ehcu} + \sum_{r=1}^{R} so_{ercu}\cdot x_{ercu}\right) + \tag{5.17}$$

$$\sum_{c=1}^{C}\sum_{u=1}^{U}\sum_{h=1}^{H}\sum_{r=1}^{R} so_{hrcu}\cdot x_{hrcu} \tag{5.18}$$

The inbound production cost is in (5.13) for the producers, while the handling one is in (5.14) for the central distributors and in (5.15) for the regional distributors. For each entity the correspondent processed units are considered. Finally, the shipment cost for the stages starting from a producer is in (5.16), for the stages starting from a central distributor is in (5.17) and for the stages starting from a regional distributor is in (5.18).

Considering the previous formulation #2 of the feasibility model the variable unitary operating cost associated to each path and product, vo_{zc}, is the following, in [€/unit]:

$$vo_{zc} = \sum\nolimits_{p:p\rhd z} pop_{pc} + \sum\nolimits_{e:e\rhd z} hoc_{ec} + \sum_{h:h\rhd z} hor_{hc} + \tag{5.19}$$

$$\sum\nolimits_{p:p\rhd z}\sum\nolimits_{e:e\rhd z}\sum\nolimits_{u:u\rhd z^{pe}} so_{pecu} + \sum\nolimits_{p:p\rhd z}\sum\nolimits_{h:h\rhd z}\sum\nolimits_{u:u\rhd z^{ph}} so_{phcu} + \sum\nolimits_{p:p\rhd z}\sum\nolimits_{r:r\rhd z}\sum\nolimits_{u:u\rhd z^{pr}} so_{prcu} \tag{5.20}$$

$$+\sum\nolimits_{e:e\rhd z}\sum\nolimits_{h:h\rhd z}\sum\nolimits_{u:u\rhd z^{eh}} (1-s)\cdot so_{ehcu} + \sum\nolimits_{e:e\rhd z}\sum\nolimits_{r:r\rhd z}\sum\nolimits_{u:u\rhd z^{er}} (1-s)\cdot so_{ercu} + \tag{5.21}$$

$$\sum\nolimits_{h:h\rhd z}\sum\nolimits_{r:r\rhd z}\sum\nolimits_{u:u\rhd z^{hr}} (1-s)\cdot so_{hrcu} \tag{5.22}$$

where the notation z^{ab} indicates the part of the path *z* from node *a* to node *b*.

In (5.19) the production and handling costs for the nodes visited by the path *z* are included, while (5.20)-(5.22) consider the shipping cost for the visited stages. In the case a stage is skipped the correspondent terms are null.

The operating cost objective function becomes the following:

$$OC^{II} = \sum\nolimits_{z=1}^{Z}\sum\nolimits_{c=1}^{C} vo_{zc}\cdot w_{zc} \tag{5.23}$$

The variable cost is grouped by path and product in (5.23).

5.2.3.2 Carbon footprint objective function

The carbon footprint objective function formulation follows the structure of the operating cost function. The sole differences are the inclusion of the emissions instead of the costs. The unitary emissions are the following.

e_{ec}	handling emissions of central distributor *e* for product *c* [kg CO2/unit];
e_{hc}	handling emissions of regional distributor *h* for product *c* [kg CO2/unit];
e_{pc}	production emissions of producer *p* for product *c* [kg CO2/unit];
e_{pecu}	emissions from producer *p* to central distributor *e* for product *c* and mode *u* [kg CO2/unit];
e_{phcu}	emissions from producer *p* to regional distributor *h* for product *c* and mode *u* [kg CO2/unit];

e_{prcu}	emissions from producer *p* to retailer/end-user *r* for product *c* and mode *u* [CO_2/unit];
e_{ehcu}	emissions from central distributor *e* to regional distributor *h* for product *c* and mode *u* [kg CO_2/unit];
e_{ercu}	emissions from central distributor *e* to retailer/end-user *r* for product *c* and mode *u* [kg CO_2/unit];
e_{hrcu}	emissions from regional distributor *h* to retailer/end-user *r* for product *c* and mode *u* [kg CO_2/unit].

According to the previous formulation #1 of the feasibility model the carbon footprint objective function is expressed as:

$$CF^{I} = \sum_{p=1}^{P} \sum_{c=1}^{C} e_{pc} \cdot \left(\sum_{e=1}^{E} \sum_{u=1}^{U} x_{pecu} + \sum_{h=1}^{H} \sum_{u=1}^{U} x_{phcu} + \sum_{r=1}^{R} \sum_{u=1}^{U} x_{prcu} \right) + \tag{5.24}$$

$$\sum_{e=1}^{E} \sum_{c=1}^{C} e_{ec} \cdot \left(\sum_{h=1}^{H} \sum_{u=1}^{U} x_{ehcu} + \sum_{r=1}^{R} \sum_{u=1}^{U} x_{ercu} \right) + \tag{5.25}$$

$$\sum_{h=1}^{H} \sum_{c=1}^{C} e_{hc} \cdot \sum_{r=1}^{R} \sum_{u=1}^{U} x_{hrcu} + \tag{5.26}$$

$$\sum_{c=1}^{C} \sum_{u=1}^{U} \sum_{p=1}^{P} \left(\sum_{e=1}^{E} e_{pecu} \cdot x_{pecu} + \sum_{h=1}^{H} e_{phcu} \cdot x_{phcu} + \sum_{r=1}^{R} e_{prcu} \cdot x_{prcu} \right) + \tag{5.27}$$

$$\sum_{c=1}^{C} \sum_{u=1}^{U} \sum_{e=1}^{E} \left(\sum_{h=1}^{H} e_{ehcu} \cdot x_{ehcu} + \sum_{r=1}^{R} e_{ercu} \cdot x_{ercu} \right) + \tag{5.28}$$

$$\sum_{c=1}^{C} \sum_{u=1}^{U} \sum_{h=1}^{H} \sum_{r=1}^{R} e_{hrcu} \cdot x_{hrcu} \tag{5.29}$$

The emissions at the three levels of the DN are in (5.24)-(5.26), while the emissions due to shipments through the stages are in (5.27)-(5.29).

Considering the previous formulation #2 of the feasibility model the unitary emissions associated to each path and product, e_{zc}, are the following, in [kg CO_2/unit]:

$$e_{zc} = \sum_{p:p \rhd z} e_{pc} + \sum_{e:e \rhd z} e_{ec} + \sum_{h:h \rhd z} e_{hc} + \tag{5.30}$$

$$\sum_{p:p \rhd z} \sum_{e:e \rhd z} \sum_{u:u \rhd z^{pe}} e_{pecu} + \sum_{p:p \rhd z} \sum_{h:h \rhd z} \sum_{u:u \rhd z^{ph}} e_{phcu} + \sum_{p:p \rhd z} \sum_{r:r \rhd z} \sum_{u:u \rhd z^{pr}} e_{prcu} + \tag{5.31}$$

$$\sum_{e:e \rhd z} \sum_{h:h \rhd z} \sum_{u:u \rhd z^{eh}} (1-s) \cdot e_{ehcu} + \sum_{e:e \rhd z} \sum_{r:r \rhd z} \sum_{u:u \rhd z^{er}} (1-s) \cdot e_{ercu} + \tag{5.32}$$

$$\sum_{h:h \rhd z} \sum_{r:r \rhd z} \sum_{u:u \rhd z^{hr}} (1-s) \cdot e_{hrcu} \tag{5.33}$$

The unitary emissions for the levels visited by path *z* for product *c* are in (5.30). In (5.31)-(5.33) the unitary emissions for the visited stages, path and product are introduced.

The carbon footprint objective function becomes the following:

$$CF^{II} = \sum_{z=1}^{Z} \sum_{c=1}^{C} e_{zc} \cdot w_{zc} \tag{5.34}$$

5.2.3.3 Delivery time objective function

The delivery time objective function aims to reduce the supply time lapse. The following delivery time, experienced through the DN, are introduced:

t_{ec}	storage fix time of central distributor *e* for product *c* [h];
t_{hc}	storage fix time of regional distributor *h* for product *c* [h];
t_{pecu}	shipping time from producer *p* to central distributor *e* for product *c* and mode u [h];
t_{phcu}	shipping time from producer *p* to regional distributor *h* for product *c* and mode u [h];
t_{prcu}	shipping time from producer *p* to retailer/end-user *r* for product *c* and mode u [h];
t_{ehcu}	shipping time from central distributor *e* to regional distributor *h* for product *c* and mode u [h];
t_{ercu}	shipping time from central distributor *e* to retailer/end-user *r* for product *c* and mode u [h];
t_{hrcu}	shipping time from regional distributor *h* to retailer/end-user *r* for product *c* and mode u [h].

According to the previous formulation #1 of the feasibility model the delivery time objective function is expressed as:

$$DT^{I} = \sum_{e=1}^{E} \sum_{c=1}^{C} t_{ec} \cdot \left(\sum_{h=1}^{H} \sum_{u=1}^{U} x_{ehcu} + \sum_{r=1}^{R} \sum_{u=1}^{U} x_{ercu} \right) + \tag{5.35}$$

$$\sum_{h=1}^{H} \sum_{c=1}^{C} t_{hc} \cdot \sum_{r=1}^{R} \sum_{u=1}^{U} x_{hrcu} + \tag{5.36}$$

$$\sum_{c=1}^{C} \sum_{u=1}^{U} \sum_{p=1}^{P} \left(\sum_{e=1}^{E} t_{pecu} \cdot x_{pecu} + \sum_{h=1}^{H} t_{phcu} \cdot x_{phcu} + \sum_{r=1}^{R} t_{prcu} \cdot x_{prcu} \right) + \tag{5.37}$$

$$\sum_{c=1}^{C} \sum_{u=1}^{U} \sum_{e=1}^{E} \left(\sum_{h=1}^{H} t_{ehcu} \cdot x_{ehcu} + \sum_{r=1}^{R} t_{ercu} \cdot x_{ercu} \right) + \tag{5.38}$$

$$\sum_{c=1}^{C} \sum_{u=1}^{U} \sum_{h=1}^{H} \sum_{r=1}^{R} t_{hrcu} \cdot x_{hrcu} \tag{5.39}$$

DT is expressed in [h·unit] and it is the weighed sum of the storage and shipping times for all levels and stages of the DN. The storage times are in (5.35)-(5.36), while the shipping time are in (5.37)-(5.39). The weights are the amount of product units flowing through the considered level and stage. Low storage time nodes and short connections are, consequently, preferred.

Considering the previous formulation #2 of the feasibility model the delivery time for each path and product, t_{zc}, is the following, in [h]:

$$t_{zc} = \sum\nolimits_{e:e\rhd z} t_{ec} + \sum_{h:h\rhd z} t_{hc} + \tag{5.40}$$

$$\sum\nolimits_{p:p\rhd z}\sum\nolimits_{e:e\rhd z}\sum\nolimits_{u:u\rhd z^{pe}} t_{pecu} + \sum\nolimits_{p:p\rhd z}\sum\nolimits_{h:h\rhd z}\sum\nolimits_{u:u\rhd z^{ph}} t_{phcu} + \sum\nolimits_{p:p\rhd z}\sum\nolimits_{r:r\rhd z}\sum\nolimits_{u:u\rhd z^{pr}} t_{prcu} + \tag{5.41}$$

$$\sum\nolimits_{e:e\rhd z}\sum\nolimits_{h:h\rhd z}\sum\nolimits_{u:u\rhd z^{eh}} t_{ehcu} + \sum\nolimits_{e:e\rhd z}\sum\nolimits_{r:r\rhd z}\sum\nolimits_{u:u\rhd z^{er}} t_{ercu} + \tag{5.42}$$

$$\sum\nolimits_{h:h\rhd z}\sum\nolimits_{r:r\rhd z}\sum\nolimits_{u:u\rhd z^{hr}} t_{hrcu} \tag{5.43}$$

The storage fix time for the visited nodes is in (5.40) and the shipping time for the stages is in (5.41)-(5.43).
The delivery time objective function becomes the following:

$$DT^{II} = \sum\nolimits_{z=1}^{Z}\sum\nolimits_{c=1}^{C} t_{zc} \cdot w_{zc} \tag{5.44}$$

Similarities between the carbon footprint and the delivery time analytic formulations are evident.

As already mentioned, the shipping cost, vo_{zc}, the delivery time, t_{zc}, and the emissions, e_{zc}, are evaluated for each path, *z*, and ton of delivered produce, c. To estimate these values the parameters so_{abcu}, t_{pecu}, e_{pecu} have to be determined. These parameters respectively represent the shipping cost, time and emissions from a certain DN node *a* to another node *b* for product *c* and transport mode *u.* The following Equations 5.45-5.47 estimate these values as functioned of d_{ab}^{u}, the travelled distance among the node couple using mode *u.* Their analytic formulation is proposed in Table 5.4.

$$so_{abcu} = \alpha^{u}(d_{ab}^{u}) \tag{5.45}$$

$$t_{abcu} = \beta^{u}(d_{ab}^{u}) \tag{5.46}$$

$$e_{abcu} = \gamma^{u}(d_{ab}^{u}), \tag{5.47}$$

Given the model solution, the *ex-post* calculation of the average operating cost, carbon footprint and delivery time per unit of product is possible, for the two model formulations, as follows:

$$DEN = \begin{cases} 2\left(\sum\nolimits_{c=1}^{C}\sum\nolimits_{u=1}^{U}\left(\sum\nolimits_{p=1}^{P}\left(\sum\nolimits_{e=1}^{E} x_{pecu} + \sum\nolimits_{h=1}^{H} x_{phcu} + \sum\nolimits_{r=1}^{R} x_{prcu}\right)\right)\right) + & \text{(5.48a)} \\ 2\left(\sum\nolimits_{c=1}^{C}\sum\nolimits_{u=1}^{U}\left(\sum\nolimits_{p=1}^{P}\sum\nolimits_{e=1}^{E}\left(\sum\nolimits_{h=1}^{H} x_{ehcu} + \sum\nolimits_{r=1}^{R} x_{ercu}\right) + \sum\nolimits_{h=1}^{H}\sum_{r=1}^{R} x_{hrcu}\right)\right) & \text{(5.48b)} \end{cases}$$

$$AOC^{I} = \frac{OC^{I}}{DEN} \tag{5.49}$$

$$AOC^{II} = \frac{OC^{II}}{\sum_{z=1}^{Z}\sum_{c=1}^{C} w_{zc}} = \frac{OC^{II}}{\sum_{r=1}^{R}\sum_{c=1}^{C} dem_{rc}} \tag{5.50}$$

$$ACF^{I} = \frac{CF^{I}}{DEN} \tag{5.51}$$

$$ACF^{II} = \frac{CF^{II}}{\sum_{z=1}^{Z}\sum_{c=1}^{C} w_{zc}} = \frac{CF^{II}}{\sum_{r=1}^{R}\sum_{c=1}^{C} dem_{rc}} \tag{5.52}$$

$$ADT^{I} = \frac{DT^{I}}{DEN} \tag{5.53}$$

$$ADT^{II} = \frac{DT^{II}}{\sum_{z=1}^{Z}\sum_{c=1}^{C} w_{zc}} = \frac{DT^{II}}{\sum_{r=1}^{R}\sum_{c=1}^{C} dem_{rc}} \tag{5.54}$$

From the delivery time perspective, the advantages of adopting the formulation #2 of the optimization model is double.

- ✓ The model formulation allows to track the product shipments. Each unit of product is associated to exactly one path so that the whole chain is monitored and the delivery time is exactly known, i.e. the value of $\boldsymbol{t_{zc}}$ for the correspondent path. As discussed above, in formulation #1 the presence of the distributors, acting as decoupling entities, causes the loss of the product traceability for the indirect channels so that only the average delivery time is computable;
- ✓ the model formulation is more compact than in formulation #1.

The overall tri-objective model formulation includes the three objective functions, i.e. $\{OC^{I}, CF^{I}, DT^{I}\}$ and $\{OC^{II}, CF^{II}, DT^{II}\}$, respectively, and the correspondent feasibility model. Such a model is behind the DSS described in the next paragraph supporting the decision makers in the design process, from the data loading, through the Pareto frontier generation, to the final DN configuration choice.

5.2.4 Decision support system for the distribution network design

To support the decision makers in the DN design process a DSS is developed and proposed in this sub-section. Aim of the DSS is to assist the logistic planner through all the DN design phases, from the input database consolidation to the DN final configuration definition. Figure 5.2 represents the DSS structure.

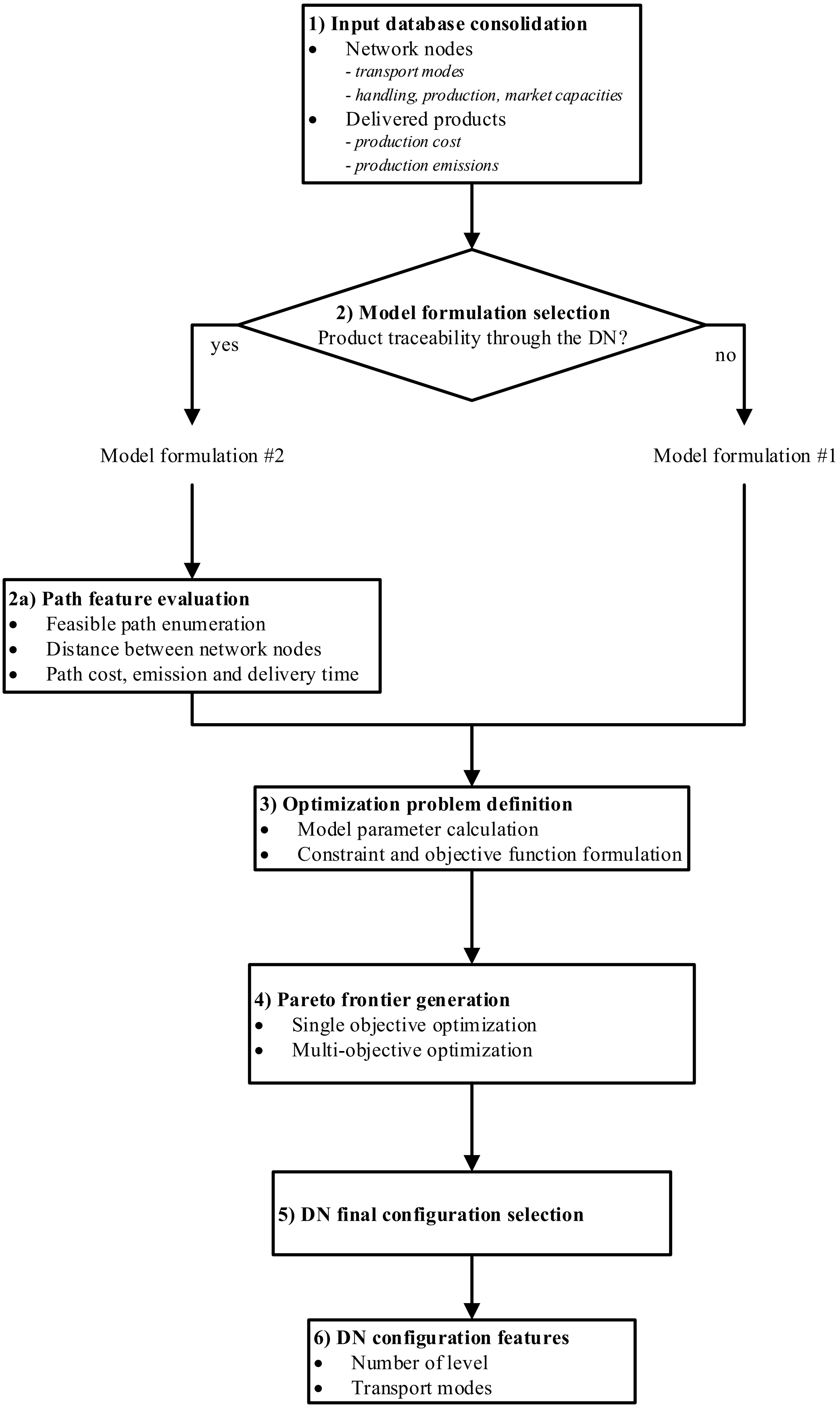
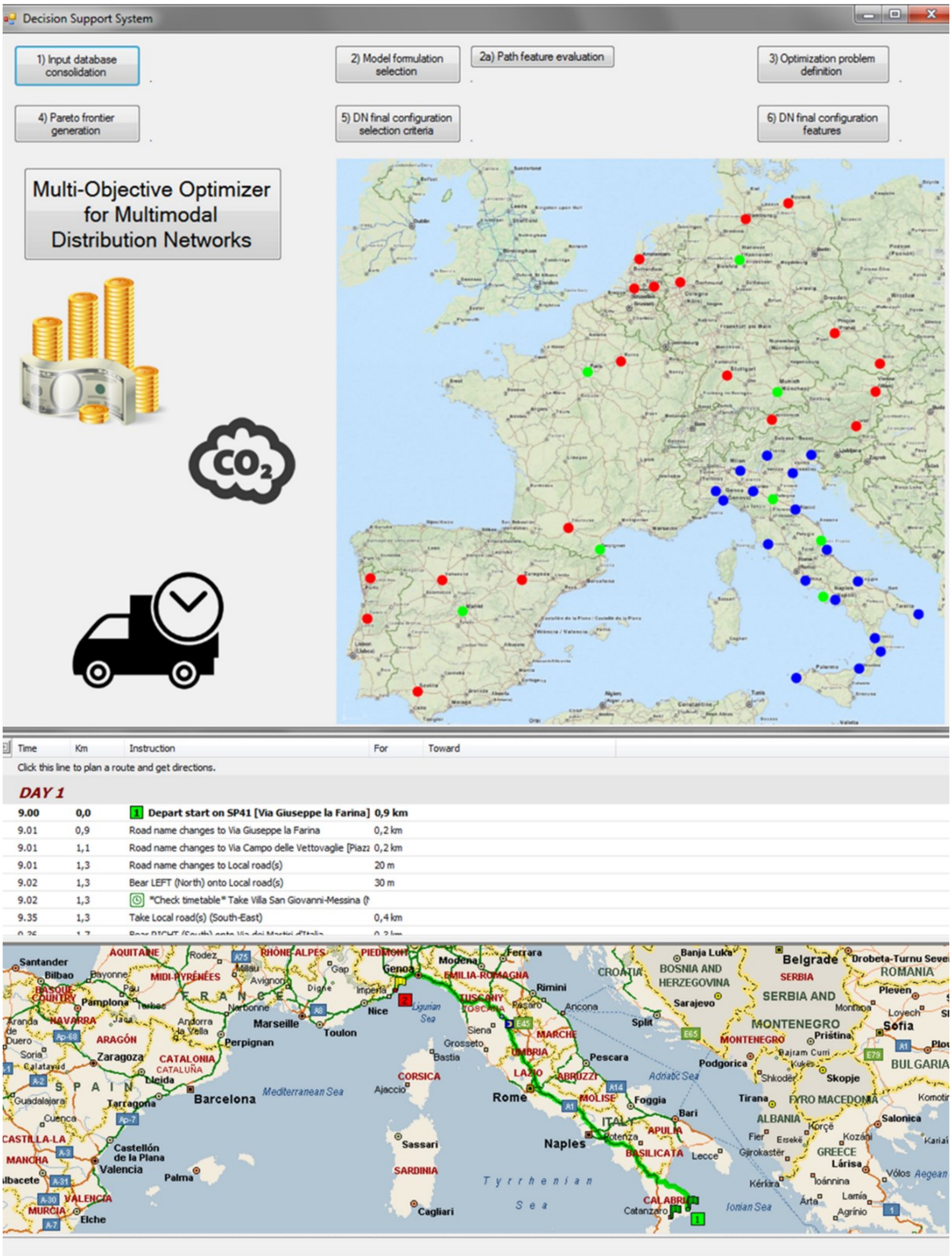


Figure 5.2. DSS structure for DN design

The first DSS phase deals with the input database consolidation. The information required concerns the network nodes and the delivered products. The formers are distinguished by their geographical location, by the transport modes and available logistic facilities and by the handling-production capacity or market demand. The latter relevant features are the production cost and emissions. The second DSS phase is the model formulation selection. If product traceability is a required feature of the considered DN, the decision maker has to adopt the model formulation #2. On the contrary, the model formulation #1 is usable. Model formulation #2 requires an additional DSS phase, i.e. the path feature evaluation. First of all, the feasible paths are enumerated. As introduced, a feasible path is distinguished by a combination of transport modes and logistic facilities available at the network nodes that belong to the path. For each couple of nodes a, b the travelled distance d_{ab}^{u} is evaluated. Finally, the path cost (vo_{zc}), emissions (e_{zc}) and delivery time (t_{zc}) are calculated. The DSS integrates transport cost ($\alpha^{uc}(d_{ab}^{u})$), emission ($\gamma^{uc}(d_{ab}^{u}$) and time ($\beta^{uc}(d_{ab}^{u})$) functions to support the users in the case of lack of field data. Figure 5.3 represents the DSS structure and the travelled distance evaluation dashboard.



Click this line to plan a route and get directions.

DAY 1

Time	Km	Instruction	For	Toward
9.00	**0,0**	🟩 **Depart start on SP41 [Via Giuseppe la Farina]**	**0,9 km**	
9.01	0,9	Road name changes to Via Giuseppe la Farina	0,2 km	
9.01	1,1	Road name changes to Via Campo delle Vettovaglie [Piazz	0,2 km	
9.01	1,3	Road name changes to Local road(s)	20 m	
9.02	1,3	Bear LEFT (North) onto Local road(s)	30 m	
9.02	1,3	*Check timetable* Take Villa San Giovanni-Messina (		
9.35	1,3	Take Local road(s) (South-East)	0,4 km	

Figure 5.3. DSS structure and the travelled distance evaluation dashboard.

Furthermore, the third DSS phase purpose is the DN optimization problem definition. The input data, collected in the first phase, enable to calculate the model parameters. Each constraint and the objective functions are formulated according to these values. The DSS phases from 1 to 3 are necessary to point out the DN optimal configurations, representing the aforementioned Pareto points. Each point is generated by the DSS phase 4. Both the anchor points and the Pareto frontier come from the normalized normal constraint method presented in Paragraph 4.4. Given the Pareto frontier, the DN final configuration has to be selected. The selection criterion is subjective. The DSS fifth phase enables the decision maker to select the preferred Pareto point. Finally, DSS last phase analyzes the DN final configuration in terms of number of DN level and transport modes providing aggregate performance indicators.

The DSS phases are coded in a customized tool developed using MS Visual Studio^{TM} integrated development environment. The tool provides an user-friendly interface (Figure 5) and it is connected to several auxiliary softwares. The input database is uploaded using MS Access^{TM} and this application collects the DN final configuration features. The path travelled distance as well the geographical representation of the DN final configuration are obtained using MS MapPoint^{TM}. The normalized normal constraint method is implemented using AMPL^{TM} modeling language, whereas the Pareto points are determined by GUROBI^{TM} optimization solver.

The next Paragraph applies the proposed multi-objective model and DSS to design a case study DN for the fresh food industry. Particularly, to guarantee product high quality standards as well to abide the regulations actually in force, traceability is a required feature. Thus, the adopted model formulation is the formulation #2.

5.3 Case study

A case study about fresh food DN design is the focus of the present Paragraph. The first sub-paragraph investigates perishability, known as the product most relevant feature. An approach is proposed to quantify it and the MO model is updated to include such a characteristic (Bortolini et al., 2016). The second sub-paragraph presents the case study input data, whereas the results, obtained adopting the optimization model and the DSS, are, finally, proposed.

5.3.1 Fresh food distribution network

The fresh food DNs differ from traditional DNs because of the peculiarity of the food produces toward manufacture goods (Gamberi et al., 2013). The fresh food quality is not constant over the produce lifetime. It rapidly decreases reaching a value of zero after the so-called shelf life (Osvald & Stirn, 2008). Several models express the correlation between quality and time. According to Osvald & Stirn (2008), a simple and effective approach adopts, for each produce, c, and path, z, a piecewise linear function between quality and time, called quality loss function, ξ_{zc}. Such a function estimates the market purchase probability and it is defined as follows (5.55):

$$\xi_{zc}(t_{zc}) = \min\left\{\frac{1-\frac{t_{zc}}{sl_c}}{(1-QRP_c)}, 1\right\} \quad \forall\, z, c \tag{5.55}$$

ξ_{zc} is function of the transport time, t_{zc}, and two other parameters: the produce shelf life, sl_c, and the Quality Reduction Point, QRP_c, both depending on the produce type, c. QRP_c represents the threshold of t_{zc} and sl_c ratio without observing any produce quality decrease. If t_{zc} makes $\frac{t_{zc}}{sl_c} < QRP_c$ the delivered produce quality is maximum and all the shipped produces are accepted by the retailer and sold to the market. Beyond the QRP_c value, the produce quality linearly decreases with t_{zc} increase (see Figure 5.4) and the retailers waste some produces (Widodo, Nagasawa, Morizawa, & Ota, 2006).

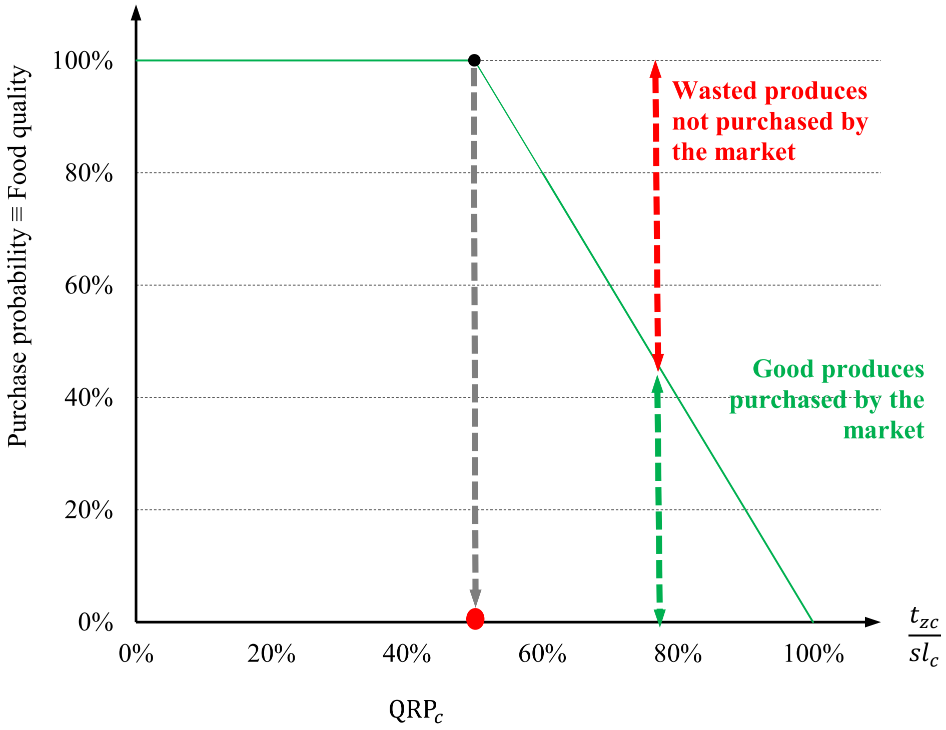


Figure 5.4: Purchase probability function ξ_{zc}.

Considering the quality loss function, the MO model upgrades are in the following. The equation numbers refer to the previous correspondent equation formulations.

$$\sum_{z:r\rhd z} \xi_{zc} \cdot w_{zc} = dem_{rc} \quad \forall r, c \tag{5.9'}$$

$$vo_{zc} = \sum_{p:p\rhd z} (1-\xi_{zc}) \cdot pop_{pc} + \sum_{e:e\rhd z} hoc_{ec} + \sum_{h:h\rhd z} hor_{hc} + \tag{5.22'}$$

$$e_{zc} = \sum_{p:p\rhd z} (1-\xi_{zc}) \cdot e_{pc} + \sum_{e:e\rhd z} e_{ec} + \sum_{h:h\rhd z} e_{hc} + \tag{5.34'}$$

The full market demand supply constraint, considering the produce quality decrease over the delivery time, is in (5.9’). Only ξ_{zc} of the delivered produces are purchased by the retailers. Thus, $(1-\xi_{zc})$ of these amounts increase the path operating cost (5.22’) and the carbon footprint (5.34’) with no contribution to the market demand satisfaction. Consequently, the production cost, pop_{pc}, and emissions, e_{pc}, of the produces not affected by the quality reduction are not included in the objective functions, because of they are constant and do not depend on the decisional variables.

5.3.2 Input data

The proposed case study focuses on the DN to distribute a variety of six fruit and vegetable produces from a set of Italian producers to a set of European retailers. Both short shelf life produces, i.e. Brussels sprouts and tomatoes, and long shelf life produces, i.e. apples, oranges, pears and potatoes, are included in the mix. The following Figure 5.5 shows the network geography. 18 producers (blue squares), i.e. production areas, 18 retailers (red circles), i.e. consumption areas, and 8 DCs are considered (green triangles). The producers are medium farmers joining a national consortium, while the retailers are, generally, middle-size city companies located in Austria, the Czech Republic, France, Germany, the Netherlands, Portugal and Spain. Finally, three alternative shipment modes are possible: truck, train and plane. The detail of the DN nodes and features are in Table 5.1 and 5.2.

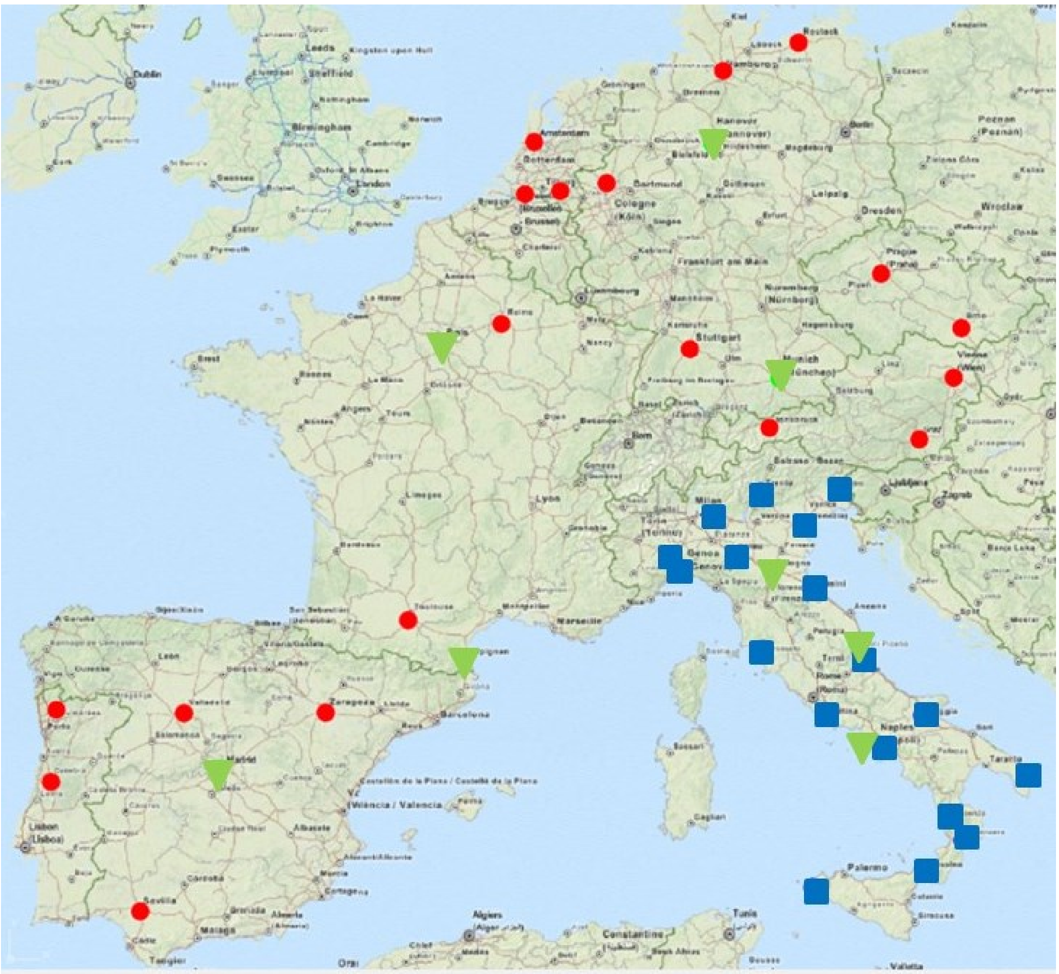


Figure 5.5. DN geographical map. Blue squares, green triangles and red circles are for producers, DCs and retailers, respectively.

Table 5.1. Producer production capacity and transport facilities

Network node	Airport	Railway station	Potatoes [ton/month]	Apples [ton/month]	Pears [ton/month]	Brussels sprouts [ton/month]	Oranges [ton/month]	Tomatoes [ton/month]
Alessandria	×	×	892	32	94	26	-	52
Brescia	×	×	95	20	-	-	-	12
Catanzaro	×	×	507	71	66	63	7350	150
Cesena	×	×	181	178	235	-	-	124
Cosenza	×	×	785	25	101	151	9761	405
Foggia	×	×	296	14	-	836	669	273
Genoa	✓	✓	434	-	-	24	-	178
Grosseto	×	×	43	15	98	-	-	15
Latina	✓	✓	102	64	32	54	635	861
Lecce	×	×	689	-	40	36	649	143
Messina	×	×	409	27	169	48	3269	124
Parma	×	×	28	-	-	-	-	-
Pescara	×	×	173	66	32	37	-	149
Salerno	×	×	1147	98	240	391	1226	1364
Trapani	×	×	122	-	-	67	1231	179
Trento	×	×	209	7212	-	-	-	-
Udine	×	×	330	282	108	-	-	-
Venice	✓	✓	52	90	469	21	-	173

Table 5.2. Retailer market demand and transport facilities.

Network node	Airport	Railway station	Potatoes [ton/month]	Apples [ton/month]	Pears [ton/month]	Brussels sprouts [ton/month]	Oranges [ton/month]	Tomatoes [ton/month]
Amsterdam	✓	✓	-	2182	-	-	6986	-
Braga	×	×	740	102	-	-	122	-
Breda	×	×	-	383	-	-	1226	-
Brno	×	×	-	134	154	190	559	326
Coimbra	×	×	412	154	-	-	112	-
Eindhoven	×	×	-	596	-	-	1909	-
Essen	×	×	-	391	190	130	313	377
Graz	×	×	-	-	-	108	127	171
Innsbruck	×	×	-	-	-	104	158	133
Prague	✓	✓	-	334	134	225	1398	815
Reims	×	×	-	-	135	-	677	-
Rostock	×	×	-	138	132	111	110	133
Seville	×	×	1319	271	-	-	-	-
Stuttgart	×	×	-	394	191	130	316	380
Toulouse	×	×	-	-	185	-	1637	-
Valladolid	×	×	591	122	-	-	-	-
Wien	✓	✓	-	-	-	152	831	468
Zaragoza	×	×	1263	260	-	-	-	-

In Table 5.1, for each of the production areas the available shipment facilities are shown (truck is available for all facilities) together with the production capacities related to the crop yield of a reference common month. An interesting further development deals with the analysis of the DN changes among time periods due to the produce seasonality effects. Similarly, table 5.2 shows the retailer available shipment facilities (truck is available for all facilities) together with the aggregate market demand for each produce. The table data refers to the same reference month.

Eight are the DCs: Bologna, Hannover, Madrid, Munich, Napoli, Paris, Perpignan, Teramo. These are for both two-stage and three-stage shipment strategies, i.e. all the DCs can be a central or regional hub. In addition, for all the DCs the three shipment modes are supposed to be available. For the sake of simplicity it is, further, supposed that all the DCs are able to handle all the quantities of produces it is convenient to be shipped through such nodes.

Concerning the produces, Table 5.3 summarizes their features, cost and emissions per ton.

Table 5.3. Produce shelf life, QRP, production cost and emissions

Produces		Potatoes	Apples	Pears	Brussels sprouts	Oranges	Tomatoes
Shelf Life [h]	sl_c	5760	2880	2880	120	1440	168
QRP [%]	QRP_c	12.5	25.0	50.0	80.0	50.0	85.7
Production cost [€/ton]	pop_{pc}	190	540	580	370	260	550
Production emissions [kg $CO_{2\ EQ.}$/ton]	e_{pc}	34.68	50.38	54.11	34.04	21.17	90.24

Particularly, the produce shelf life is from (Caccioni, 2005), the QRPs are from a customized market analysis and the production costs are from a recent agri-food market analysis (ISMEA, 2012). Finally, the production emissions are from (Pimentel, 2006). Furthermore, the production cost and emissions are considered the same for all producers.

The cost, time and emission parameters used to define the objective functions are in Table 5.4. Time and cost functions comes from a market survey and regression analysis, summarizing information obtained by the Authors analyzing the data provided by Blasioli (2011) and several international carriers, e.g. DB Schenker, Fercam, DHL, Trenitalia Cargo, Air France-KLM-Martinair Cargo, Alitalia Cargo. Transport time functions include vehicle loading and unloading times as a function of the considered transport mode. The international carriers allow to estimate the transport cost and time for several distances. The emission functions comes from the Ecoinvent database v.2.0 (Ecoinvent, 2007). These functions consider both the direct and indirect GHG emissions. The fuel consumption during the produce transportation accounts for the GHG directly emitted. On the contrary, the indirect emissions are produced by the manufacturing and the end of life treatments of the vehicles and the related infrastructures. Ecoinvent database provides, for each vehicle, the GHG emitted per transported ton and travelled km.

Table 5.4. Transport cost, time and emission functions

		Truck	Train	Airplane
Transport cost [€/ton]	$\alpha^u(d_{ab}^u)$	$0.2872 \cdot {d_{ab}^u}^{-0.183}$	$0.8705 \cdot {d_{ab}^u}^{-0.373}$	$869.32 \cdot {d_{ab}^u}^{-0.861}$
Transport time [h]	$\beta^u(d_{ab}^u)$	$0.0067 \cdot {d_{ab}^u}^{1.1465}+2.823$	$10^{-10} \cdot {d_{ab}^u}^3 - 10^{-5} \cdot {d_{ab}^u}^2$ $+0.0829 \cdot d_{ab}^u + 22.914$	$0.0023 \cdot d_{ab}^u + 19.254$
Transport emissions [kg $CO_{2\ EQ.}$/ton]	$\gamma^u(d_{ab}^u)$	$d_{ab}^u \cdot 0.484$	$d_{ab}^u \cdot 1.670$	$d_{ab}^u \cdot 0.03920$

Figure 5.6 proposes the graphical representation of the transport cost, time and emission functions highlighting trends and decoupling points among the three shipping modes. Airplane is the most expensive transport mode. Whatever the travelled distance, the cost

is greater than for truck and train. Considering these latter vehicles, truck is cheaper than train for distance shorter than 350 km and vice versa. Transport time has a similar behavior. Train is always the slowest vehicle. Due to remarkable loading and unloading times, airplane is faster than truck only for distance greater than 1000 km. Finally, for all modes, a linear function represents the relation between the produced emissions and the travelled distance.

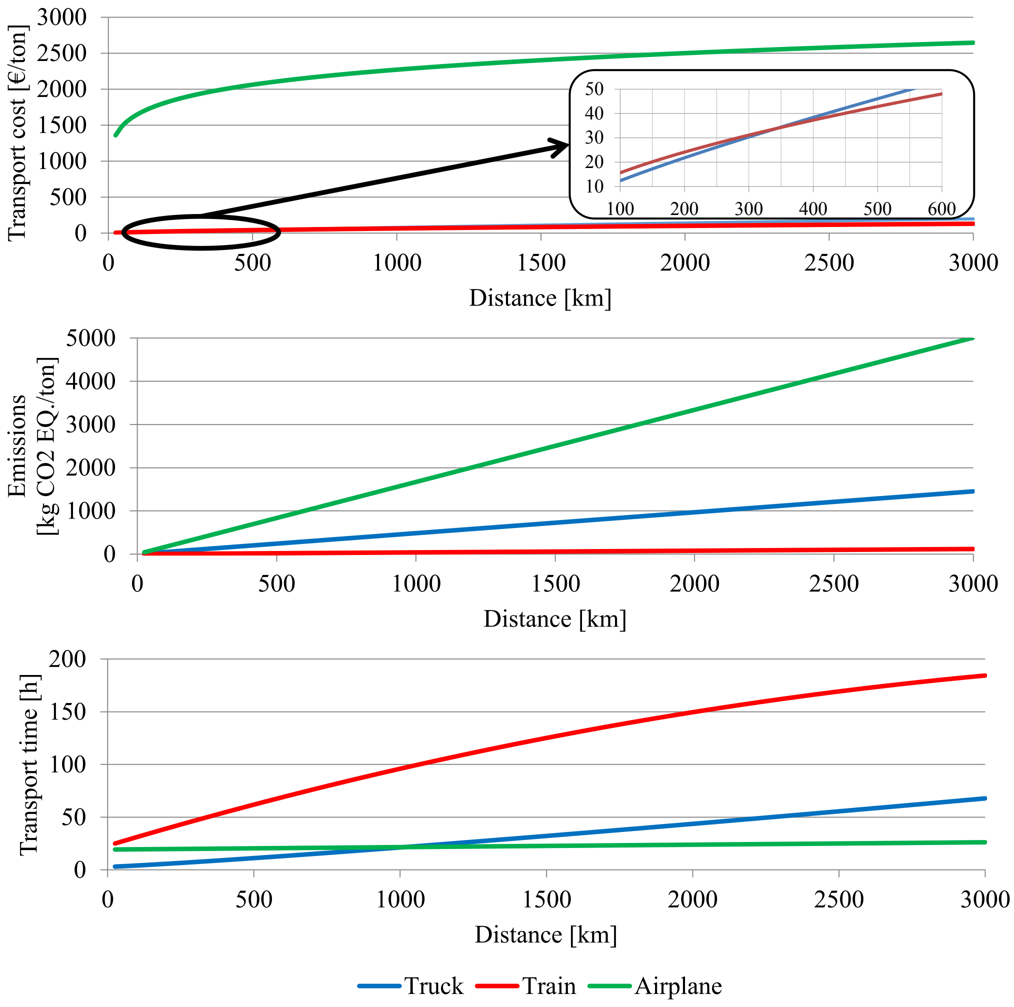


Figure 5.6. Transport cost, time and emission functions.

All the transport functions are considered equal for all produces. Finally, the inbound handling cost (hoc_{ec}, hor_{hc}), emissions (e_{ec}, e_{hc}) and the storage fix time (t_{ec}, t_{hc}) are assumed equal for all the produces and DCs. According to the data provided by several DCs, hoc_{ec}, hor_{hc}= 2.641 €/ton, e_{ec}, e_{hc}= 0.6826 kg CO$_{2\ EQ.}$/ton, t_{ec}, t_{hc}= 12 h. Furthermore, the value of 0.25 is assumed for s discount factor.

The introduced input parameters lead to, approximately, 101,700 feasible paths, 610,308 decisional variables and 610,524 constraints. The following paragraph presents and discusses the case study key results and the DN most effective configuration.

5.4 Results and discussion

Adopting the DSS proposed, the first results emerging from such analysis are the optimal network configurations, considering each objective function, separately. The optimal cost, time and carbon footprint scenarios are investigated and the correspondent results are in Tables 5.5, 5.6 and 5.7 and Figure 5.7, respectively, highlighting the objective function values and the incidence of each produce.

Table 5.5. Operating cost optimal solution.

OPERATING COST optimization						
Produce	Operating cost [€/ton]	Δ vs. Operating cost opt.	Delivery time [h]	Δ vs. Delivery time opt.	Carbon footprint [kg CO_{2EQ} /ton]	Δ vs. Carbon footprint opt.
Apples	81.0	-	73.9	235%	288.0	38%
Brussel sprouts	120.8	-	27.4	1%	687.2	8%
Oranges	106.7	-	137.9	267%	269.3	10%
Pears	71.4	-	64.5	248%	244.8	69%
Potatoes	115.8	-	132.7	213%	353.9	22%
Tomatoes	105.7	-	24.7	8%	626.2	19%
Total	*102.6*	*-*	*111.2*	*233%*	*323.7*	*18%*

Table 5.6. Delivery time optimal solution.

DELIVERY TIME optimization						
Produce	Operating cost [€/ton]	Δ vs. Operating cost opt.	Delivery time [h]	Δ vs. Delivery time opt.	Carbon footprint [kg CO_{2EQ} /ton]	Δ vs. Carbon footprint opt.
Apples	154.8	91%	22.1	-	604.7	190%
Brussel sprouts	221.7	84%	27.1	-	730.5	15%
Oranges	885.2	730%	37.5	-	1,377.1	463%
Pears	142.5	100%	18.5	-	514.2	256%
Potatoes	361.3	212%	42.4	-	1,125.2	289%
Tomatoes	763.1	622%	22.9	-	906.6	73%
Total	*620.6*	*505%*	*33.4*	*-*	*1,116.0*	*307%*

Table 5.7. Carbon footprint optimal solution.

	CARBON FOOTPRINT optimization					
Produce	Operating cost [€/ton]	Δ vs. Operating cost opt.	Delivery time [h]	Δ vs. Delivery time opt.	Carbon footprint [kg CO_{2EQ} /ton]	Δ vs. Carbon footprint opt.
Apples	92.2	14%	124.0	462%	208.2	-
Brussel sprouts	186.9	55%	47.6	76%	637.1	-
Oranges	107.7	1%	147.8	294%	244.4	-
Pears	77.8	9%	109.3	490%	144.5	-
Potatoes	124.3	7%	170.4	301%	289.6	-
Tomatoes	251.1	138%	67.7	196%	524.4	-
Total	*118.9*	*16%*	*136.1*	*308%*	*274.5*	-

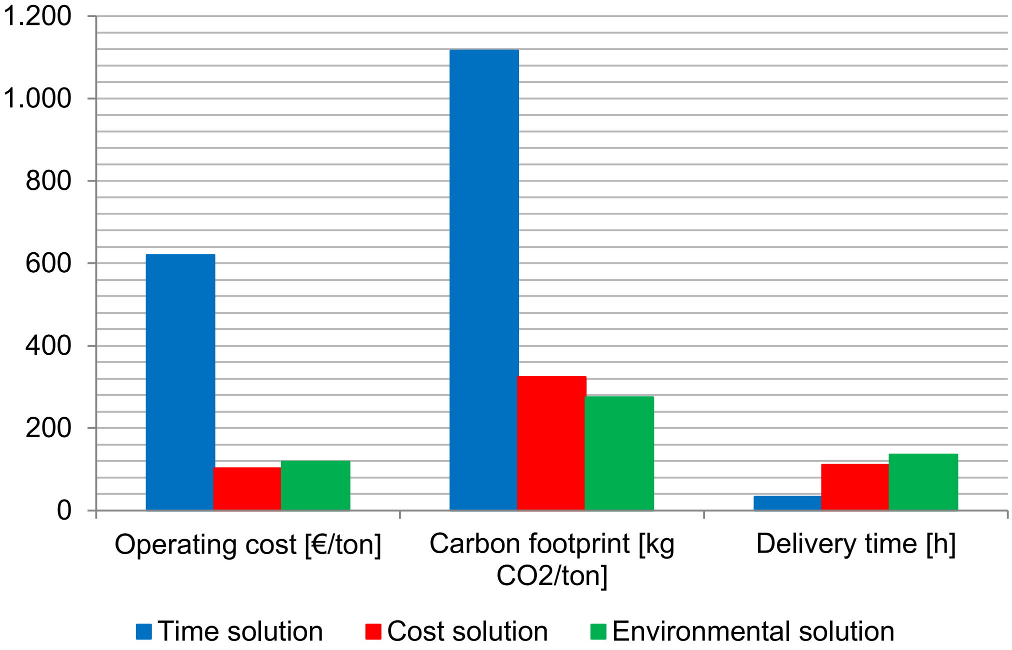


Figure 5.7. Comparison among time, cost and impact DN solutions.

Results reveal that optimizing one objective function leads to a significant worsen of the other two. As example, the operating cost optimization determines a relevant increase of both the delivery time and the carbon footprint, i.e. delivery time globally worsens of about 233%, whereas $CO_{2\ EQ.}$ total emissions increase of 18% (see Table 5.5). The same behaviour occurs considering the delivery time and the carbon footprint optimal solutions. Such outcomes are in accordance with the chosen shipment strategies, as shown in the following Figure 5.8, distinguishing between short and long shelf life produces.

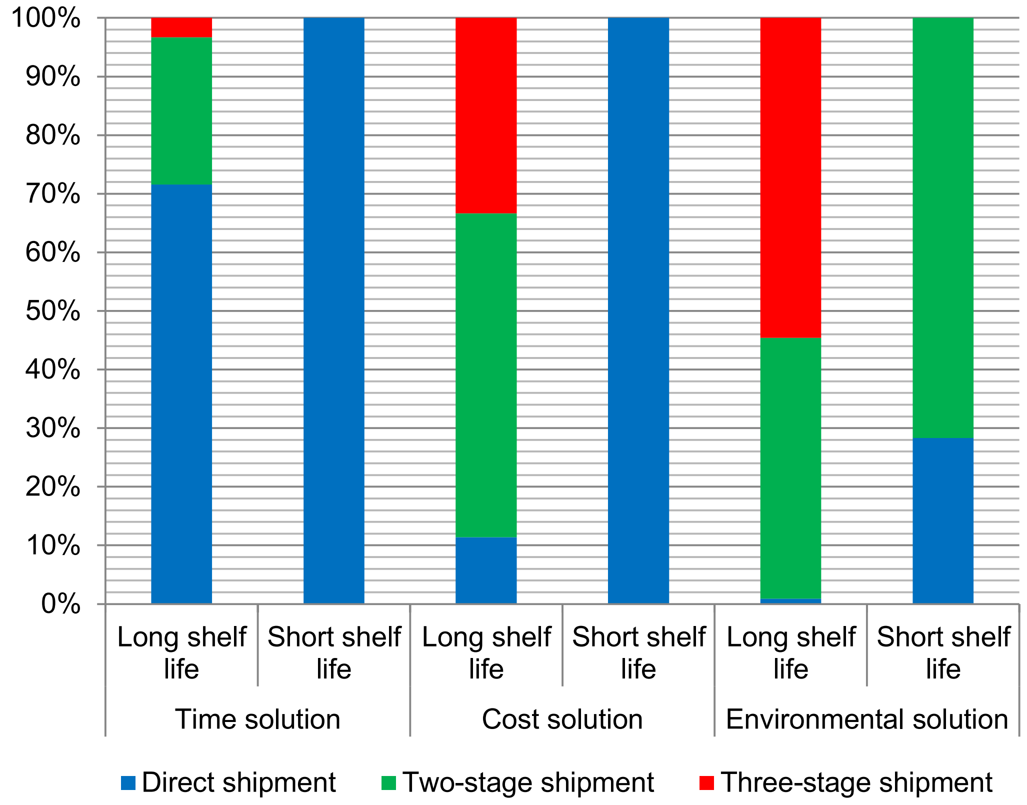


Figure 5.8. Shipment strategies for Time, Cost and Environmental solution

The *Time solution* and the *Cost solution* prefer truck direct shipments for short shelf life produces, while the two-stage and three-stage shipments are adopted for long shelf life produces, except for the *Time solution*, where approximately the 70% of the long shelf life produces is shipped through a truck direct shipment and the 27% is shipped through truck and plane, to save time.

Based on the aforementioned objective function optimal values, the Pareto frontier for the DN is determined adopting the normalized normal constraint method. Figure 5.9 depicts such a frontier within the *X*-carbon footprint, *Y*-delivery time, *Z*-operating cost Cartesian space.

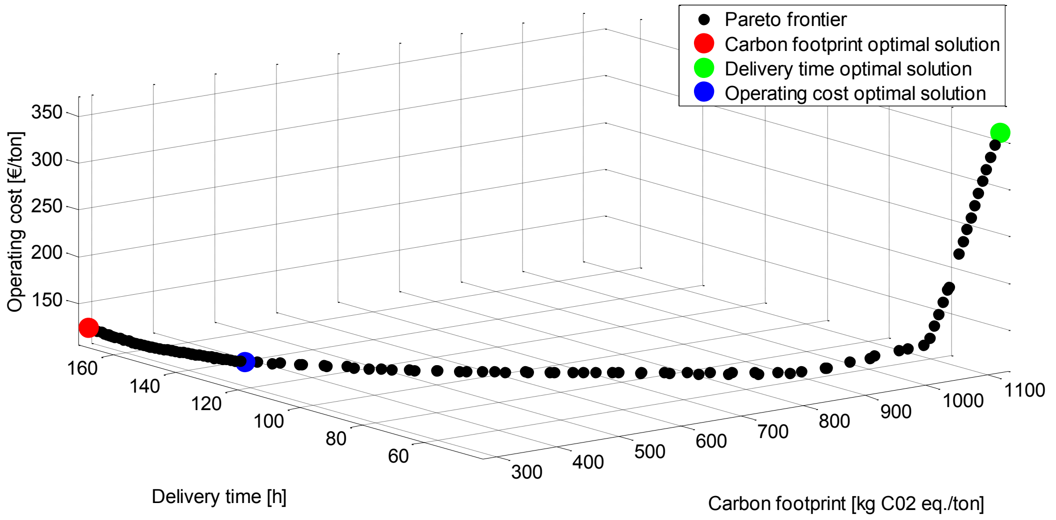


Figure 5.9. MO optimization: Pareto frontier for the case study.

The *Pareto frontier* includes all the non-dominated solutions of the MO problem. As a consequence, the final solution has to be selected within this set, using an arbitrary method. To this purpose, in order to converge to such a final solution, the empiric rule proposed in Paragraph 4.5 is adopted and exploited for the case study. The resulting equation is in the following (5.56).

$$\min_k G_k, \quad G_k = \frac{AOC^{II}{}_k}{AOC^{II*}} \cdot \frac{ACF^{II}{}_k}{ACF^{II*}} \cdot \frac{ADT^{II}{}_k}{ADT^{II*}} \tag{5.56}$$

where *k* is the index of the *k-th* solution laying on the *Pareto frontier* and $AOC^{II*}, ACF^{II*}, ADT^{II*}$ are the cost, emissions and delivery time single objective optimal solutions. The solution that solves Eq. 5.55 is the one selected for the FFDN problem. The following Table 5.8 reports it together with the detail for each produce. The cost objective function is globally similar to the single-objective optimal solution with an increase of 2.2% (from 102.6 €/ton to 104.9 €/ton). On the contrary, the delivery time increases of 208.3% compared to its minimum (from 33.4 h to 102.9 h) and the carbon footprint increments of 35.1% compared to its optimal value (from 274.5 kg $CO_{2\ EQ.}$/ton to 370.6 kg $CO_{2\ EQ.}$/ton). This trend is particularly significant for long shelf life produces, e.g. delivery time increase of 288% for oranges and 215.7% for potatoes, carbon footprint increase of 164.2% for apples and 229.8% for pears.

Table 5.8. Operating cost, delivery time and carbon footprint for MO linear programming problem chosen solution.

Produce	Operating cost [€/ton]	Δ vs. Operating cost opt.	Delivery time [h]	Δ vs. Delivery time opt.	Carbon footprint [kg CO_2 EQ./ton]	Δ vs. Carbon footprint opt.
Apples	89.5	10.5%	22.8	3.7%	549.9	164.2%
Brussels sprouts	120.8	0.0%	27.4	1.1%	687.2	7.9%
Oranges	107.2	0.5%	145.6	288.0%	245.4	0.4%
Pears	79.7	11.8%	19.3	4.5%	476.5	229.8%
Potatoes	116.9	0.9%	134.0	215.7%	344.4	18.9%
Tomatoes	105.7	0.1%	24.7	7.9%	625.8	19.3%
Total	*104.9*	*2.2%*	*102.9*	*208.3%*	*370.6*	*35.1%*

Furthermore, the chosen solution for the MO DN planning problem (Table 5.8) allows no produce waste, i.e. the shipping time is lower that QRP_c for all produces. To try to increase the solution performance from the cost and/or carbon footprint point of view, a further analysis of the same case study is developed neglecting the delivery time objective function and limiting the problem to the bi-objective cost-carbon footprint optimization. The next Figure 5.10 details the analysis results presenting the cost-carbon footprint bi-objective *Pareto frontiers* for each produce. Long and short shelf life produces have different behaviors. The former have a short and quite constant frontier that allows minimizing the carbon footprint without a significant cost increase. The latter presents a long and skewed frontier with the cost optimal point far from the carbon footprint optimum.

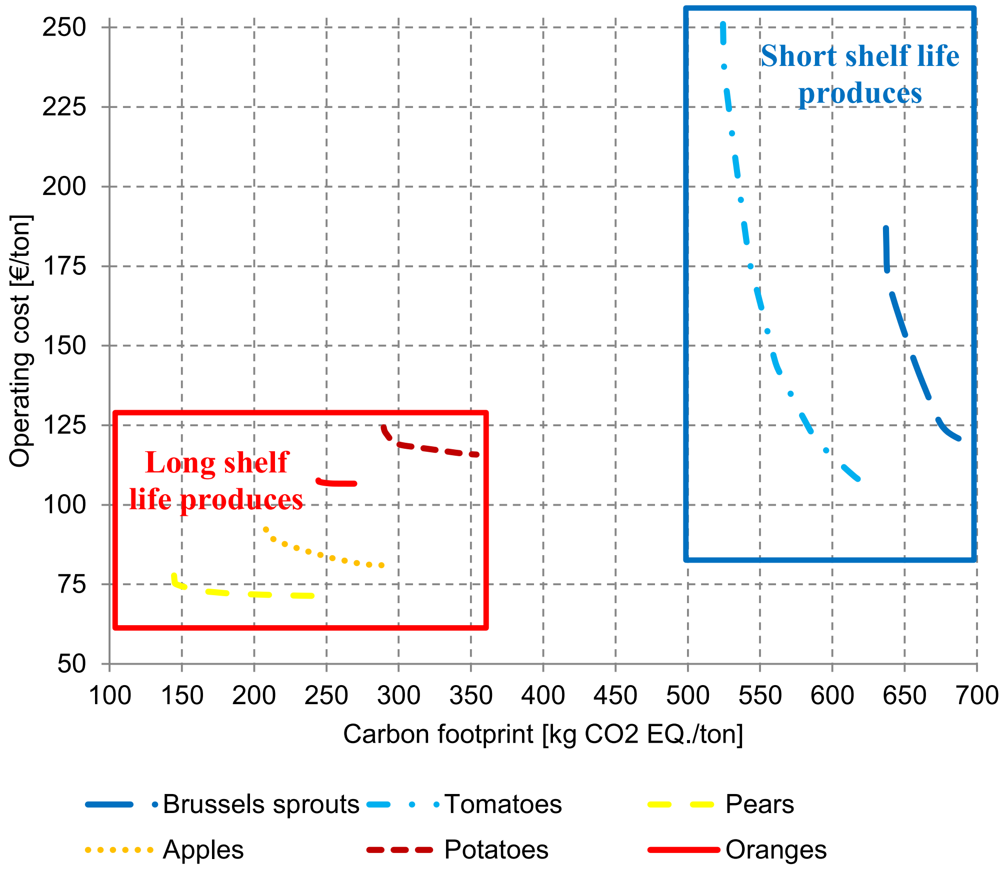


Figure 5.10: Operating cost and carbon footprint bi-objective analysis: Pareto frontiers for each considered produce.

According to the bi-objective problem limitation, the rule to choose the problem solution, presented in Eq. 5.56, changes considering the operating cost and carbon footprint objective functions, only (Eq. 5.57).

$$\min_k G'_k, \quad G'_k = \frac{AOC^{II}{}_k}{AOC^{II*}} \cdot \frac{ACF^{II}{}_k}{ACF^{II*}} \tag{5.57}$$

Table 5.9 details the chosen solution of the bi-objective analysis further including the *ex post* calculation of the delivery time.

Table 5.9. Operating cost, delivery time and carbon footprint for MO linear programming model chosen solution limited to cost-carbon footprint optimization.

Produce	Operating cost [€/ton]	Δ vs. Operating cost opt.	Delivery time [h]	Δ vs. Delivery time opt.	Carbon footprint [kg CO_{2EQ}/ton]	Δ vs. Carbon footprint opt.	% produce transported by truck & rail
Apples	90.3	11.5%	117.2	430.3%	210.3	1.0%	98%
Brussels sprouts	120.8	0.0%	27.4	1.1%	687.2	7.9%	0%
Oranges	107.4	0.7%	146.0	289.3%	244.6	0.1%	100%
Pears	75.2	5.5%	100.8	444.9%	145.2	0.5%	90%
Potatoes	120.6	4.2%	160.0	277.4%	294.1	1.6%	100%
Tomatoes	105.7	0.0%	24.7	7.9%	626.1	19.4%	0%
Total	*105.3*	*2.7%*	*126.1*	277.5%	*292.5*	*6.5%*	*87%*

Both costs and carbon footprint are, globally, similar to the corresponding single-objective solutions. Considering operating cost optimal solution, cost objective function increases from 102.6 €/ton to 105.3 €/ton (+2.7%) but carbon footprint objective function decreases from 323.7 kg $CO_{2\,EQ.}$/ton to 292.5 kg $CO_{2\,EQ.}$/ton (-9.6%). Such a value is similar to the minimum of 274.5 kg $CO_{2\,EQ.}$/ton. The delivery time worsens compared to its optimal solution (from 33.4 h to 126.1 h) but this outcome does not represent a DN weakness. The produce shelf life allows no waste even for this DN configuration. For short shelf life produces, fast and direct shipments are used, avoiding any waste. On the contrary, almost the entire quantity of long shelf life produces moves through truck&rail and two- or three-stage shipment, decreasing cost and emissions with admissible delivery times. Finally, comparing Table 5.8 to Table 5.9 the decrease of the carbon footprint (from 370.6 kg $CO_{2\,EQ.}$/ton to 292.5 kg $CO_{2\,EQ.}$/ton, -21.1%) generates a low global cost increase (from 104.9 kg $CO_{2\,EQ.}$/ton to 105.3 €/ton, +0.4%). For these reasons, the final DN planning choice is the last one, i.e. the one represented in Table 5.9.

Given the MO solution, the DSS provides the transport details. An example, for a shipment from Salerno, Italy, to Braga, Portugal, is in Table 5.10. Details of the path characteristics (nodes, arcs, transportation modes) and the three objective function values are provided. Moreover, an automatic map representation of the considered transport is given (see Figure 5.11).

Table 5.10. DSS outcomes: shipment technical description, example.

Shipment Description						
From Salerno (IT) to Braga (PRT)						
Delivered q.ty	315 ton					
Wastes	0 ton					
From	To	Transport mode	Distance [km]	Transport cost [€/ton]	Transport time [h]	Transport emissions [kg CO_2/ton]
Salerno, P	Napoli, IH	Truck	58	7,9	3,5	28
Napoli, IH	Madrid, IH	Train	1836	75,3	221,4	55
Madrid, IH	Braga, R	Truck	674	46,7	26,5	245
		Total	2568	129,9	251,5	328

Figure 5.11. DSS outcomes: automatic graphical representation of shipments, example. Solid and dashed lines are for truck and train transportation modes, respectively.

5.5 Future research directions

The DN design receives a growing attention by the literature due to their high impact on the producer, distributor and retailer performances. The proposed tri-objective model and DSS support the strategic design of a DN from the operating cost, environmental impact and delivery time view-points. Starting from this contribution and the reviewed state of the art, several research opportunities emerge.

Following the classification criteria some future research guidelines are outlined in the following.

- Concerning the DN structure, the inclusion of a further level and stage to include the producer suppliers is possible. In such a way the focus is extended from the final products to include the raw materials and the supplied components. The concept of extended DN is, consequently, modeled;

- The inclusion of the reverse loop flows, from the end-users to the collectors and recyclers, is possible to convey to the frequently discussed close-loop supply chain network. This DN structure is proposed by the literature on green SCM, following a *cradle-to-cradle* paradigm, while lower attention is paid on optimizing such a network from a multi-objective perspective;

- The proposed model and DSS do not include a service level objective function. The necessity to overcome the approach based on the full demand supply by introducing penalties and stochastic distributions of the unsuccessful deliveries is to be addressed;

- The inclusion in both the model and the DSS of the temporal dynamics, typical of the DN tactical and operational planning, is a further possible extension of the present chapter.

The proposed future research directions, together with the others emerging in the next future, are to be addressed following a structured quantitative methodology. The background analysis, to better fix the problem, is preliminary to the analytic model update and the subsequent inclusion of new DSS modules. Finally, the model and DSS validation against multiple consistent case studies, taken from several industrial sectors with their own features and peculiarities, is to be done. Feedbacks and upgrades complete the research methodology.

5.6 Conclusions

This chapter addresses the effective design of multimodal DNs from a multi-objective perspective. Three of the most relevant optimization drivers are jointly considered looking for the multi-objective optimal network configuration. The operating cost function stresses the importance of effective DNs to save money making the retailer/end-user full price convenient, the carbon footprint looks for environmentally sustainable DNs able to mitigate the impact on the climate change and to reduce emissions due to production, storage and shipment activities. Finally, the delivery time function forces to speed the distribution process to promptly supply the market demand.

Starting from the analysis of the current scenario on the DN design methodologies and the review of the most recent state of the art on the multi-objective network optimization trends, the Pareto frontier multi-criteria solving approach is described and fully adopted to support the DN configuration though a multi-objective linear programming model. Two model formulations are discussed stressing the key differences in terms of product traceability. Both the feasibility model and the objective function analytic formulations are fully described and commented. The tri-objective model is behind an optimizer decision support system (DSS) supporting the planner in the steps to design an effective supply chain network. Both the DSS logic of working and the supporting user-friendly customized tool, implementing the process, are extensively discussed and their application is exemplified through a case study taken from the fresh food industry. Particularly, the peculiarities of food produces are considered to update the general multi-objective model, e.g. produce perishability. The data are from Italian producers distributing products to multiple European countries. Short and long shelf life products are studied to highlight differences in the most effective shipping strategies. The key outcomes stress opposite trends between operating cost and environmental impact on one side and the time objective function on the other. Fast DNs are, generally, expensive and with high impact on the carbon emissions. Effective trade-offs are found to speed the distribution process for the sole high perishable fresh produces.

6. Warehouse building design

Warehouse building design purpose is the definition of the warehouse building configuration, represented by length, width and height, that optimizes a certain objective function. Two are the functions traditionally considered: travel time and operating cost. Only few contributions propose design methods that simultaneously consider more than one objective function. Among these environmental impact is typically ignored, despite the significant importance it achieved in recent years in logistic context.

This Chapter proposes an innovative multi-objective optimization model to determine the warehouse building configuration that simultaneously minimizes the travel time, total cost and carbon footprint objective functions. Travel time is defined as the average time to pick up or drop off a stock keeping unit from or to the warehousing system. Total cost and carbon footprint are estimated exploiting a life-cycle approach. All the activities related both to warehouse building installation and operating phases are evaluated from an economic and an environmental perspective. Finally, a case study of a warehouse to be built for an Italian beverage company is presented to validate the proposed model.

6.1 Background and introduction

Warehouse building (WB) design is the process of interrelated decisions whose aim is to define the WB dimensions, namely length, width and height (see Paragraph 2.3.1). This process belongs to the warehouse design phase, thus it deals with long-term decisions that affect the warehouse performances for its entire lifetime (Rouwenhorst et al., 2000). WB building design has to guarantee several requirements of warehousing systems. Storage capacity and throughput rate are the most relevant (Baker and Canessa, 2009). The former represents the maximum stock keeping unit (SKU) quantity to store. The latter defines the SKU number to be stored or retrieved in a certain time window. WB design aim is to optimize a certain objective function that represents a relevant warehousing system KPI (Gu et al., 2010; Barry 1968).

6.1.1 Travel distance and travel time

Travel distance is the KPI traditionally adopted both by researchers and practitioners (Lingfeng and Lihui 2006). It evaluates the average distance to travel to pick up or drop off a SKU from or to a generic warehouse storage location (Manzini et. al, 2007b). Francis (1967) first proposes a model to determine the WB configuration to minimize the travel distance considering random storage strategy and SKU input/output (I/O) position located in the warehouse front midpoint. Bassan et. al (1980) enhance the previous research considering the aisle disposition in the WB and multiple I/O, with random access to any I/O position. Improvements to the proposed models are determined by further researches that exploit other storage strategies different from the random one. Caron et al., (2000a and 1998) tackle the WB design problem for class based storage strategy. They propose a simulative approach to evaluate the average travel distance for each WB configuration proposed (Caron et al., 2000b). On the contrary, Roodbergen and Vis (2006) propose a non-linear programming model to determine the optimal WB length, width and height that minimize the travel distance.

A great improvement to the travel distance models is their integration with the travel performances of SKU handling vehicles. The vertical and horizontal speed as well as the SKU loading and unloading time significantly affect the time to store/retrieve a SKU in/from a storage location, namely travel time. This characteristic holds even for storage locations distinguished by the same distance from the I/O point. For instance, at equal horizontal distance, the time to store a SKU in high level locations is much greater than the one for low levels. Thus, the travel performances of SKU handling vehicles enable travel time objective function calculation based on travel distance (Lerher et al., 2006 and Chew and Tang, 1999).

6.1.2 Operating and installation cost

A further objective function traditionally adopted to evaluate the WB performance is cost (Rosenblatt and Roll, 1984). Most of the contributions propose mathematical models to determine the WB configuration that minimizes the operating cost related to warehouse storage and retrieval activities. Operating cost is typically estimated through the SKU handling vehicle usage and the worker salary. Thus, it is a function of the number of purchased handling vehicles and hired workers (Park and Webster, 1989). Instead, proper models should also include indirect costs that deal with WB operations such as lightning and winter heating (Pilati et al., 2013). A significant improvement to the operating cost approach is proposed by few authors that consider all the expenditures occurring during the WB entire lifetime (Gabbard and Reinholdt, 1975). In particular, the installation cost should be considered to correctly determine the optimal WB dimensions that minimize the warehousing system total cost (Ashayeri et al., 1985). Installation cost gathers all the expenditures related to the WB construction as well as the necessary equipment purchase.

6.1.3 Environmental impact

As deeply investigated in Chapter 3, in recent years environmental sustainability achieved a relevant importance in manufacturing and logistic industries (Dekker et al., 2012 and Bortolini et al., 2015a). The developed green manufacturing and green logistic patterns suggest to exploit environmental impact as a KPI for logistic systems (Dahen, 2010). Considering warehousing systems, just few attempts are lately proposed. Makris et al. (2006) and Lehrer et al. (2013) focus on warehouse material handling activities proposing energy saving approaches both for manual and for automated storage and retrieval systems. Other authors consider warehousing systems to assess the building environmental impact (Deheng and Yuan, 2013). Carbon footprint (CF) is one of the environmental impact indicators most commonly adopted in the construction field to assess building sustainability during its entire lifetime (Cole and Kernan, 1996). As deeply investigated in Paragraph 3.4.1, CF measures the amount of “equivalent” carbon dioxide (CO_2 eq.) emissions directly and indirectly caused by a certain activity and accumulated over the lifetime of a system. The term “equivalent” represents the amount of carbon dioxide distinguished by the same global warming potential as a certain mixture of greenhouse gases (GHG) (Kua and Wong, 2012; Wiedmann and Minx, 2007; Choi, 2013). Thus, a correct WB CF evaluation has to consider the GHG emissions produced both during the operating and the installation phases (Rai et al., 2011; Cook and Sproul, 2011). The following Figure 6.1 summarizes the aforepresented KPIs for WB design.

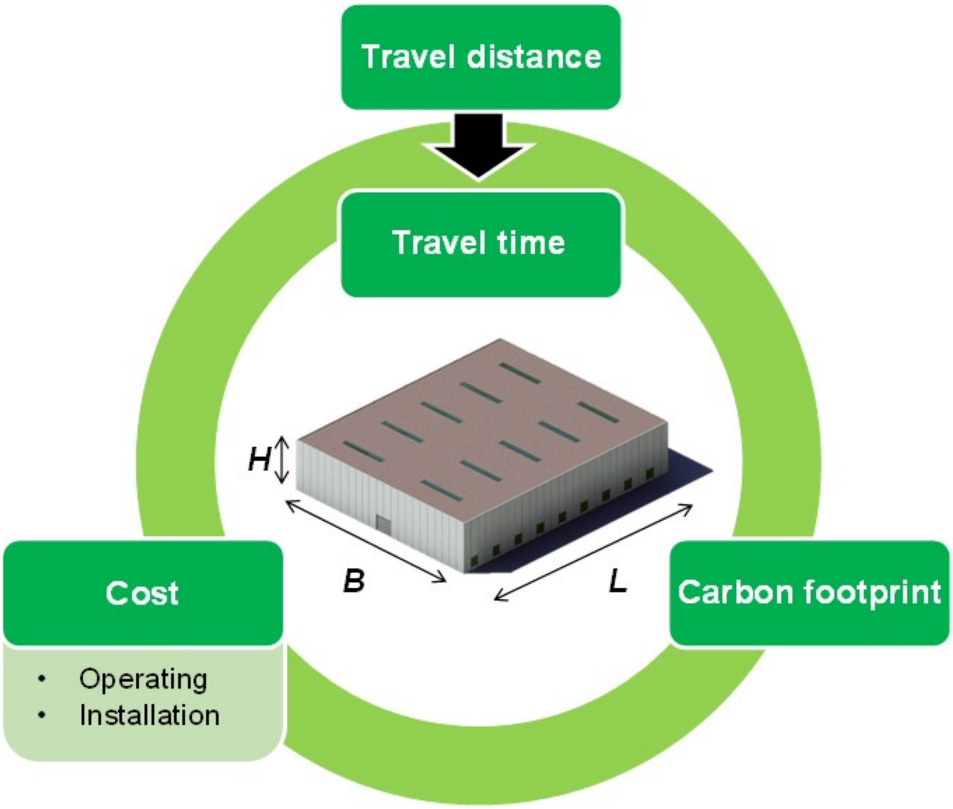


Figure 6.1. WB design key performance indices.

6.1.4 Multi criteria design

The aforementioned three objective functions, namely travel time, total cost and carbon footprint often diverge. The warehousing system configuration that minimizes one of these typically increases the remaining two, and vice-versa. Few contributions propose multi-objective approaches to define a warehousing system configuration simultaneously considering more than one objective function (Deb, 2001; Georgiadis and Besiou, 2010). Poulos et al. (2001) analyze the warehouse replenishment problem. The proposed MO model defines which product has to be stored in which location to minimize the travelled distance for picking activities and the cost related to product expiration date. Reehuis and Bäck (2010) design an automated order picking system exploiting MO. Aim of their model is to investigate the trade-off between the investment cost and the packaging filling rate. WB configuration and order fulfillment list have to be defined considering the total handling time and the order latency constraints. The unique contribution that tackles the WB design problem considering more than one objective function at a time is the one recently proposed by Tappia et al. (2015). The presented enumerative approach evaluates the GHG emissions and the total cost for several automated WB configurations. However, this approach does not consider the emissions produced during the WB installation and it does not provide any method to define the final WB configuration, namely the building length, width and height.

Aim of this Chapter is to propose a MO model to determine the WB dimensions, namely length, width and height to simultaneously minimize travel time, total cost and carbon footprint objective functions. The three aforementioned objective functions are estimated exploiting a life-cycle approach. All the activities related to installation and operating phases are evaluated from an economic and an environmental point of view. Furthermore, the method proposed in Paragraph 4.5 is exploited to determine the final WB configuration as the one distinguished by the best trade-off among the objective functions.

The remainder of this Chapter is organized as follow. Paragraph 6.2 analyzes the WB design optimization problem and defines in detail the three objective functions. Paragraph 6.3 describes a case study of an Italian beverage company used to validate the proposed MO model, whereas Paragraph 6.4 presents the main results and discussion. Finally, Paragraph 6.5 proposes the conclusions and suggests further research opportunities.

6.2 Multi-objective optimization problem

This Paragraph 6.2 presents an innovative MO model for WB design. Aim of the model is to determine the WB dimensions, namely length (L), width (B) and height (H) that minimize a set of objective functions relevant for the problem analyzed. As suggested in Paragraph 6.1, three are the objective functions to be considered.

- Travel time TC
  This objective function evaluates the average time store or retrieve a SKU to or from a warehouse storage location. Travel time formulation is highly affected by the warehousing system characteristics, namely overall structure, equipment selection, storage strategy and order picking strategy.

- Total cost TC
  Total cost evaluates the monetary expenditures over the WB entire lifetime. Two are the components considered: installation and operating costs. The former includes all the costs for building construction. The latter depends on the warehousing operating activities and it is evaluated for the entire WB lifetime through the discounted cash flow approach (see Paragraph 3.3.1).

- Carbon footprint CF
  This objective function measures the WB environmental impact during its entire lifetime. Using a life cycle approach, for each WB component, activity or process the GHG emissions are evaluated “from cradle to grave”. For instance, the GHG emitted by the SKU handling vehicle are determined by the vehicle manufacturing,

its transportation to the WB site, the electricity consumed for storage and retrieval activities and the disposal/recycling phase.

The set of the feasible solutions for the aforedescribed MO problem is limited by the following constraints (Eqs. 6.1-6.2).

$$H \leq h^{fork} + h^{x} \tag{6.1}$$

$$H \geq \frac{\frac{cap}{cap^{s}}(l^{s} b^{s} h^{s})}{(L - 2l^{x})(B - 2l^{x} - b^{x})} + h^{x} \tag{6.2}$$

Eq. 6.1 limits the WB height considering the forklift maximum height whereas Eq. 6.2 guarantees the required warehouse storage capacity (cap). Shipping and receiving SKU area (b^{x}, l^{x}) is considered along with the lighting and heating required space on the ceiling (h^{x}). The storage module concept is used in Eq. 6.2. The module dimensions are defined by parameters l^{s}, b^{s}, h^{s}. Considering these values, the module storage capacity (cap^{s}) can be easily determined. The storage module is duplicated several time in the WB to guarantee the required warehouse storage capacity. Figure 6.2 graphically represents the WB design decision variables and constraints.

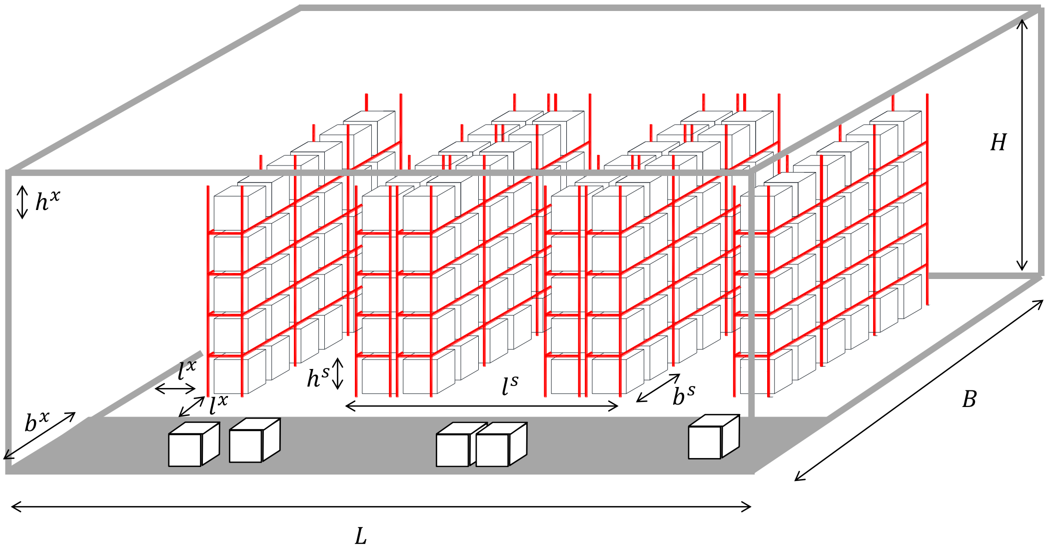
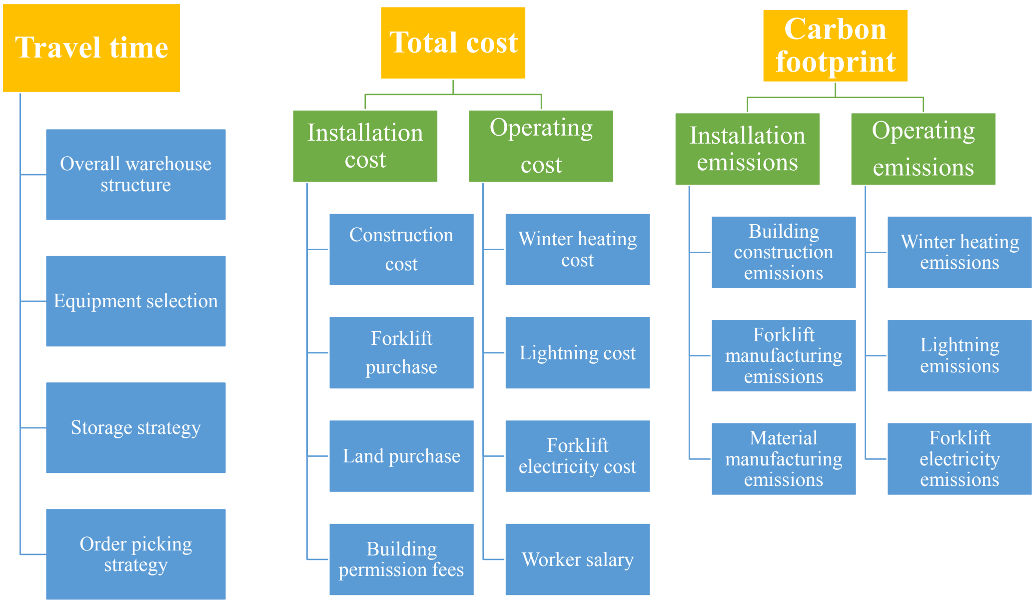


Figure 6.2. Warehouse building design decision variables and constraints. (Adapted from Bortolini et al., 2015b)

The WB design objective function considered, namely travel time, total cost and carbon footprint, are evaluated using a life-cycle approach. Both the installation and the operating phases are considered to determine the WB cost and emissions that occur during the warehouse entire lifetime. Figure 6.3 presents the objective function components belonging to these phases for TC and CF the objective function determinants for TT. The next

Paragraphs 6.2.1-6.2.3 deeply analyze each objective function proposing a mathematical formulation to estimate each component. The MO model parameters are presented and described in the Notation Paragraph (6.6).



6.3 MO model objective functions, their components and determinants

6.2.1 Travel time objective function

According to Pilati et al. (2015), travel time (TT) is the time to pick up or drop off a SKU from or to a generic warehouse storage location. TT objective function is defined considering the following warehousing system characteristics:

- <u>Overall warehouse structure</u>
  For sake of travel time evaluation the I/O position has to be defined. The number and location of I/O positions significantly affect travel time value. The most common I/O configurations are single I/O centered on WB front, single I/O on the WB corner and multi I/O positions on WB front.

- <u>Equipment selection</u>
  The material handling vehicle to store and retrieve the SKU determines different TT function configurations. The greatest difference is between automated storage/retrieval systems and manual handling vehicles, forklift for instance. The formers are distinguished by conjoint movements on the horizontal and vertical

directions (Chebyshev concept to determine TT), while the latters require disjoint movements (additive concept to determine TT).

- Storage strategy
  The strategy adopted to select in which storage location stock the SKUs has a remarkable impact on travel time. Random, dedicated or class-based storage strategy require different travel distances to pick up or drop of the same product. Travel time function is accordingly defined.

- Order picking strategy
  Considering TT objective function, two are the relevant decisions of order picking strategy. The former defines the product quantity to pick up for each trip. Less than unit load has no constraint on the picking quantity, whereas unit load requires to pick an entire SKU. The latter decision deals with the combination of storing and retrieving activities. Single command operation requires to store or retrieve one SKU at a time dropping it off or picking it up at the I/O position each time, whereas dual command operation enables to sequentially store and retrieve two SKUs with no visit to the I/O position and one empty travel from the storage to the retrieval locations.

For sake of this research the considered warehousing system characteristics are the following.

- multiple I/O positions
- forklift truck handling vehicles
- random storage strategy
- single command operation and unit load picking

Considering these warehousing system characteristics, Pohl et al. (2009) and Bassan et al. (2000) enable to evaluate the average travel distance (Figure 6.4). To store a SKU, the forklift has to pick up the product in a random I/O position x on the WB front, continuous by hypothesis. The random storage strategy determine an equal probability that the storage location is on the left (A_l) or right (A_r) WB side. Thus, Eqs. 6.3-6.4 propose the average travelled distance $d(x)$ to store (or retrieve) a SKU dropped off in x I/O position as a weighted sum of the travelled distance for each WB side. As proposed by Eq. 6.3 average travelled distance on y axis is constant and not function of the I/O position. Considering an equal probability of x distribution on the WB front, the average travelled distance $\bar{d}$ to store (or retrieve) a SKU in generic warehouse location under the aforementioned hypothesis is evaluated in Eqs. 6.5-6.7 and presented in Figure 6.5.

$$d(x)=\frac{\left(\frac{x}{2}+\frac{B}{2}\right)\cdot xB+\left(\frac{L-x}{2}+\frac{B}{2}\right)\cdot(L-x)B}{LB}= \tag{6.3}$$

$$=\left(x^2+\frac{L^2}{2}-Lx+\frac{LB}{2}\right)\frac{1}{L} \tag{6.4}$$

$$\bar{d}=\frac{1}{A}\int_A d(x)\,dA= \tag{6.5}$$

$$=\frac{1}{LB}\int_0^L\left(\int_0^B\left(x^2+\frac{L^2}{2}-Lx+\frac{LB}{2}\right)\frac{1}{L}\,dy\right)dx= \tag{6.6}$$

$$=\frac{L}{3}+\frac{B}{2} \tag{6.7}$$

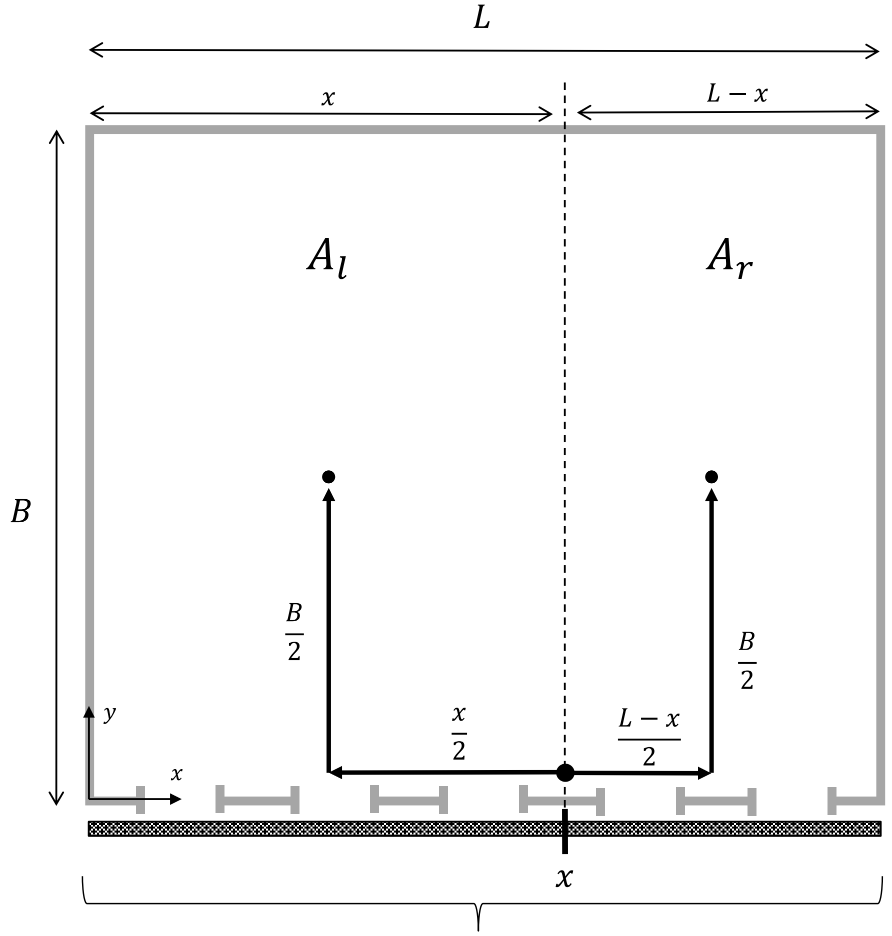


Figure 6.4. Travel distance to pick up (drop off) a SKU in a generic I/O point x and store (retrieve) it in a random warehouse location.

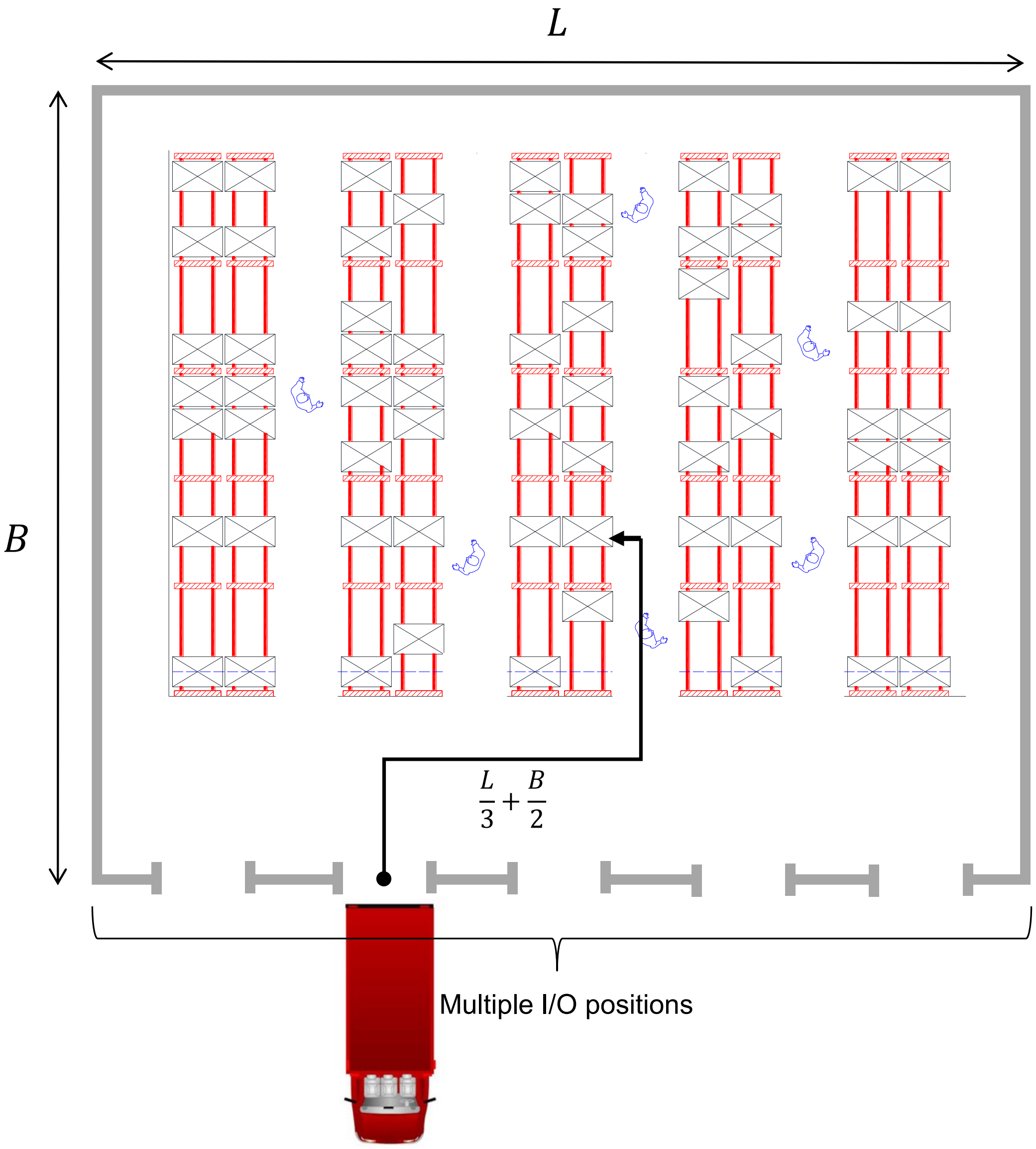


Figure 6.5. Average travel distance for the considered warehousing system (adapted from Bortolini et al., 2015b).

Thus, exploiting the average travel distance $\bar{d}$ determined by Eq. 6.7 and including the forklift horizontal (v^h) and vertical (v^v) speed as well as its pick up (lt) and drop off (ut) times, *TT* objective function is defined as follows (Eq. 6.8).

$$TT = \frac{H}{v^v} + \frac{\left(\frac{L}{3}+\frac{B}{2}\right)2}{v^h} + (lt + ut) \tag{6.8}$$

Eq. 6.8 can be easily redefined considering different warehousing system characteristics, e.g. single I/O position, dedicated storage strategy, dual command operation, etc. For instance, Eqs. 6.8’ and 6.8’’ propose travel time objective function for single I/O centered on WB front and single I/O on the WB corner, respectively. Thus, strength of the proposed

MO model is the possibility to be used for building design of several and different warehousing systems.

$$TT = \frac{H}{v^v} + \frac{\left(\frac{L}{4} + \frac{B}{2}\right)2}{v^h} + (lt + ut) \qquad (6.8')$$

$$TT = \frac{H}{v^v} + \frac{\left(\frac{L}{2} + \frac{B}{2}\right)2}{v^h} + (lt + ut) \qquad (6.8'')$$

6.2.2 Total cost objective function

Total cost objective function (TC) is defined as the total cost spent during the entire WB lifetime (m). Its value is equal to the installation cost (IC) and the sum of the discounted yearly operating cost (OC_i) (Eq. 6.9) according to the approach proposed in Paragraph 3.3.1.

$$TC = IC + \sum_{i=1}^{m} \frac{OC_i}{\left(\frac{1 + occ}{1 + ir}\right)^i} \qquad (6.9)$$

Installation cost include the expenditure determined by the land purchase, the building permission fees, its construction and the forklift purchase. Operating cost represents the yearly cash flows determined by the warehousing system activities. These include the worker salary and the electricity cost for forklift charge, but also the expenditure for building lightening and winter heating. No disposal cost is included in this objective function since this is considered equal to the WB residual value.

6.2.2.1 Installation cost

The installation cost (IC) represents the initial investment to set up the WB and it is defined as the sum of construction cost (C^C), land purchase (C^L), building permission fees (C^P) and forklift purchase (C^F) (Eq. 6.10).

$$IC = C^C + C^L + C^P + C^F \qquad (6.10)$$

- Construction cost

  This cost includes construction worker salary, building material purchase and transportation, construction equipment rental, as well as facility plant installation. It is evaluated by Eq. 6.11. This equation is defined using the Italian Ministry of Infrastructures and Transports regulation (2012).

$$C^C = LB\left[\beta' H^2 (LB)^{\gamma'} + \beta'' H (LB)^{\gamma''} + \beta''' (LB)^{\gamma'''} + \theta\right] \tag{6.11}$$

- Land purchase

  This IC component is the cost for the required building area purchase at a certain land price (p^{land}) (Eq. 6.12). The area considers the required adjacent land for the truck loading and unloading activities (l^y, b^y), as shown in Figure 6.6.

$$C^L = p^{land}(L + 2l^y)(B + 2b^y) \tag{6.12}$$

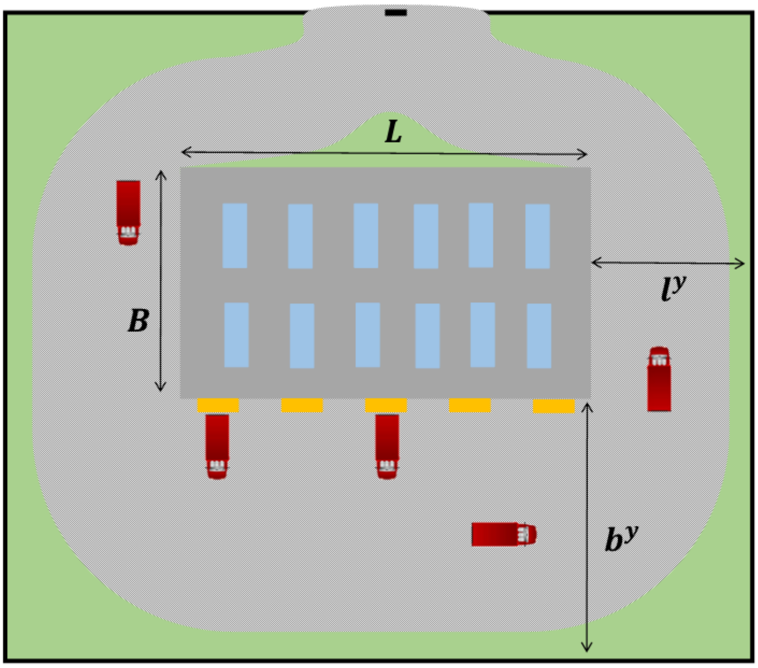


Figure 6.6. Warehouse building land requirement.

- Building permission fees

  This cost represents the compulsory payment to the government (p^{fees}) to obtain the authorization to build a warehouse on a land (Eq. 6.13).

$$C^P = p^{fees} LB \tag{6.13}$$

- Forklift purchase

  This IC component is the expenditure to buy and replace the forklift fleet (Eq. 6.14). It considers the forklift vehicle price (p^{fork}), the fleet size ($\left\lceil \frac{TT \cdot tr}{3600f} \right\rceil$) and the number of fleet replacement during the WB lifetime ($\left\lceil \frac{m}{m^{fork}} \right\rceil$). The fleet size is determined considering the travel time TT, the warehouse target throughput rate (tr) and the forklift availability and traffic congestion factor (f). The vehicle replacement is evaluated comparing the warehouse (m) and vehicle (m^{fork}) lifetimes.

$$C^F = p^{fork} \left\lceil \frac{TT \cdot tr}{3600f} \right\rceil \left\lceil \frac{m}{m^{fork}} \right\rceil \tag{6.14}$$

6.2.2.2 Operating cost

The operating cost is the annual cost determined by the warehousing system operating activities. It both considers direct and indirect costs implicated by the storage and retrieval processes. The formers are determined by the forklift usage (the forklift electricity consumption C^U) and their drivers (worker salary C^W). The latters deal with WB heating during the winter season (C^H) and its lightning (C^G). However, only a percentage $(1-\varphi)$ of these expenditures increases OC_i. The remaining portion (φ) represents the tax savings achieved decreasing by this value the yearly net cash flow. Furthermore, the operating cost is lowered by the positive effect that building ($s^C C^C j_i^C$) and forklift ($s^F C^F j_i^F$) amortization have on tax expenditure (Eq. 6.15).

$$OC_i = -\varphi(s^C C^C j_i^C + s^F C^F j_i^F) + (1-\varphi)(C^H + C^G + C^U + C^W) \tag{6.15}$$

- Forklift electricity purchase

  This cash flow is determined by the electricity consumed for the SKU handling activities. Each forklift store and retrieve SKUs for hd hours per day and dy day per year, on average, and it is distinguished by an electricity consumption of pw^{fork} kW. Considering these parameters, the electricity price (p^e) and the forklift fleet size $\left(\left\lceil \frac{TT \cdot tr}{3600f} \right\rceil\right)$ enable to determine this operating cost. (Eq. 6.16).

$$C^U = pw^{fork} dy \cdot hd \cdot p^e \left\lceil \frac{TT \cdot tr}{3600 \cdot f} \right\rceil \tag{6.16}$$

- Workers salary

  This cost depends on the forklift fleet size $\left(\left\lceil \frac{TT \cdot tr}{3600f} \right\rceil\right)$, assuming that each forklift is driven by a worker of wage p^{work} during each of the ns working shifts (Eq. 6.17).

$$C^U = p^{work} \left\lceil \frac{TT \cdot tr}{3600f} \right\rceil ns \tag{6.17}$$

- Winter heating

  This cost is determined by the quantity of natural gas required for WB heating during the winter season. This value depends on the WB winter heating energy requirement (pw^h), and the natural gas heating features, namely the natural gas lower heating value lhv, the natural gas density ρ and the gas heater efficiency η. The natural gas price cg is used to calculate this cost.

$$C^H = \frac{cg \cdot pw^h}{\eta \cdot lhv \cdot \rho} \tag{6.18}$$

pw^h is defined as the heat transferred through the WB structural elements, i.e. walls, rooftop and floor, considering their surface area, the structural element heat transfer coefficient (respectively k^w, k^r, k^f), the daily heating duration (hh) and a specific installation location. This location defines the degree day (dd) and the ground-warehouse temperature gradient (Δt) necessary to correctly evaluate Eq. 6.19.

$$pw^h = [k^w 2(LH + BH) + k^r LB] dd \cdot hh + k^f LB \cdot hh \cdot \Delta t \tag{6.19}$$

- <u>Lightning</u>
  This expenditure represents the cost necessary to light the entire warehouse area (LB). Lighting plant requires every hour of every day (hd) of the year (dy) pw^{light} electrical power per square meter of area to light. p^e is the electricity price (Eq. 6.20).

$$C^L = pw^{light} LB \cdot dy \cdot hd \cdot p^e \tag{6.20}$$

6.2.3 Carbon footprint objective function

Carbon footprint (CF) objective function is adopted in this Chapter to evaluate the environmental impact of the WB during its entire lifetime (CF) in a “from cradle to grave” approach. This objective function measures the amount of GHG emissions, measured in kg CO_2 eq. as stated in Paragraph 3.4.1, produced during both WB installation (IE) and the WB operating (OE) phases (Eq. 6.21). WB installation impact includes the emissions for the manufacturing of building materials (concrete, polystyrene, iron, etc.), the pollutants produced for forklift manufacturing and the GHGs determined by the construction of the building itself. Instead, WB operation impact is determined by the emissions produced for winter heating, building lightening and forklift usage. Emissions generated by WB end of life treatment are not considered in this model.

$$CF = IE + m \cdot OE \tag{6.21}$$

6.2.3.1 Installation emissions

Installation emissions (IE) are generated by all the activities related to WB installation. These include building material manufacturing (E^M), construction of the building itself (E^C) and forklift fleet manufacturing (E^F) (Eq. 6.22).

$$IE = E^M + E^C + E^F \tag{6.22}$$

- Building material manufacturing

  This emission category represents the quantity of GHG emitted for WB structural element manufacturing. To determine this value it is necessary to evaluate the amount of structural element used in WB construction as function of the WB dimensions (L, B, H) and the element manufacturing emissions per unit of volume (em^f for floor, em^r for rooftop, em^g for groundwork, em^p for pillars and em^w for walls) (Eq. 6.23). These parameters represent the kg CO$_2$ eq. emitted to manufacture a unit of volume of each structural element, namely floor, groundwork, pillars, roof and walls. For instance considering floor, em^f estimates the GHG emissions per square meter of this structural element for raw material extraction, their processing and transformation.

  $$E^M = LB[em^f + em^r + \delta(em^g + H \cdot em^p)] + 2(HB + HL)em^w \tag{6.23}$$

- Building construction

  This component (E^C) of installation emissions represent the GHGs produced by building construction activities. These consider materials and construction equipment transportation from and to the installation site. Furthermore, the emissions generated by the equipment on-site usage are included. Cole (1998) relates E^C to building structural elements dimensions (determined by the WB dimensions L, B, H) and their specific construction emissions (ec^f for floor, ec^{gpr} for groundwork, pillars and rooftop and ec^w for walls) (Eq. 6.24). Building construction formulation entails that each WB dimensions has a different effect on E^C value.

  $$E^C = LB(ec^f + ec^{gpr}) + 2(HB + HL)ec^w \tag{6.24}$$

- Forklift manufacturing

  GHG emitted for forklift fleet manufacturing are evaluated with Eq. 6.25. Raw materials extraction and processing, equipment production and assembly as well as its transportation to costumers are estimated by em^{fork}. The two remaining factors represent the fleet size and its number of replacement, respectively.

$$E^F = em^{fork} \left\lceil \frac{TT \cdot tr}{3600f} \right\rceil \left\lceil \frac{m}{m^{fork}} \right\rceil \tag{6.25}$$

6.2.3.2 Operating emissions

Operating emissions (OE) are GHG yearly emitted by WB operating activities. Similarly to operating cost components, OE are determined by the electricity consumption for forklift usage (E^U), heating during winter season (E^H) and building lightning (E^G) (Eq. 6.26). The emissions related to the worker activities are not considered, because negligible.

$$OE = E^H + E^G + E^U \tag{6.26}$$

- Forklift electricity emissions

  The production of these GHGs depends on several components (Eq. 6.27). The power consumed during the SKU handling activity by the forklift (pw^{fork}), the duration of this activity ($dy \cdot hd$) and the GHG emitted on average for the production of 1 electricity kWh considering the country where the WB is installed and the corresponding energy mix (e^e).

$$E^U = pw^{fork} dy \cdot hd \cdot e^e \cdot \left\lceil \frac{TT \cdot tr}{3600f} \right\rceil \tag{6.27}$$

- Winter heating

  Accordingly to the winter heating cost (see Paragraph 6.2.2.2), these emissions (Eq. 6.28) are determined by the quantity of natural gas required for WB heating during the winter season (pw^h) and some natural gas heating features (η, lhv, ρ). The GHG emissions produced for each cubic meter of burned natural gas (eg) consider its combustion, transportation, extraction as well as the related facility manufacturing.

$$E^H = \frac{eg \cdot pw^h}{\eta \cdot lhv \cdot \rho} \tag{6.28}$$

- Lightning

  These emissions are determined by the electricity required for WB lightning, as proposed in Paragraph 6.2.2.2 (Eq. 6.29). Each kWh of electricity consumed determines the emission of e^e kg CO_2 eq. This value includes the GHGs generated both during the electricity production and its transportation to the WB.

$$E^H = pw^{light} LB \cdot dy \cdot hd \cdot e^e \tag{6.29}$$

Three are the objective functions of the proposed problem, namely travel time, total cost and carbon footprint. To determine a solution, i.e. define the WB dimensions, MO techniques are of strong help. In particular, the Pareto frontier should be determined to identify the WB configurations that best represent a trade-off among the objective functions. The concepts of Pareto optimality and non-dominated solutions are used in the following to determine the MO problem optimal solutions of the presented case study (Paragraph 6.3) as well as the best length, width and height of the final WB configuration (Paragraph 6.4).

6.3 Case study

The proposed MO model is exploited to design a case study WB. It represents a warehouse located in Italy that has to be built for a beverage company. Case study parameter values are presented in the following tables (6.1-6.4). Table 6.1 proposes the forklift data provided by a European manufacturer, whereas Table 6.2 summarizes the warehousing system requirements determined both by technical specifications and company requests (cap, tr).

Table 6.1. Forklift data.

Parameter	Value
f	0.9
h^{fork}	13 m
lt	25 s
m^{fork}	10 years
v^h	0.5 m/s
v^v	4.44 m/s
ut	25 s

Table 6.2. Warehousing system requirements.

Parameter	Value
b^s	3.15 m
b^x	6 m
b^y	30 m
cap	8,000 SKU
cap^s	6 SKU
h^s	1.95 m
h^x	2 m
l^s	6.05 m
l^x	3 m
l^y	30 m
m	25 years
tr	100 SKU/hour
ns	1 shift

Table 3 summarizes several MO model parameters. Technical parameters are proposed by different technical datasheets, company requirements and established design criteria. Cost parameters are evaluated through real market data, governmental regulations and consulting company surveys. Emissions information are based on Ecoinvent database v.2.0 (Ecoinvent Center, 2007) and include all the GHGs produced during the entire lifecycle of the product or process considered, in a “from cradle to grave” approach.

Table 6.3. MO model parameters.

Parameter	Value	Reference
cg	0.561 €/m^3	European Commiss, 2007
dd	2259°C	Enea, 2013
dy	220 day/year	Company requirement
e^e	0.583 kg CO$_2$ eq./kWh	Ecoinvent Center, 2007
ec^f	11.2 kg CO$_2$ eq./m^2	Cole, 1998
ec^{gpr}	19.1 kg CO$_2$ eq./m^2	Cole, 1998
ec^w	21.3 kg CO$_2$ eq./m^2	Cole, 1998
eg	3.42 kg CO$_2$ eq./m^3	Ecoinvent Center, 2007
em^{fork}	7,900 kg CO$_2$ eq.	Jungheinrich AG, 2011
hd	8 hour/day	Company requirement
hh	24 hour	Company requirement
ir	0.01	Real market data
j_i^C	$\begin{cases} 1, i \leq (s^C)^{-1} \\ 0, \text{otherwhise} \end{cases}$	Real market data
j_i^F	$\begin{cases} 1, i \leq (s^F)^{-1} \\ 0, \text{otherwhise} \end{cases}$	Real market data
k^f	0.529 kW/°C m^2	Technical datasheet
k^r	0.529 kW/°C m^2	Technical datasheet
k^w	0.296 kW/°C m^2	Technical datasheet
lhv	13.8 kWh/kg	Technical datasheet
occ	0.05	Real market data
p^e	0.12 €/kWh	European Commiss, 2007
p^{fees}	150 €/m^2	Italian Government, 2011
p^{fork}	25,000 €	Real market data
p^{land}	100 €/m^2	Feichtinger et. al, 2013
p^{work}	30,000 €/year	Real market data
pw^{light}	10 W/m^2	Yun et al., 2012
s^C	0.03	Italian Ministry, 1998
s^F	0.20	Italian Ministry, 1998
η	0.85	Technical datasheet
ρ	0.713 kg/m^3	Technical datasheet
Δt	10°C	Technical data
β'	20.5	Italian Ministry, 2012
β''	-179	Italian Ministry, 2012
β'''	1619	Italian Ministry, 2012
γ'	-0.216	Italian Ministry, 2012
γ''	-0.205	Italian Ministry, 2012
γ'''	-0.179	Italian Ministry, 2012
δ	0.0084 pillar/m^2	Technical datasheet
θ	9.68	Italian Ministry, 2012
φ	31.4%	KPMG, 2011

Table 4 proposes the manufacturing emission evaluation for the WB structural elements. As already mentioned, five are the WB structural elements, namely floor, groundwork, pillars, roof and walls. For each of these the emission parameter represents the GHG produced to manufacture one structural element "unit". For instance, em^f estimates the kg CO_2 eq. per square meter of manufactured floor whereas, em^p evaluates the kg CO_2 eq. per meter of height of one pillar. Furthermore, each of these parameters is determined considering the composing materials, their respective thickness and emissions. For example, considering floor structural element, em^f =143 kg CO_2 eq. per floor square meter. This value is determined including all the floor four layers of different materials (concrete, reinforced concrete, sand and gravel), their respective thickness (fourth column of Table 6.4) and GHG emissions to manufacture one cubic meter of these (fifth column of Table 6.4) (Figure 6.7).

Table 6.4. WB structural element manufacturing emissions.

Parameter	Structural element	Material	Thickness (m)	Material emissions (Ecoinvent Center, 2007) (kg CO_2 eq./m^3)	Parameter value
em^f	Floor	Concrete	0.1	261	143 kg CO_2 eq./m^2
		Reinforced concrete-A	0.3	373	
		Sand	0.3	3,6	
		Gravel	1.0	3,6	
em^g	Groundwork	Reinforced concrete-A	8 m^3 volume per pillar	373	2989 kg CO_2 eq./pillar
em^p	Pillars	Reinforced concrete-B	1 m^2 section	502	502 kg CO_2 eq./m·pillar
em^r	Roof	Reinforced concrete-B	0.1	502	63 kg CO_2 eq./m^2
		Polystyrene	0.1	126	
em^w	Walls	Reinforced concrete-B	0.15	502	94 kg CO_2 eq./m^2
		Polystyrene	0.15	126	

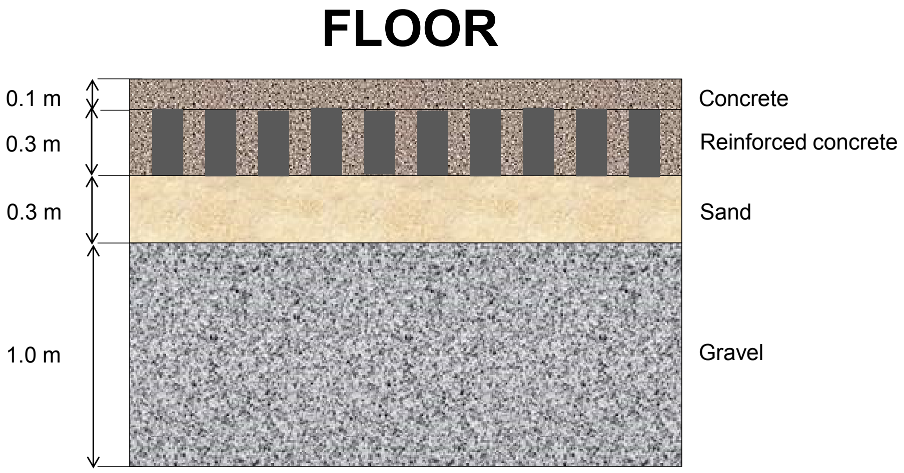


Figure 6.7. Layout of a structural element, floor exemplification.

6.4 Results and discussion

Three single-objective optimization (SO) problems are defined to evaluate how the WB configuration differs among the objective functions considered. Each SO problem optimizes one objective function at a time subject to the constraints previously proposed. SO solution is represented by the WB dimensions (L, B and H) that minimize the SO objective function considered. Table 6.5 shows for each SO problem the WB dimensions as well as the objective function values and increments compared to their optimal values.

Table 6.5 WB dimensions, objective function values and increments for each SO problem

			SO problem		
			min(TT)	***min(TC)***	***min(CF)***
Decision variables	***L***	*[m]*	111	85	78
	B	*[m]*	73	60	64
	H	*[m]*	9.5	14.6	14.9
Objective function value and increment	***TT***	*[s/SKU]*	97.0	100.4	101.0
		[%]	-	3.5	4.1
	TC	*[€]*	8,403,066	7,601,417	7,611,587
		[%]	10.5	-	0.1
	CF	*[kg CO_2 eq.]*	9,001,991	6,511,198	6,421,360
		[%]	40.2	1.4	-

The WB configurations determined by CF and TC optimization are similar. On the contrary, TT minimization is distinguished by a flatter and less compact WB (Figure 6.8). This result accordingly affects the objective function values. CF minimization determines a negligible TC increase (+1.4%) and vice-versa (+0.4%). However, TT optimization dramatically increases the WB emissions (+40.2%) and cost (+10.5%).

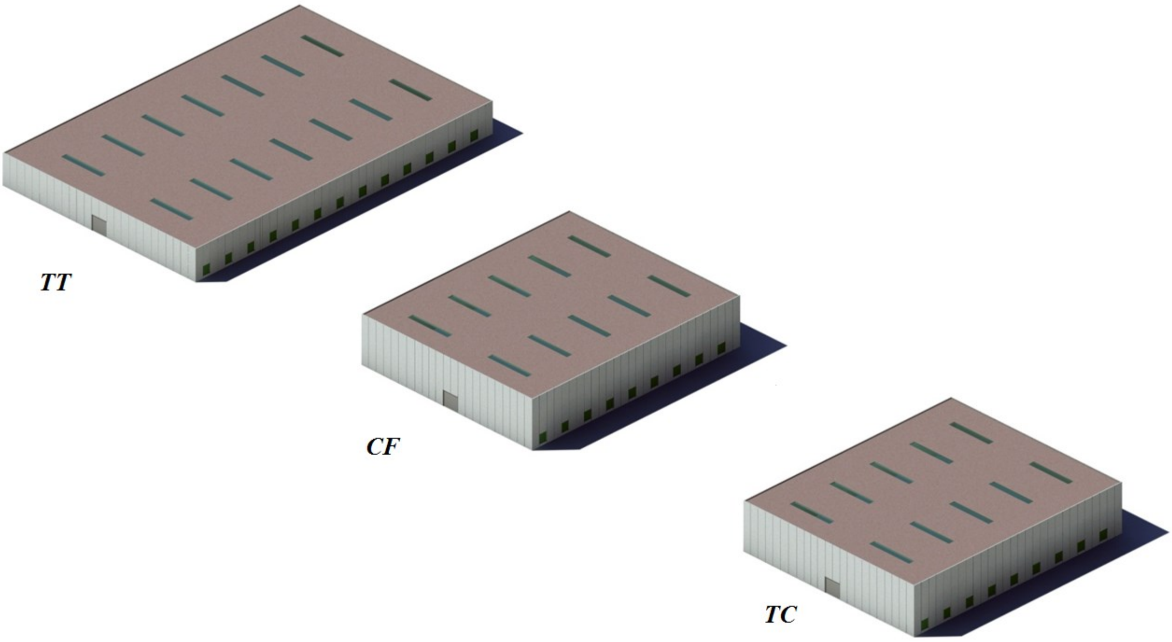


Figure 6.8. Optimal TT (left), CF (middle) and TC (right) WB configurations.

As presented in Figure 6.9, 68% of *TC* optimal value is determined by installation cost. The most relevant investment component is construction cost (35% of *TC*). Considering operating cost, worker salary accounts for almost the entire portion of this expenditure. Its value is equal to 26% of *TC*.

Considering *CF*, installation emissions are marginal compared to operating one. 34% of GHG emissions are determined by the former, material manufacturing in particular (29% of *CF*). GHG emitted during warehouse operating activity are mainly produced by winter heating (41% of CF) and forklift usage (16% of *CF*).

TC and *CF* components comparison suggests that installation activity is much more relevant for economic rather than for environmental perspective (68% and 34% of objective function optimal value), whereas operating activity significantly influences warehouse emissions and not costs. This difference is determined by the impact that the energy consumed during operating activity has on the objective functions. Natural gas used for warehouse winter heating and electricity consumed for building lightning and forklift usage represent 66% of the emissions produced during the entire warehouse lifetime. On the contrary they determine only 5% of warehouse total expenditures.

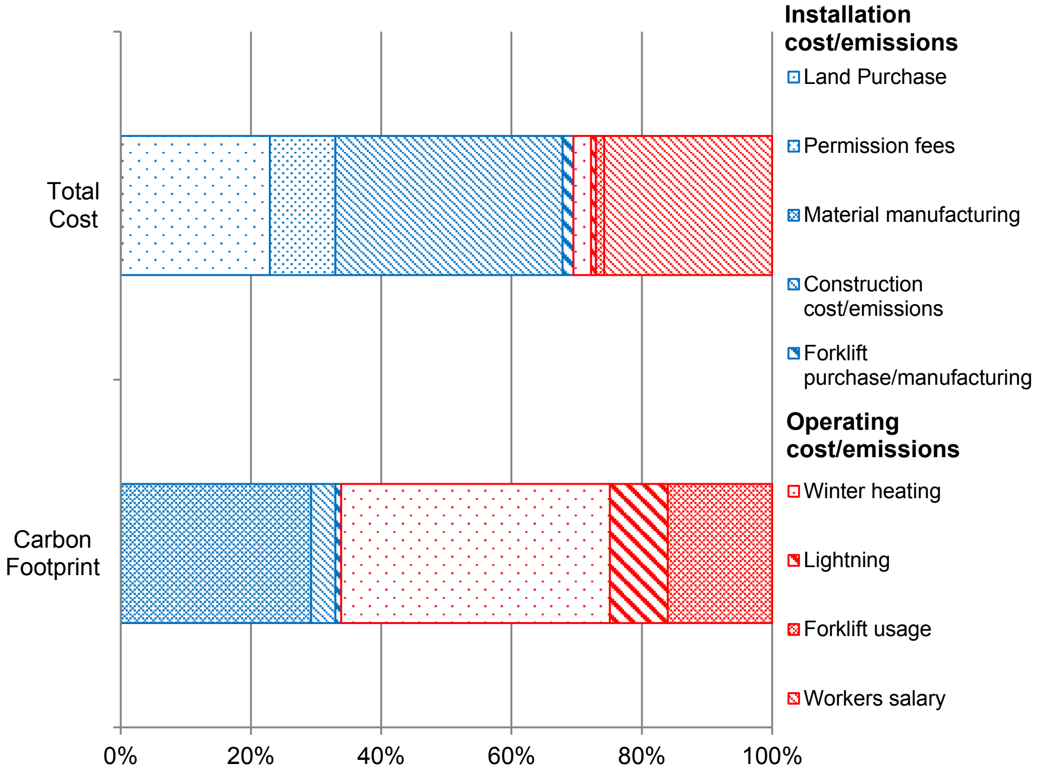


Figure 6.9. Components of total cost and carbon footprint objective functions for their respective optimal values.

To determine a trade-off WB configuration that simultaneously considers all the objective functions the MO model presented in Paragraph 6.2 is exploited. Figure 6.10 shows the MO solutions. Green points are the dominated solutions, yellow ones belong to the Pareto frontier whereas objective function optimal values are represented by the red points. Furthermore, Figure 6.11 presents the Pareto frontier detail.

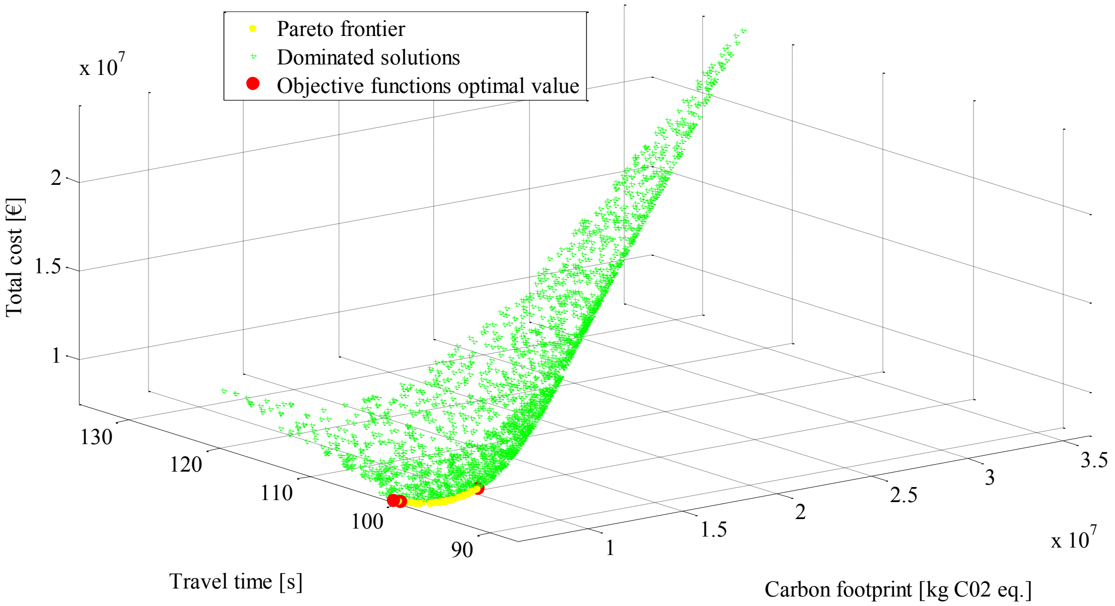


Figure 6.10. MO WB design: Pareto frontier, dominated solutions and objective function optimal values

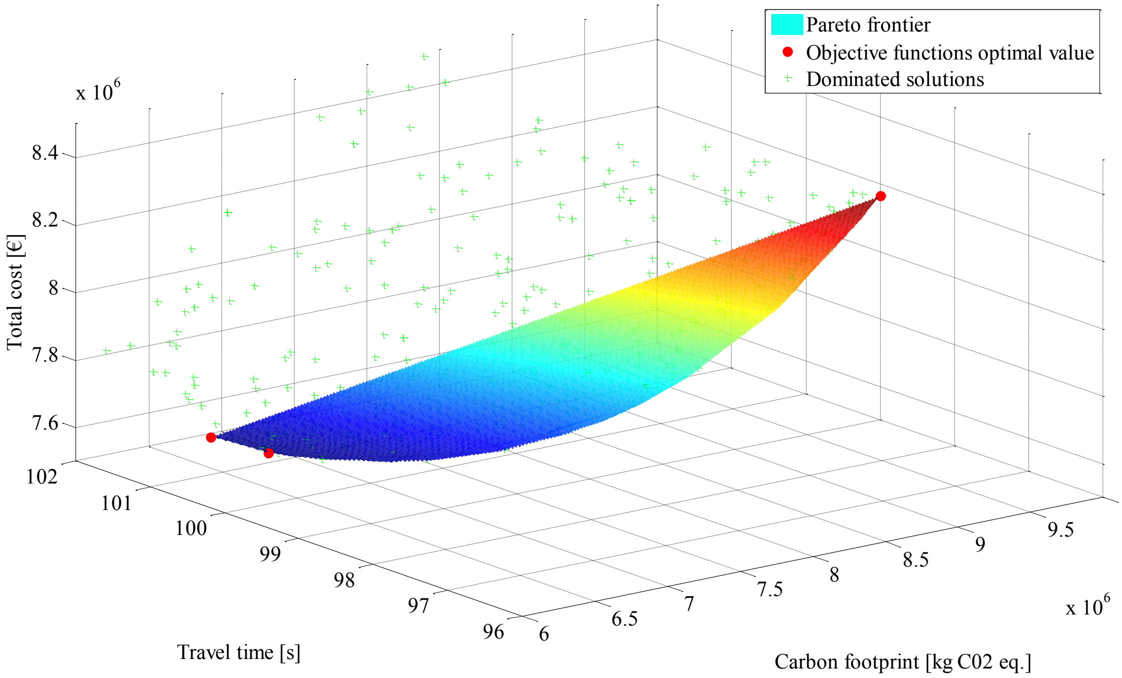


Figure 6.11. WB design Pareto frontier detail.

MO WB design results suggest that CF minimization almost ensures TC optimization and vice-versa. This characteristic is exploited to determine the final WB configuration. Without loss of generality, in the following the analysis is limited to the bi-objective TT - CF optimization. Figure 6.12 presents the TT - CF Pareto frontier along with emission and travel time values of the TC optimal solution.

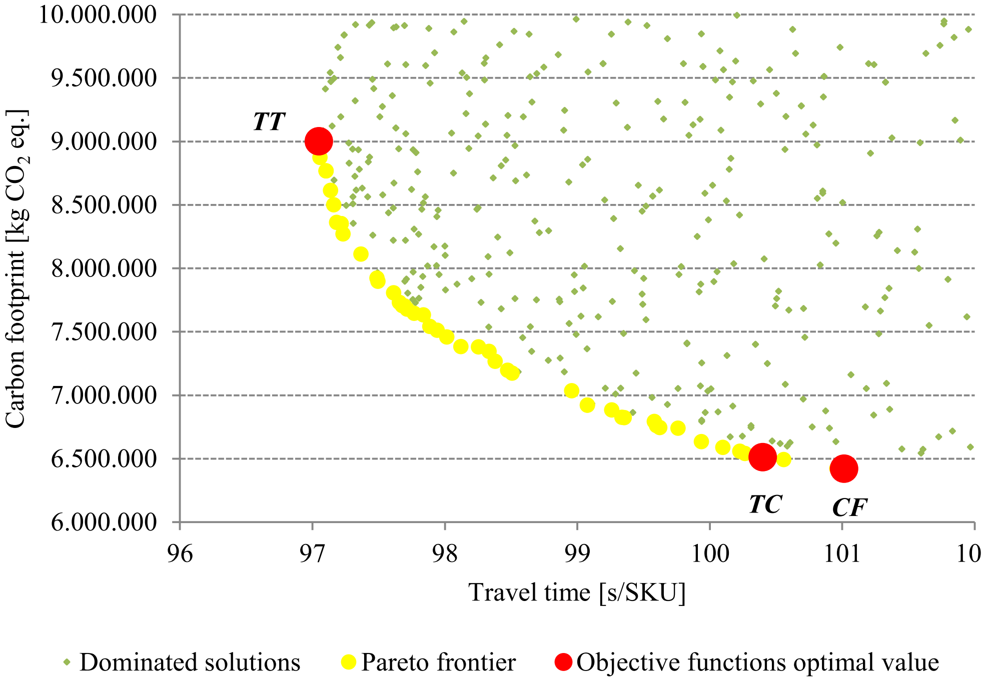


Figure 6.12. Pareto frontier of travel time and carbon footprint bi-objective analysis.

The final WB configuration has to be chosen among the presented Pareto solutions. The decision of which solution to adopt depends on the designer preference. WB design priority, performance or emissions (cost), determines which objective function to foster, therefore which Pareto solution to choose. To this purpose, in order to converge to such a final solution, the empiric rule proposed in Paragraph 4.5 is adopted and exploited for the case study. The resulting equation is in the following (6.30).

$$\min_k G_k, \quad G_k = \frac{TT_k}{TT^*} \cdot \frac{CF_k}{CF^*} \tag{6.30}$$

where k is the index of the k*-th* solution laying on the Pareto frontier and TT^*, CF^* are the travel time and carbon footprint optimal solutions.

The solution k that solves Eq. 6.30 has to be considered the best trade-off solution for the WB design problem, thus it defines the WB configuration to adopt. The next Figure 6.13 depicts the objective function increment compared to their optimum and the G trend over Pareto frontier highlighting the final trade-off solution (represented by a green circle).

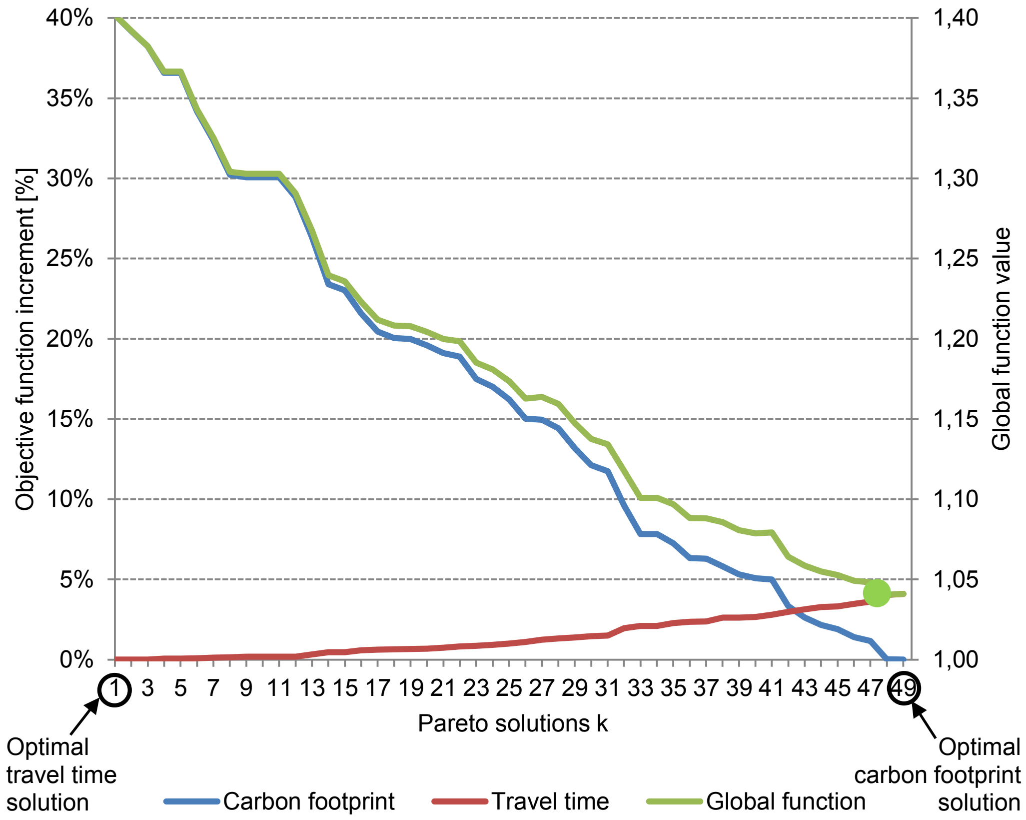


Figure 6.13. Objective function increment and $\boldsymbol{G}$ trends, along with the final WB design trade-off solution (green circle).

Pareto solutions close to optimal TT dramatically increase CF compared to its minimum (up to +40%). On the contrary, MO solutions close to minimum CF slightly worsen TT compared to its optimum (less than +5%). This outcome is strengthened by the final WB trade-off configuration proposed by G minimization. As presented in Table 6, the final WB configuration almost corresponds to CF optimal solution. CF and consequently TC objective function worsening compared to their optimal value is near to 0% whereas TT increase is limited to +4%. Final WB dimensions (L, B and H) are proposed in Table 6.6 as well.

Table 6.6. Final WB configuration: building dimensions, objective function value and increment

	Decision variable		Objective function	
	value [m]		value	increment [%]
L	97	*TT*	100.9 [s/SKU]	4.08%
B	51	*TC*	7,619,142 [€]	0.23%
H	14.9	*CF*	6,423,251 [kg CO$_2$ eq.]	0.03%

6.5 Conclusions and further research

This Chapter proposes an innovative multi-objective optimization (MO) model to determine the warehouse building (WB) configuration, namely length, width and height, to simultaneously minimize travel time (TT), total cost (TC) and carbon footprint (CF) objective functions. TT is defined as the average time to pick up or drop off a stock keeping unit (SKU) from or to a generic warehouse storage location. TC and CF objective functions are estimated exploiting a life-cycle approach. All the activities related to the WB installation and operating phases are evaluated from an economic and an environmental point of view. Installation phase includes construction material manufacturing, building construction and forklift manufacturing. Operating phase accounts for forklift usage, worker activity, WB lightning and WB winter heating. A case study of a WB to be built for an Italian beverage company is presented to both validate and apply the proposed MO model. The company requires a warehouse storage capacity of 8,000 SKU and a target throughput rate of 100 SKU/hour. The MO model parameters are accurately evaluated considering several sources. First of all, the three objective functions are independently optimized. The WB configurations determined by CF and TC disjoint optimization are similar. CF minimization determines a negligible TC increase (+1.4%) and vice-versa (+0.4%). However, TT optimization dramatically increases the WB emissions (+40.2%) and cost (+10.5%). Considering this relevant outcome and without loss of generality, the MO is limited to the bi-objective TT - CF optimization. The MO optimal solutions, called Pareto frontier, represent a set of WB configurations distinguished by the optimal trade-off between the objective functions considered. To select the final WB configuration among the Pareto frontier solutions the proposed empiric function G is exploited. The final WB configuration selected by G is, for the analyzed case study, almost identical to CF optimal solution. CF and consequently TC objective function worsening compared to their optimum are near to 0% whereas TT increase is limited to +4%. Compared to traditional single-objective optimization approaches, the proposed MO model enables to define a trade-off WB configuration that limits, for the presented case study, only to 4% the worsening of each objective function.

Further research should include additional environmental impact indicators to the MO model, such as energy consumption and resource depletion during the entire WB lifetime and investigate how these objective functions affect the final WB configuration. Moreover, the proposed MO model has to be validated and applied considering different warehousing system characteristics, as dual command operation, dedicated storage strategy, single I/O position and AS/RS handling vehicles.

6.6 Notations

Indices:

i	operating year.

Variables:

B	warehouse building width [m],
H	warehouse building height [m],
L	warehouse building length [m].

Objective functions:

CF	carbon footprint [kg CO$_2$ eq.],
TC	total cost [€],
TT	travel time [s/SKU],

Objective function components:

IC		installation cost [€],
	C^C	construction cost [€],
	C^F	forklift purchase [€],
	C^L	land purchase [€],
	C^P	building permission fees [€];
OC_i		operating cost of year i [€],
	C^H	winter heating cost [€],
	C^G	lightning cost [€],
	C^U	forklift electricity cost [€],
	C^W	worker salary [€];
IE		installation emissions [kg CO$_2$ eq.],
	E^C	building construction emissions [kg CO$_2$ eq.],
	E^F	forklift manufacturing emissions [kg CO$_2$ eq.],
	E^M	building material manufacturing emissions [kg CO$_2$ eq.];
OE		operating emissions [kg CO$_2$ eq.],
	E^H	winter heating emissions [kg CO$_2$ eq.],
	E^G	lightning emissions [kg CO$_2$ eq.],
	E^U	forklift electricity emissions [kg CO$_2$ eq.].

General parameters:

b^s	storage location width [m],
b^x	shipping and receiving bay length [m],
cap	warehouse required storage capacity [SKU],
cap^s	storage location capacity [SKU],

dd	installation location degree day [K],
dy	yearly working days [days/year],
f	forklift coefficient to consider vehicle availability and traffic congestion,
h^{fork}	forklift maximum height [m],
h^{s}	storage location height [m],
h^{x}	lighting and heating required space [m],
hd	daily working hours [hours/day],
hh	daily heating duration [hours],
k^{f}	floor heat transfer coefficient [kW/K·m^2],
k^{r}	rooftop heat transfer coefficient [kW/K·m^2],
k^{w}	walls heat transfer coefficient [kW/K·m^2],
l^{s}	storage location length [m],
l^{x}	aisle width [m],
lhv	natural gas lower heating value [kWh/kg],
m	warehouse lifetime [years],
m^{fork}	forklift lifetime [years],
pw^{fork}	forklift power consumption [kW],
pw^{h}	winter heating energy requirement [kWh/year],
pw^{light}	lightning power [W/m^2],
tr	warehouse target throughput rate (pick up or drop off) [SKU/hour],
η	gas heater efficiency [%],
ρ	natural gas density [kg/m^3],
Δt	gradient between ground and warehouse temperatures [K].

Travel time objective function parameters:

lt	fixed forklift pick up time [s],
v^{h}	forklift horizontal speed [m/s],
v^{v}	forklift vertical speed [m/s],
ut	fixed forklift drop off time [s].

Total cost objective function parameters:

b^{y}	adjacent land width [m],
cg	natural gas purchase cost [€/m^3],
ir	inflation rate,
j_i^{C}	$\begin{cases} 1, \text{if year } i \text{ belongs to building amortization period} \\ \quad 0, \text{otherwhise} \end{cases}$
j_i^{F}	$\begin{cases} 1, \text{if year } i \text{ belongs to forklift amortization period} \\ \quad 0, \text{otherwhise} \end{cases}$
l^{y}	adjacent land length [m],
ns	number of working shifts,

occ	opportunity cost of capital,
p^{e}	electricity price [€/kWh],
p^{fees}	construction permission fees [€/m^2],
p^{fork}	forklift price [€],
p^{land}	land purchase cost [€/m^2],
p^{work}	worker wage [€/year],
s^{C}	building amortization coefficient,
s^{F}	forklift amortization coefficient,
$\beta', \beta'', \beta'''$	construction cost function parameters,
$\gamma', \gamma'', \gamma'''$	construction cost function parameters,
θ	construction cost function parameter,
φ	tax rate.

Carbon footprint objective function parameters:

e^{e}	electricity emissions [kg CO_2 eq./kWh].
ec^{f}	floor structural element construction emissions [kg CO_2 eq./m^2],
ec^{gpr}	groundwork, pillars and rooftop structural elements construction emissions [kg CO_2 eq./m^2].
ec^{w}	walls structural element construction emissions [kg CO_2 eq./m^2],
eg	natural gas emissions [kg CO_2 eq./m^3],
em^{f}	floor structural element manufacturing emissions [kg CO_2 eq./m^2],
em^{g}	groundwork structural element manufacturing emissions [kg CO_2 eq./pillar],
em^{p}	pillars structural element manufacturing emissions [kg CO_2 eq./m·pillar],
em^{r}	rooftop structural element manufacturing emissions [kg CO_2 eq./m^2],
em^{w}	walls structural element manufacturing emissions [kg CO_2 eq./m^2],
em^{fork}	forklift manufacturing emissions [kg CO_2 eq.],
δ	pillars per square meter ratio [pillar/m^2].

7. Warehouse storage assignment strategy

Effectiveness in warehouse operations is crucial for the industrial companies to be competitive in the market arena by reducing the response time and inbound costs, increasing their global service level. Storage assignment deals with the definition of effective strategies to organise items into industrial warehouses to achieve high performances. This Chapter enhances the conventional approaches on storage assignment proposing a time and energy based strategy, for traditional warehouses served by forklifts, based on the joint minimisation of the travel time and the energy required by the material handling vehicles to store and retrieve the unit-loads. The models to compute the expected single-command travel time and energy are integrated into a multi-objective model, optimizing the load assignment. An application, taken from the beverage industry, is, finally, discussed. The different perspectives of adopting time and energy to drive the load assignment are stressed proposing a practical best trade-off rule.

7.1 Background and introduction

Efficiency and effectiveness in the warehouse operation play a crucial role in today market arena distinguished by a fierce competition. As suggested in Paragraph 2.3, aim of warehouse operation is the mid and short management of a warehousing system. Among the integrated set of decisions that have to be faced, storage assignment strategy is of major interest (Gagliardi et al., 2012). Purpose of this problem is to assign each incoming product to a warehouse storage location to maximize the warehousing system performances (De Koster et al., 2007).

7.1.1 Warehousing system features

The solution of this problem requires a set of information to determine which product store in which location.

- Warehouse layout
  The position of each storage location within the warehouse is required to evaluate the travelled distance to store/retrieve (S/R) a product in (or from) this. Furthermore, the input/output (I/O) configuration of the warehousing system remarkably affects this distance. Single I/O centered on warehouse front, single I/O on the warehouse corner, or multiple I/O distributed on the warehouse front determines different travel distance for the same storage location (De Koster and Neuteboom, 2001).

- Performances of material handling equipment
  First of all, the category of material handling equipment has to be selected. The greatest difference is between manual and automated vehicles. The formers require a driver for storage and retrieval activities, the latters autonomously pick up and drop off the products from and to the storage locations. Forklift are the manual vehicles traditionally adopted, whereas automated storage/retrieval systems (AS/RSs) well represent autonomous vehicles. Considering the time to S/R a product, AS/RSs differ from traditional forklifts. Forklifts follow disjoint horizontal and vertical movements, e.g. the forks can be lifted uniquely at stationary vehicle. On the contrary, AS/RSs allow simultaneous movements in the two directions (Atmaca and Ozturk, 2013). This latter feature leads to the so-called *Chebyshev* distance concept (De Koster et al., 1999). Given the generic storage location, the required time to S/R a load is the maximum time to travel the vertical and horizontal distances.

Furthermore, considering the selected vehicle type, S/R travel time is significantly affected by the specific vehicle performances. The most relevant are the nominal speed and acceleration both on horizontal and vertical motion axis and the fixed loading/unloading time to pick up/drop off a product.

- Product features

  The characteristics of the products to be stored represent a relevant aspect for assignment strategies (Heskett, 1963 and 1964). Storage capacity and demand frequency are two of the most relevant product features (Choe and Sharp, 2001). The former evaluates the storage capacity required for each product type, while the latter measures the number of SKU to be stored or retrieved in a time window due to customer orders. An item can be classified according to these two product features in slow moving, steady, intermittent or erratic (Figure 7.1).

  Furthermore, other product specific features should be considered to properly select the storage strategy. Product physical characteristic, as dimensions and weight, are the most relevant (Chiang et al., 2011; Rosenblatt and Roll, 1988).

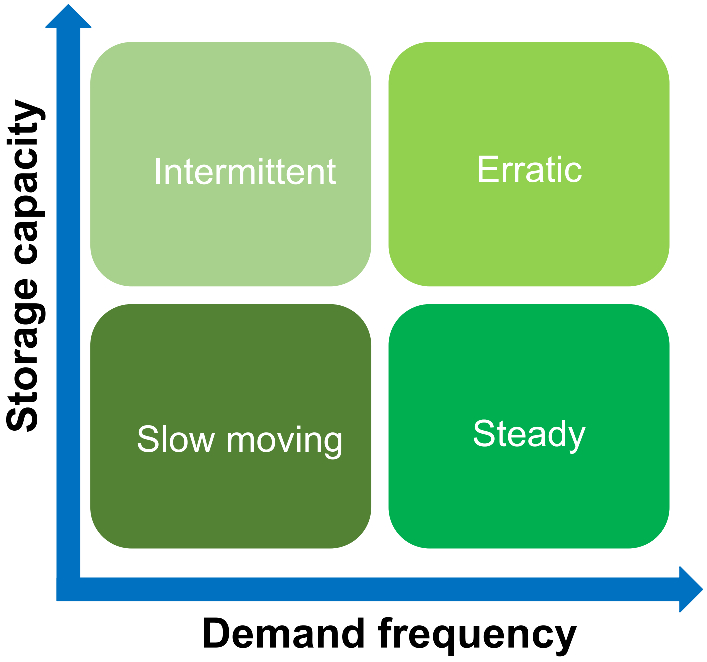


Figure 7.1. Product classification considering storage quantity and demand frequency.

- Storage location structure

  The structure of the horizontal and vertical racks used for product storage is a relevant information for storage assignment strategy definition (Chiang et al., 2014; Chuang et al., 2012). The location dimensions identify which products can be stocked in which location and which others are oversized. Load capacity constraints have to be satisfied by the weight of stocked items to ensure safety conditions and to comply with current legislations.

7.1.2 Travel time vs. energy consumption

Within this proposed framework, research contributions and logistic practices typically focus on average travelled time to S/R products from a warehouse to determine the storage assignment strategy to adopt (Fumi et al., 2013; Kasemset and Rinkham, 2011; Kofler et al., 2011). Aim of this strategy is to determine which product to store in which location to minimize the average travel time for S/R activities considering the aforedescribed problem relevant information. Traditional approaches (Bozer and White, 1984; Hwang and Ko, 1988) assume infinite vehicle acceleration both on horizontal and vertical directions to simplify the models. However, as proposed by several contributions, proper storage location assignment strategy should consider vehicle acceleration profiles (Hwang and Lee, 1990; Hwang et al., 2004; Chang and Wen, 1997; Wen et al., 2011). This enables a correct and accurate evaluation of the travel time to reach each single storage location.

The travel time minimization represents the widest adopted objective function of the strategies proposed by the literature. However, as presented in Paragraph 3.2, the last years are distinguished by an increasing rise in consciousness for sustainable manufacturing (Garetti and Taisch, 2012) and energy efficient operations in warehousing (MHIA, 2009). Meneghetti and Monti (2013a) introduce assignment rules to minimize the energy consumed by an AS/RS during the S/R operations. They estimate the energy consumed by the cranes to pick up and drop off a product from each storage location. The crane movements are considered linear with constant acceleration (Meneghetti and Monti, 2013b). Furthermore, the authors present a comparison between the storage location assignment defined by the travel time and the energy consumption minimization (Meneghetti et al., 2015). However, no suggestion is proposed to define a unique warehouse storage assignment strategy that simultaneously considers both these objective functions.

This described research is in accordance with the literature. Few contributions are presented on the definition of a multi-objective storage location assignment strategy. Fontana and Cavalcante (2014) recently propose a multi-criteria method to simultaneously minimize the travelled distance, the total operation cost and the space requirement. This method heavily depends on the weights assigned by the decision makers to the different objective functions. To overcome this weakness, Wu et al. (2010), Li et al. (2008) and Accorsi et al. (2015) propose a multi-objective optimization model to assign the products to the storage locations for AS/RS warehouses. The authors define two objective functions:

the former minimizes the S/R travel time, whereas the latter maximises the stability of the racks.
As far as the author knowledge, no contribution is proposed to simultaneously minimize the energy consumption and the travel time within the warehouse storage location assignment problem.

This Chapter presents a MO model supporting the product assignment in traditional warehouses to simultaneously minimize the energy consumed by the forklift and the travel time to S/R the products. The objective functions are accurately evaluated considering the following features.

- The forklift speed profile is evaluated both on vertical and horizontal directions modelling the motion configuration.
- Friction effect is considered to correctly estimate the energy required by the forklift.
- Relevant product features for the objective functions are included for each item, as demand frequency, storage required capacity and weight.

Single-deep stationary racks and single-command cycles are used. The closed form expressions to compute the travel time and the energy consumption are presented, integrated into the multi-objective model and exemplified through a real case study.
According to the introduced topic, the remainder of this Chapter is organised as follows. The next Paragraph 7.2 introduces the models to evaluate the travel time and the energy consumption to S/R a product from a generic storage location. Paragraph 7.3 presents the multi-objective storage assignment model for traditional warehouses. In addition to the objective function and the constraint definition, this Paragraph presents a practical rule-of-thumb to determine an effective trade-off solution. Paragraph 7.4 describes a full application of the proposed assignment strategy to a case study taken from the beverage industry. Finally, Paragraph 7.5 concludes this Chapter with final remarks and suggestions for further research.

7.2 Travel time and energy consumption models

This research considers single-deep stationary racks arranged in parallel with traditional forklifts as material handling vehicles. The vehicle capacity is of one unit-load (UL), while the vehicle picks up ULs from the I/O position and drops them off in the proper storage location defined by the tuple (b, s, l, r). Where b is the bay, s the span, l the level and r the rack. For instance, tuple (2,5,4,12) univocally identifies the storage location positioned in the 12th rack, in its 5th span, in the 2nd bay of the span and at the 4th level. Paragraph 7.6 presents a detailed description of the model notations.

7.2.1. Travel distance evaluation

The distance that a forklift has to travel to store or retrieve the generic UL in the location identified by the tuple (b, s, l, r) is made of three components (Figure 7.2). The following equation parameters distinguish the warehouse layout and are presented in Figure 7.3.

Horizontal distance from I/O to aisle, Y_r.

This value depends on the warehousing system configuration adopted. In particular, the I/O position determines two different formulations for Y_r.

- Single I/O position

  Considering the position $y^{I/O}$ of the I/O on the warehouse front, horizontal travel distance is evaluated by Eq. 7.1.

$$Y_r = \left| \left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right] - y^{I/O} \right| \tag{7.1}$$

- Multiple I/O position

  This warehouse configuration is distinguished by multiple I/O positions on the building front. Eq. 7.1 is be modified considering that the generic I/O position is one of the multiple points, thus it is represented by the variable α equally distributed on the warehouse front (Eqs. 7.2-7.4).

$$Y_r = \frac{1}{L^t} \int_0^{L^t} \left| \left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right] - \alpha \right| d\alpha = \tag{7.2}$$

$$\begin{aligned} &= \frac{1}{L^t} \int_0^{\left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right]} \left(\left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right] - \alpha \right) d\alpha + \\ &+ \frac{1}{L^t} \int_{\left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right]}^{L^t} - \left(\left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right] - \alpha \right) d\alpha \end{aligned} \tag{7.3}$$

$$Y_r = \frac{\left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right]^2}{L^t} + \frac{L^t}{2} - \left[(2D + L^C) \cdot \left(\left\lceil \frac{r}{2} \right\rceil - 1 \right) + D + \frac{L^C}{2} \right] \tag{7.4}$$

Horizontal distance from aisle to storage location, K_{bs}.

Eq. 7.5 estimates the horizontal distance K_{bs} to travel from the bottom of the aisle to the proper bay b of the exact span s where the product has to be S/R. The equation parameters are shown in Figure 7.3.

$$K_{bs} = L^{fix} + (s - 1) \cdot (W + \psi^{w}) + b \cdot (\delta + w') - w'/2 \tag{7.5}$$

Finally the total horizontal distance travelled by the forklift to S/R a product is the sum the previous two components Y_r and K_{bs} (Eq. 7.6).

$$X_{bsr} = K_{bs} + Y_r \tag{7.6}$$

Vertical distance from ground to storage location, Z_l.

Eq. 7.7 estimate the distance to lift the vehicle forks and reach the required storage level l considering the UL height H and beam width ξ^{w}.

$$Z_l = (l - 1) \cdot (H + \xi^{w}) \tag{7.7}$$

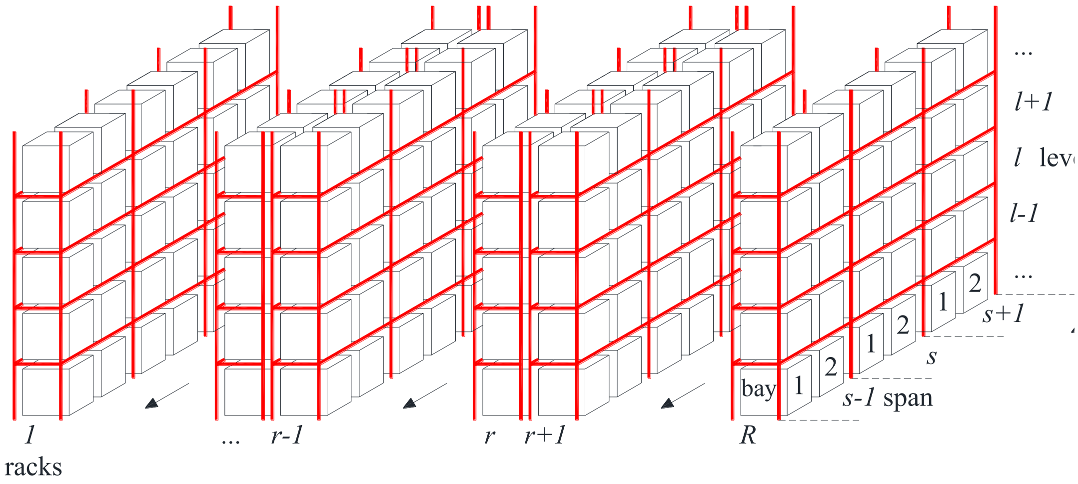


Figure 7.2. Nomenclature to identify the storage locations (from Accorsi et al., 2015).

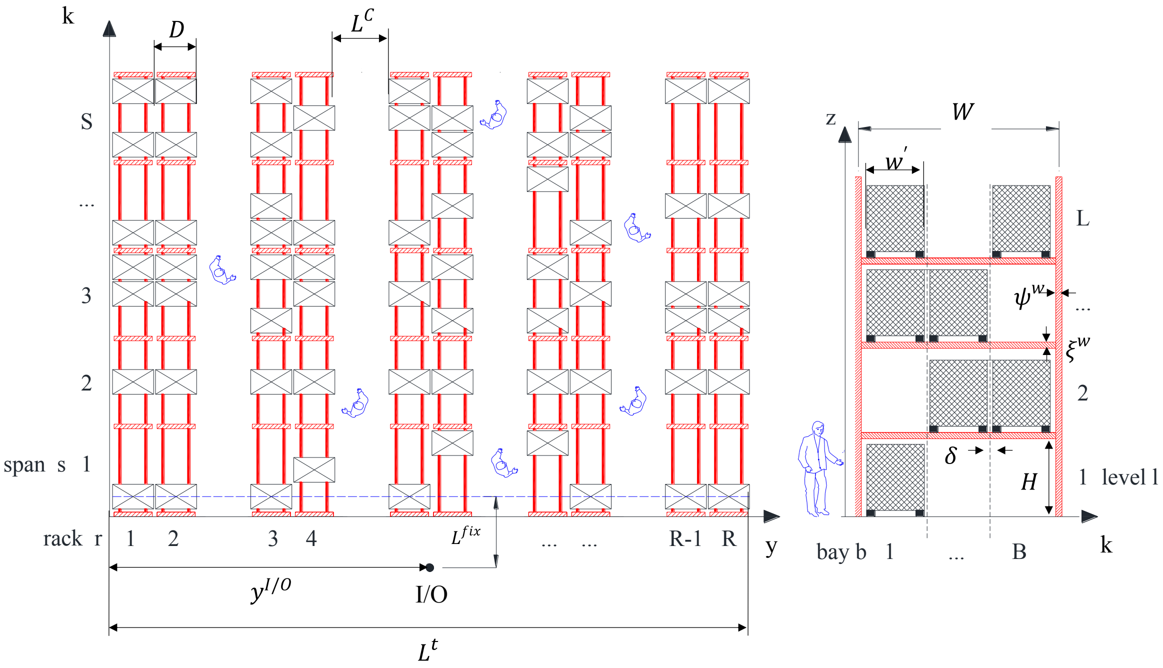


Figure 7.3. Reference storage system layout (adapted from Bortolini et al., 2015b).

7.2.2 Single command travel time model

The forklift travel time follows the so-called additive distance concept determined by disjoint movement on the motion axis, so that, given the generic couple of distances (X_{bsr}, Z_l), the required time to reach the storage location is the sum between the horizontal and the vertical time intervals. The recent literature frequently debated about the computation of such two time intervals. Both constant speed and acceleration/deceleration models are proposed. The former assumes the forklift to work at a constant speed, while the latter includes the vehicle and forks acceleration/deceleration transitory. Following such a latter model, two basic scenarios occur for each motion axis (e.g. horizontal and vertical) and they are called triangular and trapezoidal motion configurations, according to Figure 7.4.

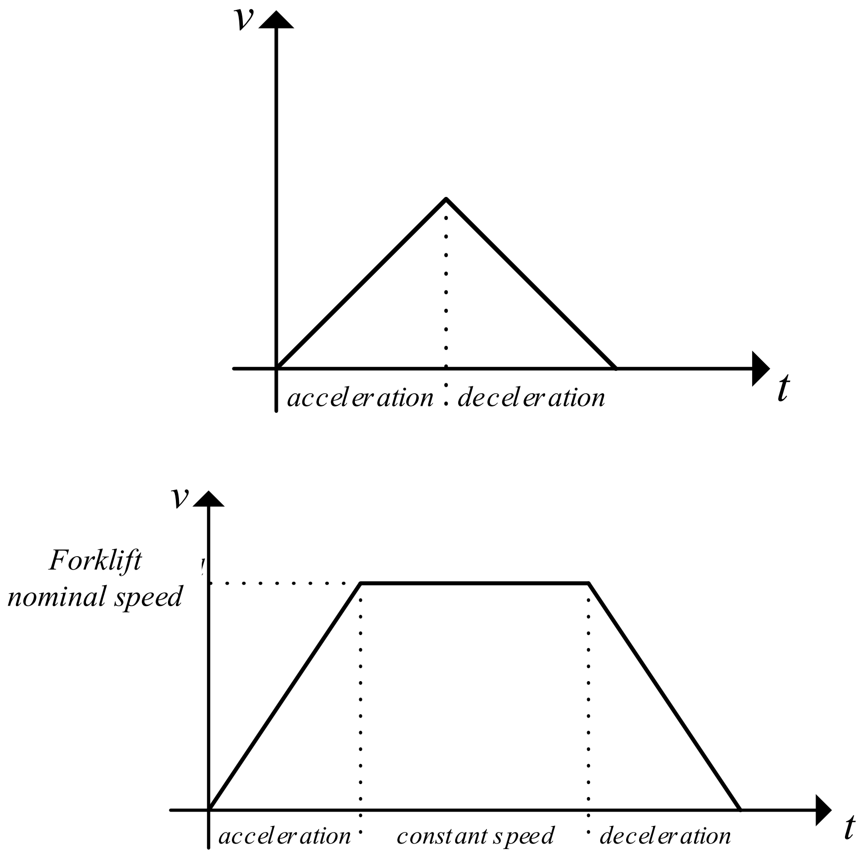


Figure 7.4. Triangular motion configuration (top) and trapezoidal motion configuration (bottom).

In the triangular motion configuration, noted with the subscript $\triangle$ in the following, the distance to cover does not allow the handling system to reach its nominal speed, v^X (in the horizontal axis) and/or v^Z (in the vertical one), so that the system accelerates for the first part of the travel time and decelerates for the last part. Concerning accelerations, for the horizontal axis of motion, a^X and d^X are the considered values, while for the vertical axis of motion a further distinction is necessary between the forks ascending and descending trajectories (noted with the subscripts ↑ and ↓ in the following) to include the effect of the gravity force. Particularly, in the former case the system is assumed to accelerate at a^Z and to decelerate at $g \cdot (1 + \mu^Z)$ due to the gravity and the positive effect of the friction force. On the contrary, in the latter case the system is assumed to accelerate at $g \cdot (1 - \mu^Z)$, due to the gravity force and the negative effect of the friction force, and to decelerate at d^Z. Such assumptions are from the field practice and behind all the models. The expressions for the horizontal and vertical travel time within the triangular motion configuration are the followings (Eqs. 7.8-7.10).

$$t_{bsr}^{X,\triangle} = \sqrt{\frac{2 \cdot X_{bsr} \cdot (a^X + d^X)}{a^X \cdot d^X}} \tag{7.8}$$

$$t_l^{Z\uparrow,\triangle} = \sqrt{\frac{2 \cdot Z_l \cdot (a^Z + g \cdot (1 + \mu^Z))}{a^Z \cdot g \cdot (1 + \mu^Z)}} \tag{7.9}$$

$$t_l^{Z\downarrow,\triangle} = \sqrt{\frac{2 \cdot Z_l \cdot (g \cdot (1 - \mu^Z) + d^Z)}{g \cdot (1 - \mu^Z) \cdot d^Z}} \tag{7.10}$$

Proof

Focusing on the horizontal axis of motion, the acceleration and deceleration spaces are the followings (Eqs. 7.11-7.12):

$$S_a^X = \frac{1}{2} \cdot a^X \cdot (t_a^X)^2 \tag{7.11}$$

$$S_a^X = \frac{1}{2} \cdot a^X \cdot (t_a^X)^2 \tag{7.12}$$

Given $S_a^X + S_d^X = X_{bsr}$ follows that (Eq. 7.13):

$$\frac{1}{2} \cdot a^X \cdot (t_a^X)^2 + \frac{1}{2} \cdot d^X \cdot (t_d^X)^2 = X_{bsr} \tag{7.13}$$

Furthermore, considering that the final speed of the acceleration part is the initial speed of the deceleration part, it follows that (Eq. 7.14):

$$a^X \cdot t_a^X = d^X \cdot t_d^X \tag{7.14}$$

Joining the previous two equations 7.13 and 7.14 and solving for t_a^X and t_d^X, respectively, follows (Eqs. 7.15-7.16):

$$t_a^X = \sqrt{\frac{2 \cdot X_{bsr} \cdot d^X}{a^X \cdot (a^X + d^X)}} \tag{7.15}$$

$$t_d^X = \sqrt{\frac{2 \cdot X_{bsr} \cdot a^X}{d^X \cdot (a^X + d^X)}} \tag{7.16}$$

Finally, $t_{bsr}^{X,\triangle} = t_a^X + t_d^X$ leading to Eq. 7.8. The proof for the vertical axis is logically the same and it is omitted for the sake of brevity.

■

In the trapezoidal motion configuration, noted with the subscript $\sqcap$ in the following, the distance to cover allows the forklift to reach its nominal speed, v^X and/or v^Z, so that the system accelerates for the first part of the travel time, travels at its constant nominal speed for the second part of the travel time and decelerates for the last part. Adding such parts, for each motion axis, independently, the final expressions are the followings (Eqs. 7.17-7.19).

$$t_{bsr}^{X,\sqcap} = \frac{X_{bsr}}{v^X} + \frac{v^X}{2} \cdot \left(\frac{1}{a^X} + \frac{1}{d^X}\right) \tag{7.17}$$

$$t_l^{Z\uparrow,\sqcap} = \frac{Z_l}{v^Z} + \frac{v^Z}{2} \cdot \left(\frac{1}{a^Z} + \frac{1}{g \cdot (1 + \mu^Z)}\right) \tag{7.18}$$

$$t_l^{Z\downarrow,\sqcap} = \frac{Z_l}{v^Z} + \frac{v^Z}{2} \cdot \left(\frac{1}{g \cdot (1 - \mu^Z)} + \frac{1}{d^Z}\right) \tag{7.19}$$

Proofs of such equations are logically similar to the previous one and they are omitted for brevity.

The boundaries between the triangular and trapezoidal motion configurations are from the possibility to accelerate until the forklift nominal speed. Distance boundaries can be analytically evaluated through Eqs. 7.20-7.22. A hypothesis is made for the curve between Y_r and K_{bs} paths. The motion configuration is not affected by the curve. The forklift continue on the horizontal direction without any variation in its speed or acceleration. Indeed, the curve effect on the travel time model can be considered negligible for the sake of this research.

$$S_{lim}^{X} = \frac{(v^X)^2}{2} \cdot \left(\frac{1}{a^X} + \frac{1}{d^X}\right) \tag{7.20}$$

$$S_{lim}^{Z\uparrow} = \frac{(v^Z)^2}{2} \cdot \left(\frac{1}{a^Z} + \frac{1}{g \cdot (1 + \mu^Z)}\right) \tag{7.21}$$

$$S_{lim}^{Z\downarrow} = \frac{(v^Z)^2}{2} \cdot \left(\frac{1}{g \cdot (1 - \mu^Z)} + \frac{1}{d^Z}\right) \tag{7.22}$$

If X_{bsr} and/or Z_l is lower than the correspondent limit the triangular motion configuration occurs, otherwise the trapezoidal motion configuration has to be considered. Formally (Eqs. 7.23-7.25):

$$t_{bsr}^{X} = \begin{cases} t_{bsr}^{X,\Delta} & \text{if } X_{bsr} \leq S_{lim}^{X} \\ t_{bsr}^{X,\sqcap} & \text{if } X_{bsr} > S_{lim}^{X} \end{cases} \tag{7.23}$$

$$t_l^{Z\uparrow} = \begin{cases} t_l^{Z\uparrow,\Delta} & \text{if } Z_l \leq S_{lim}^{Z\uparrow} \\ t_l^{Z\uparrow,\sqcap} & \text{if } Z_l > S_{lim}^{Z\uparrow} \end{cases} \tag{7.24}$$

$$t_l^{Z\downarrow} = \begin{cases} t_l^{Z\downarrow,\Delta} & \text{if } Z_l \leq S_{lim}^{Z\downarrow} \\ t_l^{Z\downarrow,\sqcap} & \text{if } Z_l > S_{lim}^{Z\downarrow} \end{cases} \tag{7.25}$$

Finally the total travel time to S/R a product to/from the generic storage location defined by the tuple (b, s, l, r) for each unit of throughput and under single-command cycles (2 empty and two loaded travels between the I/O and the storage location), is the following and accurately determined by Eq. 7.26:

$$t_{bslr} = 4\,t_{bsr}^{X} + 2\left(t_l^{Z\uparrow} + t_l^{Z\downarrow}\right) + 4 \cdot t^{fix} \tag{7.26}$$

Eq. 7.26 is a key input of the multi-objective storage assignment strategy presented in the following Paragraph 7.3.

7.2.3 Single command energy consumption model

Despite the travel time models are common results already spread by the literature, the study of the energy requirements within a UL traditional warehouse is an issue of major interest and rarely investigated. The key difference between the time and the energy models is the following. The time model is not mass dependent, while the energy model is mass dependent, i.e. the masses of the ULs transported by the forklift and of the vehicle itself are not relevant to compute the travel time, while they heavily affect the energy requirements.

Furthermore, the energy contributions to compute deal with:

- the energy requirement for accelerating/decelerating the forklift;
- the energy requirement to overcome the friction force acting on the forklift.

The analytic model to compute such energy requirements per unit of moved mass is presented in the following. Given the forklift and considering the horizontal motion axis the amount of energy required per unit of mass to cover the X_{bsr} distance is different in the case of triangular and trapezoidal motion configuration. The analytic expressions are in the following (Eqs. 7.27-7.28).

$$e_{bsr}^{X,\vartriangle} = \frac{1+\eta^m \theta^b}{2\eta^m} \cdot \frac{2 \cdot X_{bsr} \cdot a^X \cdot d^X}{a^X + d^X} + \frac{\mu^X \cdot g \cdot X_{bsr}}{\eta^m} \tag{7.27}$$

$$e_{bsr}^{X,\sqcap} = \frac{1+\eta^m \theta^b}{2\eta^m} \cdot \frac{2 \cdot S_{lim}^X \cdot a^X \cdot d^X}{a^X + d^X} + \frac{\mu^X \cdot g \cdot X_{bsr}}{\eta^m} \tag{7.28}$$

where S_{lim}^X is from Eq. 7.20.

Proof

From dynamics, the energy per unit of mass under a constant acceleration field is the product between the acceleration and the travelled distance. During the forklift acceleration $e_a^X = a \cdot S_a^X = (v^X)^2/2$. Similarly, during deceleration $e_d^X = d \cdot S_d^X = (v^X)^2/2$. However, acceleration and deceleration energy significantly differ. The former is the mechanical energy for wheels rotation determined by the conversion of the electricity stored in the forklift battery through a traction electric motor of efficiency η^m. The latter is dissipated as heat by the friction between wheels and brakes to decelerate the system. Thus, the electricity required for brake activation is just a small portion of this latter, namely θ^b.

In addition, to overcome the friction force on horizontal axis, due to the system weight, the mechanical energy requirement per unit of mass is $e_f^X = \mu^X \cdot g \cdot X_{bsr}$. As previously described, even this energy has to discount the conversion factor η^m from electrical to mechanical energy.

The total energy requirement, for the triangular motion configuration, is by adding the three introduced contributions (Eq. 7.29):

$$e_{bsr}^{X,\triangle} = \frac{e_a^X}{\eta^m} + \theta^b e_d^X + \frac{e_f^X}{\eta^m} = \frac{1 + \eta^m \theta^b}{2\eta^m} (v^X)^2 + \frac{\mu^X \cdot g \cdot X_{bsr}}{\eta^m} \tag{7.29}$$

Furthermore, due to $S_a^X + S_d^X = X_{bsr}$ (Eq. 7.30).

$$\frac{(v^X)^2}{2} \cdot \left(\frac{1}{a^X} + \frac{1}{d^X}\right) = X_{bsr} \tag{7.30}$$

So that (Eq. 7.31).

$$(v^X)^2 = \frac{2 \cdot X_{bsr} \cdot a^X \cdot d^X}{a^X + d^X} \tag{7.31}$$

Substituting Eq. 7.31 in Eq. 7.29, previous Eq. 7.27 follows. For the trapezoidal motion configuration Eq.7.30 becomes the following (Eq. 7.31):

$$\frac{(v^X)^2}{2} \cdot \left(\frac{1}{a^X} + \frac{1}{d^X}\right) = S_{lim}^X \tag{7.31}$$

Excluding the constant speed distance requiring no energy except for the friction force to overcome. Consequently (Eq. 7.32):

$$(v^X)^2 = \frac{2 \cdot S_{lim}^X \cdot a^X \cdot d^X}{a^X + d^X} \tag{7.32}$$

Substituting Eq. 7.32 in Eq. 7.29, previous Eq. 7.28 follows.

■

For the vertical axis of motion, the energy required per unit of mass to cover the Z_l distance is in Eq. 7.33 for ascending trajectories and in Eq. 7.34 for descending trajectories.

$$e_l^{Z\uparrow} = \frac{(1 + \mu^Z) \cdot g \cdot Z_l}{\eta^h} \tag{7.33}$$

$$e_l^{Z\downarrow} = (1 - \mu^Z) \cdot g \cdot Z_l \cdot \theta^h \tag{7.34}$$

Both ascending and descending trajectories are affected by the vertical friction coefficient of the forks during lifting and descending operations. The ascending trajectory is negatively affected by the friction, thus the system has to overcome both this and gravity force to lift a product. On the contrary, descending trajectory is positively affected by friction. The gravity force is decreased by this factor to evaluate the energy for deceleration purpose.
Furthermore two conversion factors are proposed to evaluate the electricity consumption during ascending and descending operations. The former includes the efficiency η^h of the hydraulic pump motor to convert the electricity stored in the vehicle batteries in hydraulic power for the fork hydraulic circuit (Eq. 7.33). The latter represents the electricity required to decelerate the forks during descending motion as a small portion (θ^h) of the mechanical energy determined by Eq. 7.34. Indeed, most of this energy is dissipated, thus it does not have to be provided as electricity.

The distinction between triangular and trapezoidal motion configurations is not relevant in the vertical case. The proof for these equations is logically the same as for the horizontal motion axis and it is omitted for the sake of brevity. For the horizontal axis, the boundary between the triangular and trapezoidal motion configurations is in previous Eq 7.20 so that (Eq. 7.35):

$$e_{bsr}^X = \begin{cases} e_{bsr}^{X,\triangle} & \text{if } X_{bsr} \leq S_{lim}^X \\ e_{bsr}^{X,\sqcap} & \text{if } X_{bsr} > S_{lim}^X \end{cases} \tag{7.35}$$

Finally, given the product p to store in the generic location (b, s, l, r), the global expression for the UL energy requirement, e_{bslr}^p, for each unit of throughput, storage location and under single-command cycles (2 empty and two loaded travels between the I/O and the storage location), is the following (Eq. 7.36):

$$e_{bslr}^p = \frac{2\,(m_p + 2\,m^V + 2\,m^F) \cdot e_{bsr}^X + (m_p + 2\,m^F) \cdot (e_l^{Z\uparrow} + e_l^{Z\downarrow})}{\eta^c} \tag{7.36}$$

This formulation considers the masses transported by the forklift to determine the total electrical energy required for S/R a product. The vertical motion has to consider both the mass of the product to lift (m_p) and of the forks themselves (m^F). Horizontal motion has even to include the mass of the forklift vehicle (m^V) that travels along with the delivered product. Parameter η^c increases the electrical energy required due to recharging cycle efficiency of the forklift batteries. Thus, e_{bslr}^p represents the amount of electricity purchased from the grid for the analysed S/R activity. Eq. 7.36 is a further key input of the multi-objective storage assignment strategy presented in the following Paragraph.

7.3 Multi-objective storage assignment model

The travel time and energy models are integrated in a multi-objective storage assignment strategy for UL traditional warehouses. The overall goal is to define the most effective storage location for each UL to jointly optimize the single-command travel time and the total energy requirement. As introduced in Paragraph 7.1, and according to Eqs. 7.26, 7.36, the travel time minimization does not immediately lead to the energy minimization and vice versa due to the different elements to compute, i.e. the mass dependence, so that effective trade-offs between such two objectives are of interest. In this context, a multi-objective integer linear programming model to face the UL storage assignment is proposed as an effective strategy to tackle the problem. The binary decisional variable is the following:

A_{bslr}^{p} 1 if a UL of the product type p is assigned to the storage location (b, s, l, r) $\forall\, p, b, s, l, r$

The following two objective functions are introduced (Eqs. 7.37-7.38):

$$TT = \sum_{p=1}^{P} f_p \cdot \frac{1}{q_p} \cdot \sum_{r=1}^{R} \sum_{l=1}^{L} \sum_{s=1}^{S} \sum_{b=1}^{B} A_{bslr}^{p} \cdot t_{bslr} \tag{7.37}$$

$$EC = \sum_{p=1}^{P} f_p \cdot \frac{1}{q_p} \cdot \sum_{r=1}^{R} \sum_{l=1}^{L} \sum_{s=1}^{S} \sum_{b=1}^{B} A_{bslr}^{p} \cdot e_{bslr}^{p} \tag{7.38}$$

TT computes the average single-command travel time to store and retrieve the ULs for all products by weighting the average value for each product type p by the correspondent demand frequency f_p considering the number of this product to be stored q_p. The value of t_{bslr} is from Eq. 7.26. Similarly, EC computes the average energy requirement to store and retrieve the ULs for all products by weighting the average value for each product type p by the correspondent demand frequency f_p considering the number of this product to be stored q_p. The value of e_{bslr}^{p} is from Eq. 7.36. The analytic formulation of the MO storage assignment model is in the following (Es. 7.39-7.44).

$$min\{TT, EC\} \tag{7.39}$$

s.t.

$$\sum_{r=1}^{R} \sum_{l=1}^{L} \sum_{s=1}^{S} \sum_{b=1}^{B} A_{bslr}^{p} = q_p \qquad \forall\, p \tag{7.40}$$

$$\sum_{p=1}^{P} A_{bslr}^{p} \leq 1 \qquad \forall\, b, s, l, r \tag{7.41}$$

$$\sum_{p=1}^{P}\sum_{b=1}^{B}\sum_{p=1}^{P} A_{bslr}^{p} \cdot m_p \leq \xi^m A_{bslr}^{p} \leq 1 \qquad \forall\, r, s, l = 2, \dots, L \qquad (7.42)$$

$$\sum_{l=2}^{L}\sum_{b=1}^{B}\sum_{p=1}^{P} \left(\frac{A_{bslr}^{p} \cdot m_p}{2} + \frac{A_{b(s-1)lr}^{p} \cdot m_p}{2} \right) \leq \psi^m \qquad \forall\, r, s = 2, \dots, S \qquad (7.43)$$

$$A_{bslr}^{p} \quad \text{binary} \qquad \forall\, b, s, l, r, p \qquad (7.44)$$

Eq. 7.39 minimises the introduced objective functions. Eq. 7.40 forces to allocate all the q_p ULs for each product type, p. Eq. 7.41 limits to one the load capacity of each storage location. Eq. 7.42 and 7.43 set upper limits to the load capacity of the horizontal and vertical rack structures, respectively. Particularly, in Eq. 7.42 the ground level is not computed because the correspondent ULs are generally placed on the floor, directly. Furthermore, in Eq. 7.43 each abutment is supposed to sustain half of the total weight of the spans located on its left and right. Finally, Eq. 7.44 gives consistence to the binary variables.

The introduced model is general and fits with the most of the traditional warehouses. Nevertheless it can be easily adapted to match further constraints from the operative context, e.g. unavailable locations for certain product types, required empty spaces, different configuration of the racks, etc. The proposed model is a reference benchmark driving the multi-objective storage assignment in UL traditional warehouses. Concerning its complexity, the binary variable number is $P \cdot B \cdot S \cdot L \cdot R$, while the constraints are $P - R + (B+1) \cdot S \cdot L \cdot R$, expect those defining the variable consistency.

Solving a multi-objective linear programming model means defining a set of efficient *non-dominated* points constituting the so-called Pareto frontier. In the following case study, the MO approach proposed by Messac et al. (2003) is adopted to build the Pareto frontier considering the time and energy objective functions, i.e. Eqs. 7.37 and 7.38, together with the constraints in Eqs. 7.40 to 7.44. According to the common practice, among the Pareto points, i.e. the points of the Pareto frontier, the decision makers have to identify, adopting a subjective and informal approach, the solution to select, representing the final trade-off solution for the specific case study under consideration. To support such a phase, this research exploits the empiric rule-of-thumb proposed in Paragraph 4.5 (Eq. 7.45)

$$\min_k G_k, \quad G_k = \frac{TT_k}{TT^*} \cdot \frac{EC_k}{EC^*} \qquad (7.45)$$

where k is the index of the k-*th* solution laying on the Pareto frontier and TT^*, EC^* are the travel time and energy consumption optimal solutions. A full application of the proposed assignment strategy is in the case study, taken from the beverage industry, described in the next Paragraph 7.4.

7.4 Case study

The present case study deals with the redesign of the assignment strategy in a traditional warehouse with multiple I/O distributed on the building front of a leading company operating in the beverage sector production and distribution. Such a company aims at fully revising the UL positions of its different $P = 44$ items to join time and energy efficiency. The average number of ULs to store is equal to 7272, while the existing storage system is of $R = 28$ racks, $L = 5$ levels, $S = 20$ spans and $B = 3$ bays per rack, level and span. The overall storage capacity is of 8400 ULs. The other relevant parameters, according to the introduced notations, are in the following Tables 7.1-7.2. Forklift parameters are obtained from technical datasheets, whereas warehouse data are determined by the existing warehousing system, its layout and equipment in particular.

Table 7.1. Case study parameters.

Forklift		Products		Warehouse	
a^X	0.5 m/s^2	d'	1.2 m	D	1.4 m
a^Z	0.25 m/s^2	f_p	Table 7.2	H	1.5 m
d^X	0.5 m/s^2	m_p	Table 7.2	L^C	3.8 m
d^Z	0.25 m/s^2	q_p	Table 7.2	L^{fix}	5 m
m^V	3080 kg	w'	0.8 m	W	2.9 m
m^F	120 kg			δ	0.1 m
t^{fix}	20 s			ξ^m	2200 kg
v^X	4.4 m/s			ξ^w	0.1 m
v^Z	0.47 m/s			ψ^m	10000 kg
μ^X	0.10			ψ^w	0.1 m
μ^Z	0.10			L^t	93 m
θ^b	0.05				
η^m	0.95				
θ^h	0.05				
η^h	0.95				
η^c	0.40				

Table 7.2. Features of the products to assign

p	m_p	q_p	f_p	p	m_p	q_p	f_p	p	m_p	q_p	f_p
1	18	536	1.418%	16	907	71	1.898%	31	839	265	1.780%
2	382	71	7.503%	17	74	38	1.865%	32	636	64	1.294%
3	649	187	1.463%	18	76	205	1.785%	33	125	205	2.531%
4	330	160	1.096%	19	84	80	4.622%	34	203	40	1.209%
5	708	47	1.209%	20	272	73	1.729%	35	740	714	1.198%
6	507	114	4.153%	21	173	152	1.509%	36	952	445	1.170%
7	45	406	4.096%	22	320	91	1.509%	37	669	47	1.130%
8	571	121	3.633%	23	220	659	1.469%	38	144	168	1.124%
9	354	21	1.085%	24	908	131	8.266%	39	737	54	5.187%
10	290	63	3.390%	25	349	185	1.452%	40	849	10	1.300%
11	80	156	4.916%	26	911	77	1.424%	41	490	747	1.034%
12	525	100	2.311%	27	749	17	1.379%	42	798	98	1.028%
13	598	16	2.237%	28	747	8	1.407%	43	600	87	1.023%
14	714	191	2.226%	29	821	109	3.588%	44	864	128	0.966%
15	680	3	2.034%	30	555	112	1.356%				

Data show a high variability in the product quantities and masses. In some cases very heavy ULs occur, e.g. items 16, 24, 26, 36. Such condition is typical of the beverage industry in which some products have a high incidence in the market mix, e.g. mineral water, and weights are often relevant, e.g. water based products. As discussed in the model description section, mass is not relevant in the time model but it plays a crucial role in the energy model. Consequently, the present case study is relevant to measure the assignment differences between these two strategies in a potentially critic scenario.

7.5. Results and discussion

This Paragraph presents the case study results along with a detailed discussion of the proposed storage assignment strategies. The time and energy models proposed in Paragraph 7.3 (Eq. 7.26 and Eq. 7.36) are exploited to determine the travel time and energy consumption to S/R each UL in every storage location, thus defining the value of parameters t_{blsr} and e^{p}_{bslr}. These parameters are included in the travel time and energy consumption objective functions to determine the optimal storage assignment strategy for each of these objective functions separately. Then, the MO model proposed (Eq.7.39) is used to calculate the Pareto frontier, namely the set of non-dominated solutions. Among these, the original rule-of-thumb presented in Eq.7.45 determines the one that represents the best trade-off for the considered MO problem.

7.5.1. Time and energy model application

To apply the multi-objective assignment strategy based on the model proposed in previous Paragraph 7.3 the preliminary computation of the UL travel time, t_{blsr}, and energy requirement, e^{p}_{bslr}, is necessary. Such parameters come from the models proposed in Paragraph 7.2 and the application of Eqs. 7.26, 7.36, respectively.

In the following, the analytic computation of $t_{3,20,5,28}$ and $e^{36}_{3,20,5,28}$ is exemplified, i.e. the farthest storage location and the heaviest product (worst case). From the input data and Eqs. 7.4-7.7 the travel distances are computed (Eqs. 7.46-7.49)

$$Y_{28} = \frac{\left[6.6 \cdot \left(\left\lceil\frac{28}{2}\right\rceil - 1\right) + 1.4 + \frac{3.8}{2}\right]^2}{93} + \frac{93}{2} - \left[6.6 \cdot \left(\left\lceil\frac{28}{2}\right\rceil - 1\right) + 1.4 + \frac{3.8}{2}\right] = 42.6\ m \tag{7.46}$$

$$K_{3,20} = 5 + (20 - 1) \cdot (2.9 + 0.1) + 3 \cdot (0.1 + 0.8) - \frac{0.8}{2} = 64.3\ m \tag{7.47}$$

$$X_{3,20,28} = 64.3 + 42.6 = 106.9\ m \tag{7.48}$$

$$Z_5 = (5 - 1) \cdot (1.5 + 0.1) = 6.4\ m \tag{7.49}$$

The considered location position requires trapezoidal motion configuration. Eqs. 7.17-7.19 compute the forklift travel time for each motion axis (Eqs. 7.50-7.52):

$$t^{X,\sqcap}_{3,20,28} = \frac{109.6}{4.4} + \frac{4.4}{2} \cdot \left(\frac{1}{0.5} + \frac{1}{0.5}\right) = 33.08\ s \tag{7.50}$$

$$t^{Z\uparrow,\sqcap}_{5} = \frac{6.4}{0.47} + \frac{0.47}{2} \cdot \left(\frac{1}{0.25} + \frac{1}{9.81 \cdot (1 + 0.1)}\right) = 14.58\ s \tag{7.51}$$

$$t^{Z\downarrow,\sqcap}_{5} = \frac{6.4}{0.47} + \frac{0.47}{2} \cdot \left(\frac{1}{0.25} + \frac{1}{9.81 \cdot (1 - 0.1)}\right) = 14.61\ s \tag{7.52}$$

and finally (Eq. 7.53),

$$t_{3,20,5,28} = 4 \cdot 33.08 + 2(14.58 + 14.61) + 4 \cdot 20 = 270.71\ s \tag{7.53}$$

To compute $e^{36}_{3,20,5,28}$ Eqs. 7.28, 7.33, 7.34 are used. From Eq. 7.20 follows that $S^{X}_{lim} =$ 38.72 m so that (Eqs. 7.54-7.56):

$$e^{X,\sqcap}_{3,20,28} = \frac{1 + 0.95 \cdot 0.05}{2 \cdot 0.95} \cdot \frac{2 \cdot 38.72 \cdot 0.5 \cdot 0.5}{0.5 + 0.5} + \frac{0.10 \cdot 9.81 \cdot 38.72}{0.95} = 167.47\ kJ/kg \tag{7.54}$$

$$e^{Z\uparrow}_{5} = \frac{(1 + 0.05) \cdot 9.81 \cdot 6.4}{0.95} = 72.20\ kJ/kg \tag{7.55}$$

$$e_5^{Z\downarrow} = (1 - 0.05) \cdot 9.81 \cdot 6.4 \cdot 0.05 = 2.66\ kJ/kg \tag{7.56}$$

and, consequently, from Eq. 7.36 (Eq. 7.57):

$$e_{3,20,5,28}^{36} = \frac{2\ (952 + 2 \cdot 3080 + 2 \cdot 120) \cdot 167.47 + (952 + 2 \cdot 120) \cdot (72.20 + 2.66)}{0.95} = 2685.26\ kJ \tag{7.57}$$

The high values of both the single-command travel time and energy consumption suggest not to assign items to this location, if possible, or to assign low frequency and low weight ULs. Furthermore, such an example further stresses the relevance of adopting an effective assignment strategy to reduce the travel time and the energy requirement.

7.5.2. Single objective unit-load assignment

The storage assignment strategy introduced in Paragraph 7.3 is applied to the case study by preliminary solving, separately, the time and energy single-objective models, i.e. considering TT and EC objective functions, separately. Each model includes 475'200 binary variables and 14'436 constraints. The model, together with the input data, are coded in AMPL language and processed adopting Gurobi Optimizer© v.5.5 solver. An Intel® CoreTM i7-3770 CPU @ 3.40GHz and 16.0GB RAM workstation is used. The average solving time is, approximately, of 10 seconds per model.

Results are $TT = 171.53$ s for the time model and $EC = 1028.67$ kJ for the energy model. Both models gives high importance to frequently picked products stored in few quantities (namely, high $\frac{f_p}{q_p}$ ratio) because of high occurrences of access to the correspondent storage locations, e.g. products 15, 28, 13, 40. Nevertheless, differences in the load position are experienced due to the different focus of the two objective functions. Basically, the time model neglects the UL masses and focuses on the single-command travel time, only. On the contrary, the energy model includes the UL masses in the assignment process because of the dependence of the energy requirement on such a parameter. Differences between the two objective functions are evident by computing EC given the UL assignment from the time model and by computing TT given the UL assignment from the energy model. The former value is 1159.25 kJ while the latter value is 183.01 s. Energy increase of 12.7% and time increase of 6.7% follow suggesting looking for an effective trade-off between these two scenarios.

7.5.3. Multi-objective unit-load assignment

As introduced, the MO approach proposed by Paragraph 4.5 is adopted to build the Pareto frontier considering the time and energy objective functions in Eqs. 7.37-7.38. 21 points of the Pareto frontier are determined and for each of them both the time and energy functions are calculated. Results are in Table 7.3 and Figure 7.5.

Table 7.3. Pareto points.

Pareto point	*TT* [s]	*EC* [kJ]
1	182.98	1028.68
2	181.89	1029.13
3	180.85	1030.32
4	179.86	1032.20
5	178.94	1034.74
6	178.07	1037.91
7	177.26	1041.70
8	176.50	1046.12
9	175.79	1051.11
10	175.14	1056.70
11	174.54	1062.88
12	173.98	1069.62
13	173.47	1076.87
14	173.02	1084.75
15	172.63	1093.29
16	172.29	1102.52
17	172.01	1112.40
18	171.80	1122.99
19	171.65	1134.31
20	171.56	1146.36
21	171.53	1159.10

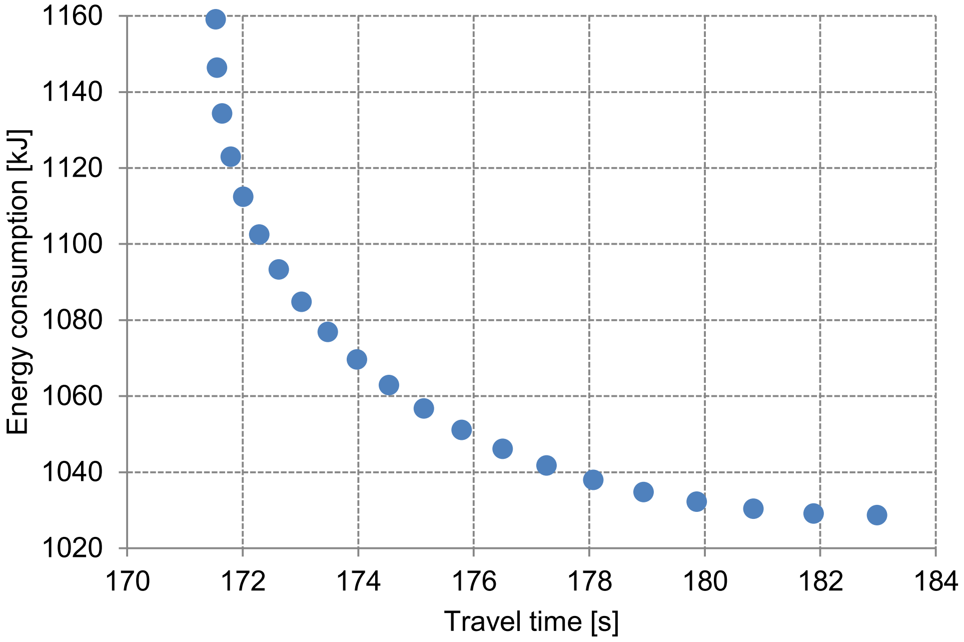


Figure 7.5 Pareto frontier.

The range of variation of TT is of 11.45 s, in $[171.53; 182.98]$ s, while the range of variation of EC is 130.43 J, in $[1028.68; 1159.10]$ kJ so that, for the considered case study, it is possible to reduce the energy requirement without a relevant increasing of the expected single-command travel time.

The choice among the Pareto points, i.e. the definition of the final trade-off between the time and energy perspectives in the UL assignment, aims at best balancing the opposite trends of saving time and saving energy while S/R the ULs from the warehouse. In this context, the practical rule-of-thumb based on Eq. 7.45 is used extending the analysis to the 21 Pareto points.

$$\min_k G_k, \quad G_k = \frac{TT_k}{TT^*} \cdot \frac{EC_k}{EC^*} \tag{7.45}$$

Results are $G = 1.04643$ for $k = 8$, $TT_8 = 176.50$ s and $EC_k = 1046.12$ kJ. Such a trade-off solution is the green spot of Figure 7.6. Globally, by adopting such a UL configuration respect to the standard solution suggested by the literature, based on the travel time minimisation, an energy saving of 9.7% becomes possible with an increase of the single-command travel time of about 2.9%.

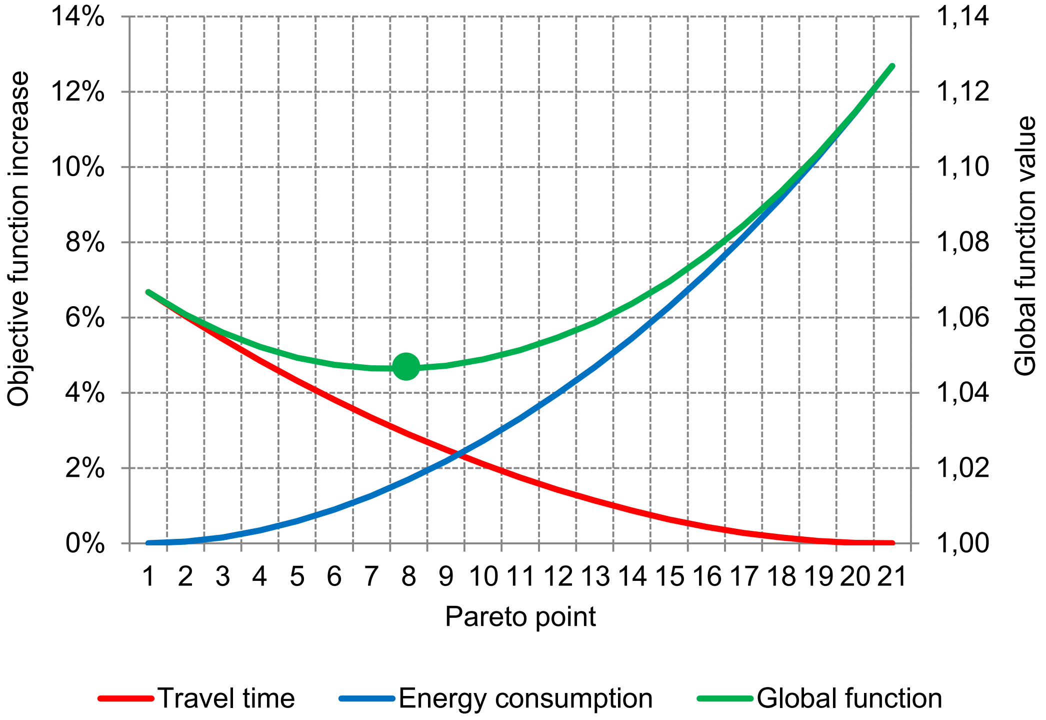


Figure 7.6. Objective function increment and G trends, along with the final trade-off solution (green spot).

The following Figure 7.7 considers the central aisle (rack 14) and compares the storage assignment strategies proposed by time minimization model, the energy minimization model and the final trade-off configuration from multi-objective UL assignment presenting the access ratio ($\frac{f_p}{q_p}$), e.g. the color from red to blue, for each stored product.

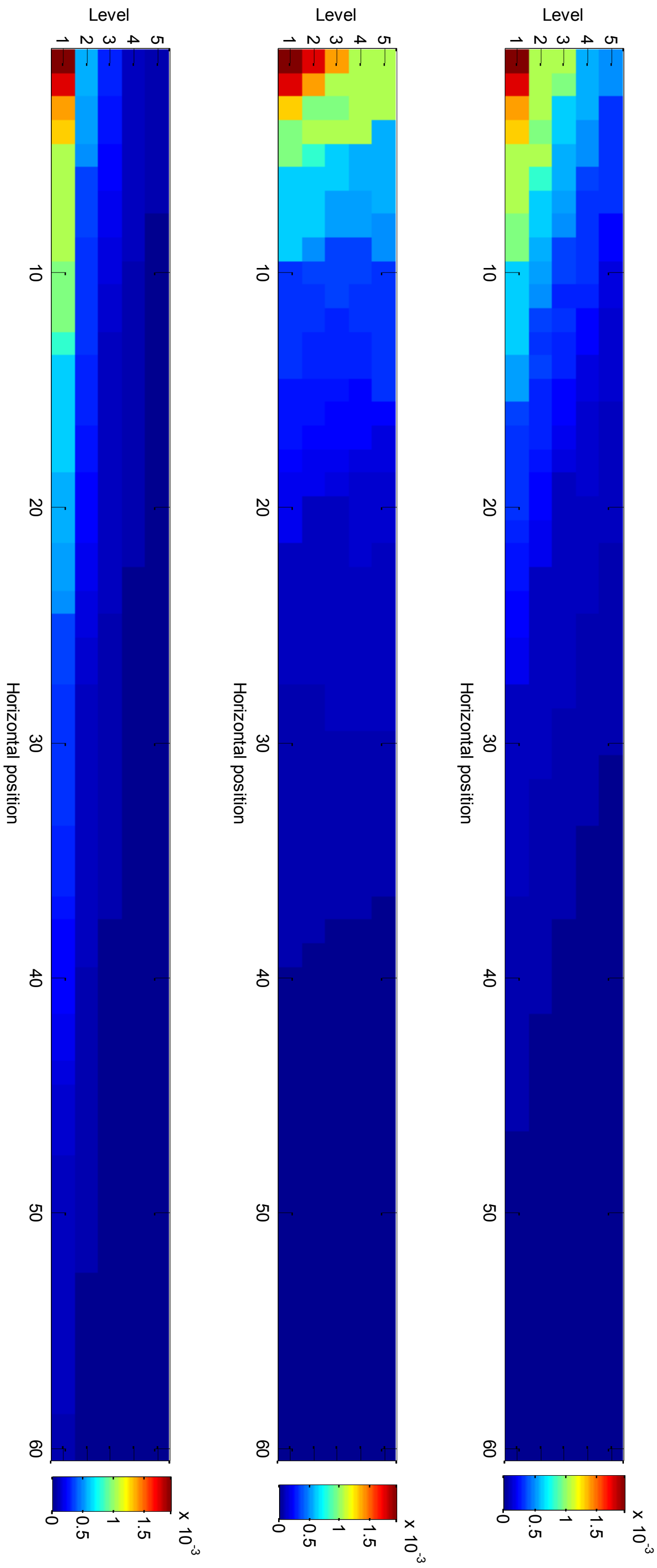


Figure 7.7. Access ratio ($\frac{f_p}{q_p}$) to access the storage areas of central aisle (rack 14) for time minimization assignment strategy (left), energy minimization assignment strategy (middle) and best trade-off configuration (right).

Travel time minimization suggests to store the most picked products (high access ratio, ↑ $\frac{f_p}{q_p}$) at level 1 (on the floor) even far from the aisle entrance, i.e. far from the I/O positions. On the contrary, energy optimization prefers small horizontal distance (i.e. close to the aisle entrance or I/O positions) and even high levels for the most picked products. This pattern is determined by composition of the energy consumption objective function. Thus, the kg to handle vertically are less than the one to handle horizontally for every product type. For a unit of throughput (4 travels from I/O to storage location or vice versa) of the heaviest product (952 kg), the UL is transported for 2 times (the loaded one) whereas the forklift travels for all the 4 times along with all its 3080 kg.

Last, as presented by Figure 7.7, final storage assignment strategy is a trade-off the previous two trends. To conclude, the evidences coming from the case study support the logic behind the proposed time and energy based assignment strategy, suggesting the adoption of the trade-off configuration as an effective alternative to the commonly adopted UL assignment based on the single-command travel time minimisation, only.

7.6 Conclusions and further research opportunities

The growing concern on environmental sustainability and energy saving within the company activities increases the interest in developing effective strategies to design and manage the logistic systems joining high productivity standards to lower resource consumption. Warehousing is among the logistic activities most requiring efficiency because it does not directly add value to the final products and losses negatively affect the whole production process, increasing the system costs.

From the time saving point of view, the past and the recent literature widely investigate, both qualitatively and quantitatively, techniques and methods to increase the performances of warehouse material handling systems. Lower attention is paid on the analysis and modelling of the energy need and even less attention is paid on defining strategies to reduce such an energy requirement.

Together with the adopted handling system, the storage assignment strategy plays a crucial role in obtaining high handling performances and reducing the overall energy consumption. The position of each unit-load (UL), within the storage system, is directly responsible of the material handling vehicle travel time and of its energy consumption. Nevertheless, while the travel time depends on the distance between the points to connect, the energy consumption further depends on the UL features and from its mass, particularly.

Time and energy savings within the handling activities and UL assignment may diverge so that multi-objective strategies are of interest to find effective trade-off configurations.

This Chapter presents a time and energy based assignment strategy for single-deep rack traditional warehouses served by forklifts to carry the ULs from the I/O points to the warehouse storage location. The analytic expressions to compute the average single-command travel time and energy to S/R the ULs are integrated into a multi-objective linear programming model, best assigning the loads to the bays. The strategy leads to build the so-called Pareto frontier including the set of the most effective assignment configurations. Among them, the proposed practical rule-of-thumb selects an effective final trade-off solution. The whole strategy is applied to a case study dealing with the traditional warehouse redesign of a beverage company. Results demonstrate to possibility to decrease the energy requirement of about 9.7% with an average single-command travel time increase of about 2.9%, only.

Further research opportunities on this topic deal with the refinement of the proposed model through the inclusion of dual command cycles and different material handling vehicles, e.g. automated storage/retrieval systems. In addition, a deep investigation of the system dynamic performances is strongly encouraged. The conversion factor as well as the efficiency parameters should be considered as functions of the operating conditions, e.g. the efficiency of the hydraulic pump motor as a function of the lifted product weight. Finally, further applications to the storage systems of companies belonging to different market sectors are strongly encouraged.

7.7. Notations

Indices

b	index for bays per rack, level and span, $b = 1, \dots, B$
k	indices for points of the Pareto frontier, $i, j = 1, \dots, NP$
l	index for levels per rack, $l = 1, \dots, L$
p	index for product type to store, $p = 1, \dots, P$
r	index for racks, $r = 1, \dots, R$
s	index for spans per rack, $s = 1, \dots, S$

Forklift parameters

a^X	horizontal acceleration [m/s^2]
a^Z	vertical acceleration for ascending trajectories [m/s^2]
d^X	horizontal deceleration [m/s^2]
d^Z	vertical deceleration for descending trajectories [m/s^2]
$e_{bsr}^{X,\triangle}$	horizontal triangular energy need to move between the I/O position and bay b of span s of rack r [J/kg]
$e_{bsr}^{X,\sqcap}$	horizontal trapezoidal energy need to move between the I/O position and bay b of span s of rack r [J/kg]
e_{bsr}^{X}	horizontal energy need to move between the I/O position and bay b of span s of rack r [J/kg]
e_{bslr}^{p}	single-command energy need for bay b, span s, level l, rack r and product p [J]
$e_{l}^{Z\uparrow}$	vertical ascending energy need to move between the I/O position and level l [J/kg]
$e_{l}^{Z\downarrow}$	vertical descending energy need to move between the I/O position and level l [J/kg]
K_{bs}	horizontal distance between the beginning of rack r and bay b of span s the same rack [m]
m^V	mass of the forklift vehicle [kg]
m^F	mass of the forklift forks [kg]
S_{lim}^{X}	horizontal boundary between triangular and trapezoidal motion configurations [m]
$S_{lim}^{Z\uparrow}$	vertical ascending boundary between triangular and trapezoidal motion configurations [m]
$S_{lim}^{Z\downarrow}$	vertical descending boundary between triangular and trapezoidal motion configurations [m]
t^{fix}	forklift load/unload fix time [s]
$t_{bsr}^{X,\triangle}$	horizontal triangular time to move between the I/O position and bay b of span s of rack r [s]
$t_{bsr}^{X,\sqcap}$	horizontal trapezoidal time to move between the I/O position and bay b of span s of rack r [s]
t_{bsr}^{X}	horizontal time to move between the I/O position and bay b of span s of rack r [s]
t_{bslr}	single-command travel time for bay b, span s, level l and rack r [s]
$t_{l}^{Z\uparrow,\triangle}$	vertical triangular ascending time to move between the I/O position and level l [s]
$t_{l}^{Z\downarrow,\triangle}$	vertical triangular descending time to move between the I/O position and level l [s]
$t_{l}^{Z\uparrow,\sqcap}$	vertical trapezoidal ascending time to move between the I/O position and level l [s]
$t_{l}^{Z\downarrow,\sqcap}$	vertical trapezoidal descending time to move between the I/O position and level l [s]

$t_l^{Z\uparrow}$	vertical ascending time to move between the I/O position and level l [s]
$t_l^{Z\downarrow}$	vertical descending time to move between the I/O position and level l [s]
v^X	forklift horizontal nominal speed [m/s]
v^Z	forklift vertical nominal speed [m/s]
X_{bsr}	horizontal distance between the I/O position and bay b of span s of rack r [m]
Y_r	horizontal distance between the I/O position and the rack r [m]
Z_l	vertical distance between the I/O position and level l [m]
θ^b	forklift brake activation coefficient
θ^h	fork deceleration coefficient
η^c	battery charging cycle coefficient
η^h	hydraulic pump motor efficiency
η^m	forklift traction electric motor of efficiency
μ^X	forklift horizontal friction coefficient
μ^Z	fork vertical friction coefficient

Product parameters

d'	UL depth, typically standard pallet [m]
f_p	demand frequency of product type p [%]
m_p	mass of product type p [kg]
q_p	number of loads of product type p to store [load]
w'	UL width, typically standard pallet [m]

Warehouse parameters

D	bay and rack depth [m]
H	bay height [m]
L^C	aisle width [m]
L^t	warehouse total length [m]
W	bay width [m]
δ	lateral gap between adjacent ULs [m]
ξ^m	beam weight capacity [kg]
ξ^w	beam width [m]
ψ^m	abutment weight capacity [kg]
ψ^w	abutment width [m]

Model variable and objective functions

A_{bslr}^{p}	1 if a UL of the product type p is assigned to bay b of span s, level l and rack r, 0 otherwise [binary]
TT	average single-command travel time to S/R the ULs [s]
EC	average single-command energy need to S/R the ULs [J]
G	trade-off function

8. Conclusions

Logistic purpose is the development of design criteria and management strategies for material handling and information sharing along the supply chain through proper systems. Traditional models and methods for logistic system design and management focus on the optimization of the techno-economic performances. However, logistic activities are distinguished by a huge environmental impact. For instance, the final energy consumption for freight transportation reached the alarming value of 13% of the total end-use energy worldwide, equal to 40 EJ per year (IEA, 2012). Innovative approaches for logistic system design should ensure their overall sustainability jointly optimizing the technical, economic and environmental performances.

Aim of this Ph.D. thesis is to develop and propose multi-objective models and methods for design and management of sustainable logistic systems.

This dissertation firstly analyzes the traditional design criteria and management strategies proposed by the literature and adopted by the practitioners for logistic system planning (Chapter 2). Among the most relevant logistic systems, distribution networks and warehouses are of major interest. The material flow from suppliers to assembly or manufacturing areas and from these to the final customers is fully managed by these two systems. The most relevant distribution network features are described along with the configurations typically adopted. Considering warehousing systems, the problems concerning their design and operation are analyzed. Warehouse design is the process of interrelated decisions that defines the long term structure of the warehousing system, whereas warehouse operation techniques are described as the one that define the short term system management to enable the product flow across the warehouse.

To overcome the commonly adopted design criteria for logistic systems based on the maximization of technical performances and economic profitability, only, the concept of sustainability and its application to the industrial context are proposed (Chapter 3). An overview on sustainability is presented, from its former definition in the 1987 Brundtland report to its latter contained in the United Nations 2015 Sustainable Development Goals. Considering the industrial context, the three pillars of sustainability are presented along with quantitative models and method for their evaluation. Economic profitability is estimated through the net present value approach and similar techniques, environmental impact is evaluated through the standardized carbon footprint and life cycle assessment, whereas social wealth is assessed to determine how the considered system impacts on the society.

This Ph.D. thesis proposes multi-objective optimization as a mathematical programming technique to support design criteria and management strategies for sustainable logistic systems (Chapter 4). Distinctive feature of this technique is the systematically and simultaneously optimization of a collection of objective functions, often conflicting among them. An overview of the multi-objective optimization concept is presented along with its formulation, characteristics and the different methods to solve such problem. Furthermore, a novel criterion is proposed to select the final trade-off solution for multi-objective problems.

Within this framework, an original decision support system is developed to minimize the operating cost, carbon footprint and delivery time in the design of multi-modal multi-level distribution networks (Chapter 5). The multi-objective optimization model proposed allows multiple transport modes and inter-modality options looking to the most effective distribution network configuration from the introduced multi-objective perspective considering the most relevant features of the delivered products. The model is validated against a case study about the delivery of Italian fresh food to several European retailers. The results show that a multi-objective perspective is of strong help. It enables to decrease the greenhouse gas emissions with a limited cost increase and admissible delivery time, i.e. with no produce waste. For the final chosen solution, the carbon footprint reduction is equal to 9.6% and the operating cost increase is 2.7% compared to the traditional distribution network configuration based on cost minimization, only. Considering warehousing systems, both design and operation problems are tackled. A multi-objective optimization model is developed to determine the warehouse building configuration, namely length, width and height, which simultaneously minimizes the travel time, total cost and carbon footprint objective functions (Chapter 6). Travel time is defined as the average time to pick up or drop off a stock keeping unit from or to the warehousing system. Total cost and carbon footprint are estimated exploiting a life-cycle approach. All the activities related to warehouse building installation and operating phases are evaluated from an economic and an environmental perspective. Finally, a case study of a warehouse to be built for an Italian beverage company is presented to validate the proposed model. Compared to traditional single-objective optimization approaches, the proposed model enables to define a trade-off warehouse building configuration distinguished by identical economic performances, limited travel time increase (4.1%) but terrific environmental impact reduction (40.2% of CO_2 emissions avoided). Warehousing system operation is analyzed by mean of storage assignment strategy (Chapter 7). Conventional approaches are enhanced proposing a time and energy based strategy, for traditional warehouses served by forklifts, based on the joint minimization of the travel time and the energy required by the material handling vehicles to store and retrieve the unit-loads. The models to accurately compute the expected single-command travel time and energy are integrated into a multi-objective model, optimizing the load assignment to storage locations considering the product distinctive features, as weight. An application, taken from the beverage industry, is finally discussed. The different perspectives of adopting time and energy to drive the load assignment are stressed exploiting a practical best trade-off rule that enables to decrease the energy requirement of about 9.7% with an average single-command travel time increase of 2.9%, only.

8.1. Future developments

A set of future developments is strongly encouraged staring from the proposed research framework along with the presented models and methods developed.

The proposed multi-objective optimization models and methods should be exploited to develop innovative design criteria and management strategies to ensure the sustainability of other logistic areas, as inventory management and material handling.

Considering the logistic systems analyzed in this Ph.D. thesis, distribution network planning could benefit from the inclusion of the reverse loop flows, from the end-users to the collectors and recyclers, to convey to the frequently discussed close-loop supply chain network. This distribution network structure is proposed by the literature on green supply chain management, following a cradle-to-cradle paradigm, while lower attention is paid on optimizing such a network from a multi-objective perspective. Furthermore, the inclusion both in the optimization model and in the decision support system of the temporal dynamics, typical of the operational management, is a further possible extension for distribution network planning.

The models developed both for warehouse building design and storage assignment strategy should be revised for automatic warehouses. Automated storage/retrieval systems (AS/RSs) are usually equipped with one crane per aisle. Thus, typical building for AS/RSs are distinguished by few, long and high aisles. Furthermore, AS/RSs allow simultaneous movements on the horizontal and vertical motion axes. The travel time to store/retrieve a product to/from a storage location have to be modified according to the Chebyshev distance concept. The required time to store/retrieve a load is the maximum time to travel the vertical and horizontal distances. In addition, a deep investigation of dynamic performances of the material handling vehicles is strongly encouraged. The motion efficiency parameters should be considered as functions of the vehicle operating conditions.

Furthermore, this manuscript strongly encourages additional tests and validations of the proposed multi-objective models and methods using other representative case studies belonging to market sectors different to the food and beverage industry.

Finally, a breakthrough contribution to this field of research would be the inclusion of the social dimension of sustainability in logistic system design criteria and management strategies. An additional objective function for the proposed multi-objective optimization models should quantitatively and accurately evaluate the impact that a certain logistic system configuration has, for instance, on the ergonomic aspect or occupational safety of the working conditions.

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