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RESPONSIBLE INVENTORY MODELS FOR OPERATION AND LOGISTICS MANAGEMENT

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RESPONSIBLE INVENTORY MODELS FOR OPERATION AND LOGISTICS MANAGEMENT

By

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INTRODUZIONE

L'industrializzazione ed il conseguente sviluppo economico avvenuti nello scorso secolo hanno spinto le società industrializzate a perseguire obiettivi economico-finanziari sempre più alti, mettendo momentaneamente in secondo piano la tutela per l'ambiente e per la salute umana. Tuttavia, nel corso dell'ultimo decennio le moderne società hanno cominciato a riconsiderare l'importanza degli aspetti sociali ed ambientali contestualmente agli obiettivi economici. Nel mondo industriale, così come nell'attività di ricerca scientifica odierna, sono stati introdotti nuovi concetti quali lo sviluppo sostenibile, la green supply chain e l'ergonomia dei posti di lavoro. La nozione di "triple bottom line" (3BL) è divenuta sempre più importante nella gestione industriale negli ultimi anni (Norman and MacDonald, 2004). L'idea che sta alla base del concetto di 3BL è che il successo finale di una azienda non dovrebbe essere misurato solo in termini di risultati finanziari, ma anche dai risultati in ambito etico ed ambientale. I concetti di responsabilità sociale ed ambientale sono oggi essenziali poiché una società forte e sana non si può realizzare e mantenere se i singoli individui che la compongono non godono di ottima salute. L'interesse crescente verso lo sviluppo sostenibile spinge il mondo industriale e della ricerca scientifica a trattare i problemi di operations management con un approccio integrato, in modo da inglobare in un'unica procedura obiettivi economici, ambientali e sociali (Bouchery et al., 2012).

Vista la vastità degli aspetti contemplati dal settore, in questa tesi di dottorato si affronterà solo una parte ristretta dei molteplici aspetti in gioco, quelli della gestione delle scorte di magazzino e più in dettaglio della determinazione del lotto economico. Si tratta senza dubbio di uno dei problemi più tradizionali in ambito di operations management, tanto che il primo problema di lot sizing è stato affrontato più di un secolo fa (Harris, 1913).

Questo lavoro di tesi si pone i seguenti obiettivi principali:

1) Lo studio e l'analisi dettagliata della letteratura riguardante i problemi di Inventory Management e Lot Sizing a supporto della gestione delle attività produttive e logistiche. In particolare dopo aver analizzato i diversi fattori e approcci decisionali alla base dei modelli esistenti in letteratura, lo sviluppo di un innovativo framework concettuale identifica i sotto-problemi associati, le variabili decisionali e i principali aspetti che influenzano la sostenibilità nelle decisioni logistiche, aiutando a delineare i requisiti delle ricerche future.

2) L'elaborazione di nuovi modelli di calcolo a supporto dell'Inventory Management e del Lot Sizing sostenibile. A questo scopo è stata sviluppata una nuova procedura metodologica, elaborando un'applicazione matematica completa del metodo di Lot Sizing Sostenibile. Tale metodo è stato opportunamente validato con dati provenienti da casi reali.

3) La comprensione e l'applicazione delle tecniche di ottimizzazione multi-obiettivo al fine di analizzare l'impatto economico, ambientale e sociale nelle scelte di approvvigionamento, trasporto e gestione dei materiali in ingresso ad un sistema produttivo.

4) L’analisi della fattibilità e convenienza di sistemi governativi di incentivazione per promuovere la riduzione delle emissioni ambientali dovute alle attività di approvvigionamento e stoccaggio dei materiali di acquisto. Sfruttando i modelli sviluppati e conducendo una analisi di sensitività, è stato sviluppato un metodo basato sulla teoria multi-obiettivo per quantificare l’effetto di incentivi per la riduzione delle emissioni in relazione ai parametri in ingresso del problema.

5) L’estensione del metodo sviluppato per il caso di approvvigionamento tradizionale “Single-Buyer”, in ottica “multi-buyer” introducendo la possibilità di Cooperazione Orizzontale e Haulage Sharing da parte di aziende diverse nelle fasi di acquisto e trasporto di materia prima e componenti su scala globale.

Questo lavoro di ricerca è stato supportato da una proficua collaborazione con il Prof. Robert W. Grubbström (University of Linkoping, Svezia), e fin dall’inizio si è posto l’obiettivo di apportare un’innovazione sia nella base teorica riguardante il Lot Sizing sostenibile, sia nella conseguente applicazione pratica in contesti industriali a noi contemporanei.

ABSTRACT

The industrialization and the subsequent economic development occurred in the last century have led industrialized societies to pursue increasingly higher economic and financial goals, laying temporarily aside the safeguard of the environment and the defense of human health. However, over the last decade, modern societies have begun to reconsider the importance of social and environmental issues nearby the economic and financial goals. In the real industrial environment as well as in today research activities, new concepts have been introduced, such as sustainable development (SD), green supply chain and ergonomics of the workplace. The notion of “triple bottom line” (3BL) accounting has become increasingly important in industrial management over the last few years (Norman and MacDonald, 2004). The main idea behind the 3BL paradigm is that companies’ ultimate success should not be measured only by the traditional financial results, but also by their ethical and environmental performances. Social and environmental responsibility is essential because a healthy society cannot be achieved and maintained if the population is in poor health. The increasing interest in sustainable development spurs companies and researchers to treat operations management and logistics decisions as a whole by integrating economic, environmental, and social goals (Bouchery et al., 2012).

Because of the wideness of the field under consideration, this Ph.D. thesis focuses on a restricted selection of topics, that is Inventory Management and in particular the Lot Sizing problem. The lot sizing problem is undoubtedly one of the most traditional operations management interests, so much so that the first research about lot sizing has been faced more than one century ago (Harris, 1913).

The main objectives of this thesis are listed below:

1) The study and the detailed analysis of the existing literature concerning Inventory Management and Lot Sizing, supporting the management of production and logistics activities. In particular, this thesis aims to highlight the different factors and decision-making approaches behind the existing models in the literature. Moreover, it develops a conceptual framework identifying the associated sub-problems, the decision variables and the sources of sustainable achievement in the logistics decisions. The last part of the literature analysis outlines the requirements for future researches.

2) The development of new computational models supporting the Inventory Management and Sustainable Lot Sizing. As a result, an integrated methodological procedure has been developed by making a complete mathematical modeling of the Sustainable Lot Sizing problem. Such a method has been properly validated with data derived from real cases.

3) Understanding and applying the multi-objective optimization techniques, in order to analyze the economic, environmental and social impacts derived from choices concerning the supply, transport and management of incoming materials to a production system.

4) The analysis of the feasibility and convenience of governmental systems of incentives to promote the reduction of emissions owing to the procurement and storage of purchasing materials. A new method based on the multi-objective theory

is presented by applying the models developed and by conducting a sensitivity analysis. This method is able to quantify the effectiveness of carbon reduction incentives on varying the input parameters of the problem.

5) Extending the method developed in the first part of the research for the “Single-buyer” case in a "multi-buyer" optics, by introducing the possibility of Horizontal Cooperation. A kind of cooperation among companies in different stages of the purchasing and transportation of raw materials and components on a global scale is the Haulage Sharing approach which is here taken into consideration in depth.

This research was supported by a fruitful collaboration with Prof. Robert W. Grubbström (University of Linkoping, Sweden) and its aim has been from the beginning to make a breakthrough both in the theoretical basis concerning sustainable Lot Sizing, and in the subsequent practical application in today industrial contexts.

ACKNOWLEDGEMENTS

First of all I would like to express sincere gratitude to the whole research group of Logistics and Industrial plants of the University of Padua. In particular, my acknowledgements go to my supervisor Prof. Daria Battini for supporting and guiding my research activities along these 3 years, and to Dr. Fabio Sgarbossa for his unceasing assistance in the technical aspects of the research. Moreover, I mainly would like to thank Prof. Alessandro Persona who has always been the greatest example of expertise and humanity, for his strong encouragement and for the precious advice. Thank you all for having put your trust in me and in my capacities.

All my appreciation goes to my colleagues and friends Umberto, Martina, Ilenia and Giorgia. Thanks for your collaboration and friendship, especially for having taught me the power of the word "teamwork". I'll never forget the time we spent together, the hard work, the summer schools and the gala dinners. Heartfelt thanks to Umberto, the best fellow I might have had, with the certainty that left and right sides of the football field will be desert without us. Thank you all for the unforgettable memories. Working hours will be longer without you.

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Vicenza (Italy)
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1 INTRODUCTION

1.1 Purpose of the thesis

Nowadays, modern societies are looking at the importance of social and environmental sustainability in their daily activities, alongside the traditional financial objectives. Such a growing awareness is defined Corporate Social Responsibility (CSR), or Sustainable Responsible Business (Wood,1991). Even if the most important contribution about CSR dates back to the 80's (Freeman, 1984), the first remarks about social responsibility have been formulated in 1928, when the "Pioneer fund" of Boston stressed the need to realize more ethic-oriented investments. Anyway, CSR is a very actual and debated concept both in the research field (Eilbirt and Parket 1973, McWilliams and Siegel 2001, Porter and Kramer 2006) and in the international regulatory institutions. European commission in the communication n.681 of 2011, defined Corporate Social Responsibility as *"The responsibility of enterprises for their impacts on society"*. CSR is a form of corporate self-regulation integrated into a business model, that acts as a self-regulatory mechanism whereby a business monitors and ensures its active compliance with the spirit of the law, ethical standards and international norms. In some models, a firm's implementation of CSR goes beyond compliance and engages in *"actions that appear to further some social good, beyond the interests of the firm and that which is required by law"* (McWilliams and Siegel 2001). The role of researchers in this scenario is to provide innovative tools supporting companies to reduce their social and environmental impact without renouncing to be profitable. In the last four years, research on inventory management and lot sizing has been considerably enriched of works regarding the study of quantitative methods for the assessment of the environmental impact of logistics decisions, in particular transportation, storage and deterioration of goods. On the other hand, only few works have considered the social impact using a quantitative method, therefore the aim of this research is to overcome this lack. In the light of these considerations, the main goal of this Ph.D. thesis is to develop an integrated framework which is capable of providing an easy-to-use approach supporting companies and practitioners to face the daily lot sizing decisions, taking into account both the social and the environmental aspects with a quantitative method. The framework and the analytical models developed during the whole Ph.D. course, already material for publications in different international journals and conferences, will be described extensively in this work.

1.2 Thesis structure

The present Ph.D. thesis has been structured in the following parts, according to the main aims of the research:

- **Chapter 2:** in this chapter, the introduction of the Economic Order Quantity (EOQ) problem and the state of the art of scientific contribution in this field are discussed. First, the basic Lot Sizing model developed in 1913 by Harris is presented and discussed; then the evolution of the trends in this research field is examined through a thorough literature analysis. The main research directions concerning the Lot Sizing problem are identified and discussed providing a classification framework that tries to capture the whole research area studied along the entire century. At the end of this chapter, new interesting future research topics in the lot sizing field are identified and discussed. In particular, the focus is on environmental sustainability considerations related to transportation problem that are finding growing interests in the literature in the last year.

- **Chapter 3:** this chapter develops an innovative methodological framework that is capable to consider environmental and social aspects connected with the lot sizing decision. This approach provides an easy-to-use method to couple the total cost functions with emission consequences due to transportation and storage of items, and social aspects linked with material purchasing and handling. These three different objective are put together using a multi-objective approach, that conjugates different goals without mixing them in a unique objective function.

- **Chapter 4:** In this chapter the social impact of different inventory management decisions is addressed in terms of Ergonomics of the Manual Material Handling tasks with a quantitative approach, along with the traditional financial aspects. The most influential decision variable in the In-House Logistics is the size of the Stock Keeping Units (and therefore its weight) constituting the purchased lot, since it influences the cost and the safety of the MMH tasks. Following the framework presented in Chapter 3, the Lot-sizing decisions concerning the “In-House” problem are here analyzed and modeled using a bi-objective method.

- **Chapter 5:** In this chapter the environmental aspects concerning the “In-bound” problem of lot sizing issue are analyzed and discussed with a critical approach. A typical global supply chain purchasing problem is modeled, in which total purchasing costs and total greenhouse gas emissions are taken into account. Then, such a model is extended to different scenarios characterized by different values of four product features (weight, product density, obsolescence risk, purchase price), while a set of input data are kept fixed (the annual demand, cost and emission parameters, the travelling distances and the mix of transportation modes used). The parametric analysis thus developed permits us to analyze the different shapes of the Pareto efficient frontiers according to variations in these key parameters and to evaluate the effect in providing “carbon reduction incentives” to companies in order to stimulate the reduction of emissions in purchasing strategies.

- **Chapter 6:** In this chapter the traditional “non-cooperative” approach and an innovative horizontal collaboration, the so called “haulage sharing” method, are put in comparison. Nowadays, cooperative transportation modalities are recognized to be highly beneficial in reducing the environmental impact of material purchasing and transportation. In order to prove this statement, the EOQ framework here developed is adapted to a “multi-buyer” purchasing problem in which cost and emission functions are jointly investigated. A new three step procedure is thus presented aiming to provide managers and logisticians with the necessary tools to take a better and faster decision. The procedure is then applied to two different numerical cases and the outcomes are extensively discussed.

- **Chapter 7:** This chapter reports the conclusions of the researches carried out in this thesis and outlines some possible future research steps.

- **Chapter** 8: In this chapter all the references are listed divided by chapter in which they are mentioned.

1.3 Personal research publications

In this section the references to the articles published and submitted during the Ph.D. course are briefly listed.

PAPERS PUBLISHED ON INTERNATIONAL JOURNAL

- Andriolo A., Battini D., Persona A., Sgarbossa F., “Haulage Sharing approach to achieve sustainability in material purchasing: a new method and numerical applications”, Accepted for publication on December, the 6th, 2014 in the International Journal of Production Economics (IJPE), Special Issue “Carbon-Efficient PSC&L”.

- Andriolo A., Battini D., Grubbstrom R.W., Persona A., Sgarbossa F., “A century of evolution from Harris′s basic lot size model: Survey and research agenda”, International Journal of Production Economics (IJPE), 155, September 2014, 16-38. Special Issue “Celebrating a century of the economic order quantity model”.

PAPERS UNDER JOURNAL REVIEW

- Andriolo A., Battini D., Persona A., Sgarbossa F., “A new approach for including ergonomic principles into EOQ model", Submitted on September 22th, 2014 to International Journal of Production Research (IJPR).

- Andriolo A., Battini D., Persona A., Sgarbossa F., “Multi-objective lot-sizing model and monetary incentive computation in a global purchasing scenario”, submitted on April 15th , 2014 to: International Journal of Production Economics, Special Issue of the International Working Seminar on Production Economics, Innsbruck 2014.

PAPERS ON INTERNATIONAL CONFERENCE

- Andriolo A., Battini D., Persona A., Sgarbossa F., “Parametric analysis of a sustainable lot-sizing model in a global supply chain scenario”, in: PROCEEDING International Working Seminar on Production Economics, Innsbruck, February 24-28, 2014.

- Andriolo A., Battini D., Persona A., Sgarbossa F., “Ergonomoc Lot Sizing: a new integrated procedure towards a sustainable inventory management" in: PROCEEDING 22th ICPR International Conference of Production Research “Challenges for Sustainable Operations” (Iguassu Falls, Brazil) - July 28th - August 1st 2013.

- Andriolo A., Battini D., Gamberi M., Persona A., Sgarbossa F., "1913-2013: The EOQ theory and next steps towards sustainability" in: PROCEEDING IFAC MIM "Conference of Manufacturing Modelling, Management and Control" (Saint Petersburg, Russia) - June 19-21 2013.

PAPERS ON NATIONAL CONFERENCE

- Andriolo A., Battini D., Persona A., Sgarbossa F., “Sustainable lot-sizing: an innovative approach to incorporate the 3BL paradigm into inventory management”. In: PROCEEDING XIX Summer School “Francesco Turco” Impianti Industriali Meccanici (Senigallia, Italy) - September 9-12 2014.

- Andriolo A., Battini D., Persona A., Sgarbossa F., “1913-2013: The EOQ theory and a future research agenda”. In: PROCEEDING XVII Summer School “Francesco Turco” Impianti Industriali Meccanici (Venice, Italy) - September 12-14 2012.

2 STATE OF THE ART ANALYSIS

2.1 Preface to the state of the art

The economic order quantity (EOQ) model is undoubtedly one of the oldest models in the inventory analysis literature. The first who tackled the problem of determining the economic lot size in production systems was Ford Whitman Harris, born on August 8, 1877, and who passed away on October 27, 1962. In February 1913 at the age of 35, he proposed his formulation of this problem under the assumption of a continuous constant rate for demand and his recognition of the need to balance intangible inventory costs against tangible costs for ordering. Harris's solution has become the well-known "Square root formula". Even though its wide circulation, Harris's original paper was apparently unnoticed before its rediscovery in 1988 (Erlenkotter, 1989, 1990). In the first decades of the last century a large number of researchers formulated their own models, so that nowadays Harris's formula is also known as the "Wilson lot size formula" (Wilson 1934) or "Camp's formula" (Camp 1922), or the "Barabas formula". Erlenkotter (1989, 1990) provides an interesting historical account of the formula's early life including a biography of F.W. Harris. The second major contribution focusing on this problem was authored by Taft (1918), who incorporated a finite production rate and developed the classical Economic Production Quantity (EPQ) model, the first in a long sequence of generalizations to come. As reported by Best (1930) an EOQ formula was used at Eli Lilly and Company from 1917 onwards. The EPQ/EOQ inventory control models are still widely accepted by many industries today for their simplicity and effectiveness. However, these simple models have several weaknesses. The obvious one is the number of simplifying assumptions. In these traditional inventory models in fact the sole objective is to minimize the total inventory-related costs, typically holding cost and ordering cost. For this reason many researchers studied the EOQ extensively under real-life situations and provided mathematical models that more closely conform to actual inventories and respond to the factors that contribute to inventory costs. The result was a very vast literature on inventory and production models generalizing the economic order quantity model in numerous directions, a major example being the famous *dynamic lot sizing* algorithm devised by Harvey M. Wagner and Thomson M. Whitin (1958) for solving the problem, in the case when requirements may vary between different discrete points in time, and this formulation has gained many followers. The large number and broad range of papers using the EOQ inventory model have also raised important concerns about the state of the lot sizing literature stream. It is unclear what this large stream of papers has collectively accomplished. Now, after one century from the first EOQ model, there is a need to assess what our collective understanding of lot sizing appears to be at this point in time, and what directions might be fruitful for future research.

The aim of this chapter is to examine how lot sizing research has built on Harris's basic model idea by analyzing a selection of 219 papers published in relevant peer-reviewed management journals between 1913 and 2012 (see Tab.(2.1)), and how the Lot Sizing research community is cohesive

2.2 The traditional Economic Order Quantity Model EOQ

Following the well-known assumptions used by Harris (1913) but applying a more modern notation, the "classical" EOQ model is formulated (Harris's original notation and terminology within brackets):

Q — *order quantity* [size of order, lot size, X]

D — *annual demand* [number of units used per month, movement, M]

K — *cost of placing one order* [set-up cost, S]

c — *unit purchase/production cost per item* [quantity cost, without considering the set-up or getting-ready expense, or the cost of carrying the stock after it is made, C]

h — *unit stock holding cost per item per year including interest and depreciation in stock* [not given an own symbol in Harris's work, assumed to be 10% per annum on average value of stock, which makes $h = 0.1 \cdot C / (12M)$]

Q^* — *optimal order/production quantity* [lot size, which is most economical]

C_{tot} — *total cost per unit* [Y]

Harris developed his model assuming that the demand rate ("movement") was known and constant, shortages were not allowed, and replenishments were instantaneous. Under these assumptions the total cost per unit consists of only three elements: inventory holding cost, ordering cost and purchase/production cost:

$$C_{tot} = \frac{(h/c)\cdot\left(cQ+K\right)}{2\cdot D} + \frac{K}{Q} + c = \frac{h\cdot Q}{2\cdot D} + \frac{K}{Q} + c + \frac{h\cdot K}{2\cdot c\cdot D} \tag{2.1}$$

In this original expression, Harris had added an interest charge also on the setup cost value of stocked items $h\cdot K/\left(2\cdot c\cdot D\right)$, a practice which has later been abandoned in the literature. This additional term is constant and will not influence the optimal order quantity. The total cost is a continuous convex function of the order quantity as shown by Harris (1913). For this reason it can be differentiated to minimize the total cost. This operation leads to the well-known square root formula for determining the Economic Order Quantity, Q^*.

$$Q^* = \sqrt{\frac{2\cdot K\cdot D}{h}} \tag{2.2}$$

The same result can be derived using an algebraic method based on the observation that EOQ objective functions most often include pairs of terms of the type $\left(ax+b/x\right)$, such as in Eq.(2.1), where *a* and *b* are positive parameters and *x* a positive decision variable. The terms can be rewritten according to

$$ax + \frac{b}{x} = \frac{a}{x}\left(x-\sqrt{b/a}\right)^2 + 2\sqrt{ab} \tag{2.3}$$

From the expression on the right-hand side, it is immediate to see that the positive quadratic term vanishes for $x=\sqrt{b/a}$ leaving $2\sqrt{ab}$ as the minimum value of the objective function regarding these two terms. Roach (2005) points out that Kelvin's law minimizing the cost of transmitting electricity is analogous with $\left(ax+b/x\right)$, *x* here denoting the cross-sectional area of the wire, and Grubbström (1974) notes that the total air resistance for an aeroplane has the same structure with *x* now interpreted as the dynamic pressure, both cases leading to square-root formulae for the optimum design decisions. Minner (2007) proposed a different approach for obtaining the economic order quantity formula without taking derivatives, by using the cost comparisons in a finite horizon and analysing the limiting behaviour instead of performing algebraic manipulations of the average cost function and comparison of coefficients. It is easy to note that the "Square root formula" Eq.(2.1) is completely characterized by three key parameters that are briefly discussed below; the holding cost *h*, the order cost *K* and the demand rate *D*.

- *Holding costs* are usually defined as the cost of holding inventory for one year. Typically they are expressed as a percentage of the price of the item, supposing that the large proportion of the holding cost is represented by the cost of capital. Inventory holding costs h cover not only the cost of capital tied up in inventory, but originally also the depreciation that inventory is subject to. But, as several authors have added, some cost items to be included are related to the value of inventory (such as insurance premiums), others to physical properties, such as handling, controlling, warehousing, etc., often named "out-of-pocket holding costs" (Azzi et al. 2014). Obviously, Harris took for granted that a good approximation for the aggregate costs should be an annual interest percentage charged on the value of the average physical level. Despite the vast amount of literature on lot sizing developed during the last 100 years, the majority of contributions have been concerned with a total cost function definition from an economic point of view, following Harris's basic approach by using a direct costing method, although financial considerations following an NPV (Net Present Value) evaluation have added new aspects during the latter half of this century. The cost-oriented aggregate approach was questioned as to its accuracy, for instance because it is insensitive to the temporal allocation of payments within a period. For this reason, Hadley (1964), Trippi and Levin (1974) and others (Aucamp and Kuzdral 1986, Kim, Philippatos, and Chung 1986, Klein Haneveld and Teunter 1998, Horowitz 2000, Van Delft and Vial 1996) followed up this approach by arguing that the discounted value offers a more correct logical basis for analysing effects from investments in inventory. In 1980, Grubbström introduced the Annuity Stream concept (a constant payment flow providing a given NPV value), providing comparisons with the average costs per time (AC). Comparing the AC and NPV approaches, he found that the holding cost h should be approximated by $h = \rho \cdot c$, when demand has a constant rate and by $h = \rho \cdot p$, when demand is in batches, where ρ is the continuous interest rate, c the unit production cost, and p the unit revenue (sales price). The main difference between the two approaches is that the traditional periodic cost minimisation is focussed on the average inventory level, whereas the discounted cash flow methodology instead focusses on payments and their timing. Although the two approaches are conceptually different, the optimum does not differ significantly over a wide range of the values of the pertinent parameters, other than under special circumstances, cf. Teunter and van der Laan (2002), Beullens and Janssens (2011).

- *Ordering costs*, also called set-up costs, are the sum of all costs incurred as a result from ordering items. While holding cost includes all those costs that are proportional to the amount of inventory on hand, the cost of placing one order K is traditionally considered as a fixed cost of each batch, thus it is independent of the amount ordered/produced. However, it could be argued that in real applications, the order cost K has two components as stated in Eq.(2.4): a fixed cost k_f that is incurred independently of the size of the order and a variable cost k_v that is incurred on a per-unit basis.

$$K = k_f + Q \cdot k_v \tag{2.4}$$

  The fixed costs would include the costs of contacting the supplier and the cost of invoicing in case of external purchasing, or the setup cost of the production system in case of internal production. The variable costs may include the cost for transporting, handling and inspecting the goods. Eq.(2.2) and Eq.(2.4) show that the Economic Order Quantity increases with the order cost. This simple but important observation induced several authors to study the effect of setup cost reductions (e,g, Porteus 1985, Porteus 1986). The reduction of setup times from investment or a more clever design, reduces setup costs and leads towards applying the Japanese Just-In-Time JIT philosophy (Shingo 1981), according to which work-in-process inventories are not desirable and inventory should be reduced to its bare minimum. So EOQ and JIT theory are strictly linked to each other in this sense, and there should be strength in incorporating the lean manufacturing paradigm into Lot Sizing theory.

- The third key parameter in Eq.(2.2) is the *demand rate D*. Assumptions made about the pattern and characteristics of demand often turn out to be significant in determining the complexity of the inventory control model. The simplest models such as the basic EOQ, assume a constant deterministic demand rate. The literature on extensions to stochastic demand is immense. For example, interest has been devoted to analysing the size of errors incurred when replacing stochastic demand by its expected value in the model, e.g. (Zheng, 1992) and Axsäter (1996). Demand may be sequences of discrete demand events with variable size and in-between time intervals. Roundy (1985) studied how well models assuming systems with one warehouse and two retailer operated when using different order size policies. A further related branch of studies concerns assumptions of the demand process belonging to a specific class of stochastic processes, such as Poisson demand (Presman and Sethi, 2006). When shortages are allowed in an inventory model, similarly as for holding costs, it is possible to make a distinction between the capital costs for backlogging or lost sales, i.e. the consequence of postponing or losing the revenue in-payment, and other costs related to loss of goodwill, etc. A classification scheme for inventory models has been developed by Chikán and his associates, cf. (Chikán 1990).

2.3 Review methodology and descriptive analysis

As stated above, F.W. Harris has undoubtedly provided the earliest and most important contribution in lot sizing theory. For this reason he can be considered as the Father of EOQ theory. This paragraph attempts to investigate how lot sizing research has emanated from the first Harris model published in 1913. By using the Scopus and Google Scholar data bases to locate papers citing Harris's (1913) article, 177 pieces of work have been found, ranging from 1996 to 2012 in Scopus and 517 pieces of work in Google Scholar, in the same time period (Fig.(2.1)). From this analysis, it becomes evident that in the many years since it was introduced, the EOQ/EPQ construct has been used in around 700 peer-reviewed journal papers. This number would be very much higher if also conference papers and books were included. The instantaneous picture reported in Fig.(2.1) makes clearly understandable to the reader the necessity of the authors to develop a selection procedure to analyze only a sub-set of papers as sample of the entire literature. Moreover, the Harris paper citation count was not sufficient to review the whole literature on EOQ and EPQ problems, since it was published in a time when citations were not fully registered. Since no data are available to verify the true number of citations to Harris's model before 1996, the need to apply a different research approach for this earlier period arise. Therefore different search techniques have been used, depending on the different periods of time. Tab.(2.1) lists the research steps applied and keywords adopted. In particular the Scopus database allowed to find the most important literature from 1996 until today. The retrieving approach has involved the use of the keywords "EOQ", "EPQ", "Economic order quantity", "Economic production quantity" in the field "Title". Then, titles containing the specific words "Review", "Survey" or "Case study", have been excluded in order to confine the literature selection only to the paper developing new methods and models rather than analysis or application of existing theory.

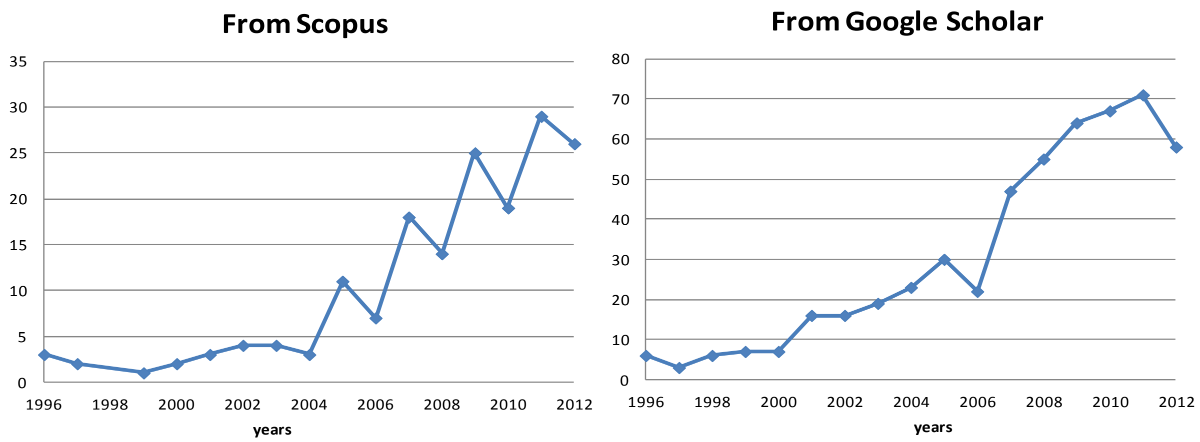


Figure 2.1. Papers citing Harris's work retrieved by Scopus and by Google Scholar on May 10, 2013 for the period 1996-2012.

After this, the search has been limited to the following subject areas: Decision Sciences, Engineering, Business Management and Accounting, Economics, Econometrics and Finance, Multidisciplinary. Finally, the results have been filtered in order to exclude conference papers, articles in press, reviews, letters, notes. This resulted in 259 papers that were made subject to a further analysis of their abstracts and contents, and ranked for a citation count in Scopus. To consider only the most relevant pieces of work, 95 papers (out of 259) that represented 90% of the total count of citations have been selected. The results of this analysis are shown in the Pareto Curve reported in Fig.(2.2).

STEP	YEARS	KEYWORDS	EXCLUSION CRITERIA	SELECTION CRITERIA	PAPERS FOUND
1	1996-2009	Title= "EOQ" or Title= "EPQ or Title="Economic Order Quantity" or Title="Economic Production Quantity"			352
2	1996-2009		and not Title= "Review" and not Title="Survey" and not Title= "Case Study"		349
3	1996-2009			LIMIT-TO Subject Area = "Decisions Science" or "mathematics" or "engineering" or "business management and accounting" or "economic econometrics and finance" or "multidisciplinary"	311
4	1996-2009		LIMIT-TO Document Type = Article		259
5	1996-2009			Citation number: papers contributing to the 90% of total citations	***95***
6	2010-2012	Title= "EOQ" or Title= "EPQ or Title="Economic Order Quantity" or Title="Economic Production Quantity"			208
7	2010-2012		and not Title= "Review" and not Title="Survey" and not Title= "Case Study"		181
8	2010-2012			LIMIT-TO Subject Area = "Decisions Science" or "mathematics" or "engineering" or "business management and accounting" or "economic econometrics and finance" or "multidisciplinary"	169
9	2010-2012		LIMIT-TO Document Type = Article		133
10	2010-2012			Papers classification applying a 4 point scale evaluation according to the level of centrality of the "EOQ/EPQ construct" (according to Lane et al., 2006)	***49***
Total 1996-2012					***144***
11	1913-2012	Title= "Title 1", "Title 2", "Title 3", ...all belonging to the reference lists of the 144 selected papers	none	Citation number and journal relevance (Impact Factor)	***75***
Total 1913-2012					***219***
****From Scopus: steps 1-10, from Google Scholar: step 11***					

Table 2.1. Review methodology: keywords and the 11 search steps adopted.

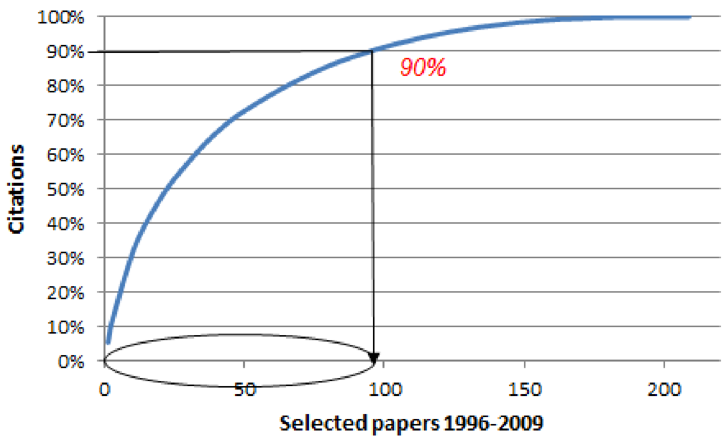


Figure 2.2. Pareto analysis of the 259 papers selected in step 4 of this research procedure.

Then, in order to identify the most relevant contribution in the recent period 2010-2012, according to the approach presented by Lane et al. (2006), each paper selected by Scopus with the same keywords has been read and classified according to the *“centrality of the EOQ/EPQ construct”.* In particular, a 4 point scale evaluation has been applied in accordance with the methodology applied by Lane et al. (2006), by using the following four categories for evaluating each paper:

(1) The paper extends the EOQ/EPQ construct’s definition by developing new EOQ/EPQ models and methods;

(2) The paper is centered on the subject (EOQ/EPQ) and on its dynamics by further investigating or extending previous EOQ/EPQ models and methods including new criteria or input parameters;

(3) The EOQ/EPQ construct is a necessary part of the paper’s hypotheses;

(4) The EOQ/EPQ construct is only instrumental (not necessary) in developing the logic for the paper’s propositions, or the paper uses the EOQ/EPQ construct to explain the results, or the paper uses the EOQ/EPQ construct as a minor citation with little or no discussion.

By selecting articles with an evaluation of (1), (2) or (3) and by excluding articles belonging to the fourth set, the final output consists of a set of 49 papers published in 2010-2012. These, added to the previous selected pieces of work, gave a total set of 144 papers on EOQ and lot sizing theory published in the period 1996-2012. To recover the older articles, a snowball-approach was performed by checking articles that were cited in the 144 previously selected pieces of work and where the citation received together with the journal relevance (impact factor) indicated that the paper might be relevant for this review. These papers and their citation counts were found using the Google Scholar database. The attention is focussed on the EOQ and EPQ problems and their extensions, and therefore work dealing with the Joint Economic Lot Size determination have been excluded, except for the first contribution given by Goyal (1976). For further insight into the JELS literature the reader can refer to the recent work of Glock (2012). In this stage 75 relevant papers published in ISI journals have been identified. In total, 219 relevant papers were finally collected after this stage and subsequently included in this analysis.

Fig.(2.3) illustrates that the number of pieces of work on EOQ/EPQ models has increased considerably over the last years, highlighting the importance that researchers have attributed to this topic especially in the current business environment. Certainly, this is also due to the constant increment in the interest in publishing.

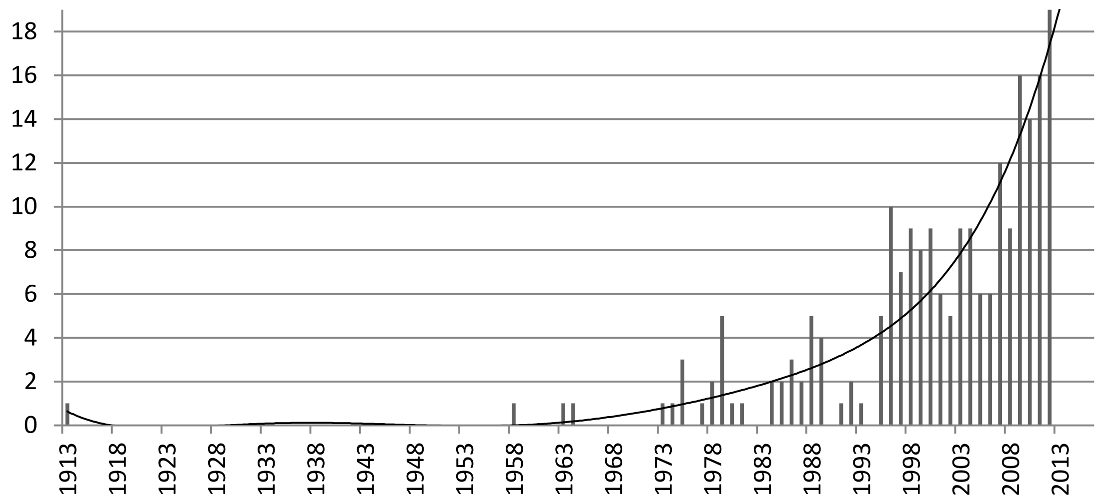


Figure 2.3. The distribution of the 219 selected papers over the time (year of publication).

Tab.(2.2) shows the list of the ten journals to which the major part of the selected articles belong, ranked in descending order of paper published. It can be stated that these ten journals published more than half of the total number of paper considered. To keep the length of this review within reasonable limits, not all the 219 papers are explained in detail in the following, but only those papers that are most representative according to the existing literature, and enable the reader to clarify rather exhaustively the scenario that has been created in a century of research in the field of economic lot sizing computation. All the papers considered in this review are listed in the reference section.

Journal	*Number of papers*
International Journal of Production Economics	*40*
Journal of the Operational Research Society	*32*
European Journal of Operational Research	*9*
International Journal of Systems Science	*7*
Production Planning and Control	*7*
Applied Mathematical Modelling	*6*
Computers and Operations Research	*6*
International Journal of Information and Management Sciences	*6*
Management Science	*6*
Omega	*6*

Table 2.2. The top 10 journals publishing 125 of the 219 papers selected in the period 1913-2012.

2.4 State of the art and classification framework

A deeper analysis of the 219 papers selected for the period 1913-2012 leads immediately to a first classification into three major sub-systems in relation to the type of input data considered in the models:

- *Deterministic models:* All the input data are completely known a priori. Due to the easiness in dealing with known parameters, the majority of the existing literature consists of deterministic models. Some of these try to give an optimal solution of the problem, others give some heuristic approach in order to gain good results for practical situations.

- *Stochastic models:* Some input data are described by a known/unknown probability density function.

- *Fuzzy models:* Some input data belong to a set of variables having degrees of membership according to Fuzzy Set theory (Zadeh 1965).

In the following, a holistic description of the existing literature on lot sizing is given. In particular the attention is focused particularly on deterministic models that represent the vast part of the research in this field. Fig.(2.4) anticipates the considerations made in in the next paragraphs, by outlining the evolution from Harris's basic model along the last century.

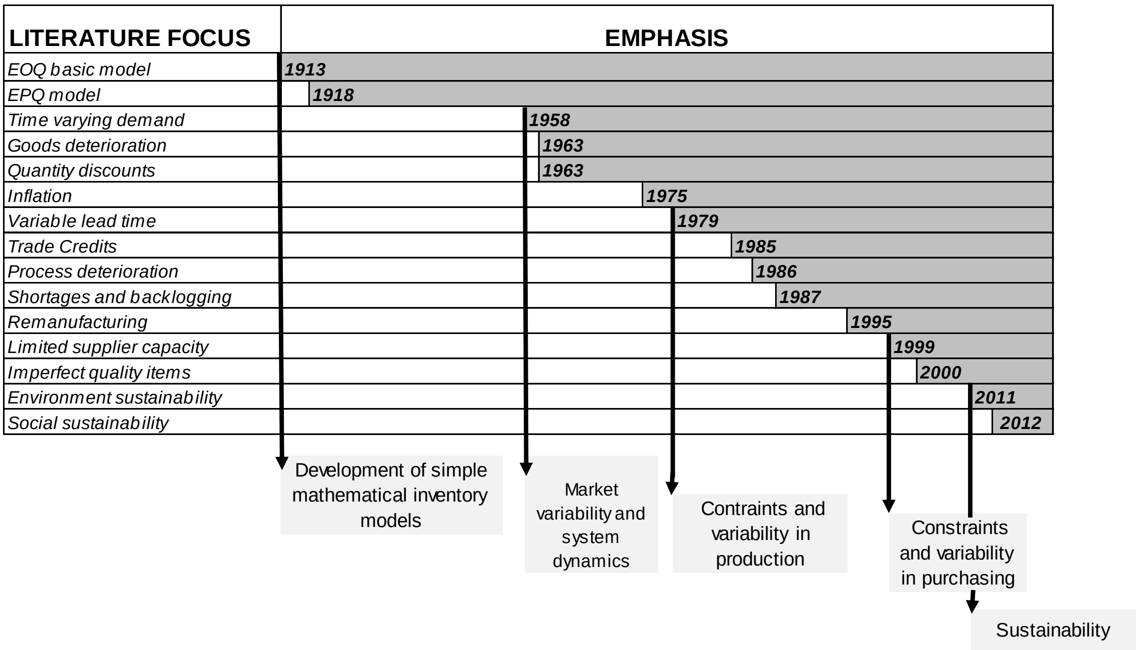


Figure 2.4. EOQ literature historical evolution in relation to the aspects and assumptions considered (the analysis is based on the 219 papers selected).

Fig.(2.5) provides a classification framework including the 219 selected papers, that permits the reader to easily identify the main research directions developed inside the EOQ theory along the entire century. According to the three major sub-systems previously identified, the framework is organized in deterministic, stochastic and fuzzy models. In order to increase the clarity and the effectiveness of the framework, each of these papers is represented by a numerical marker, whose correspondence with the reference can be easily found in Tab.(2.4).

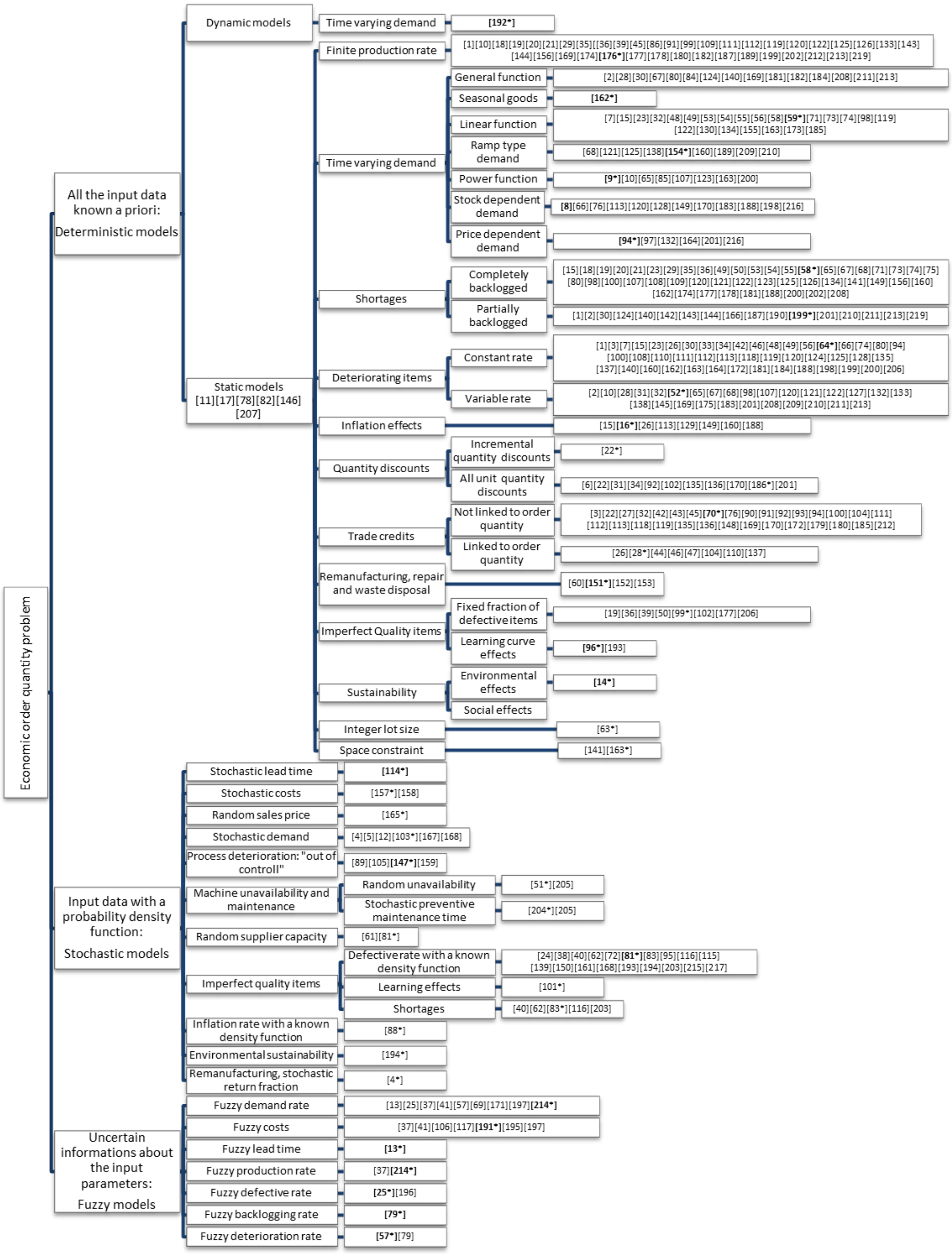


Figure 2.5. EOQ-theory classification framework related to the 219 selected papers: starred numbers refer to the most representative work in the corresponding area.

2.4.1 Deterministic models

One of the classic EOQ assumptions is that each replenishment happens instantaneously at the moment at which the retailer places the order. In the industrial real world indeed, a lead time occurs between the two moments, and in case of limited production capacity of the production plants, the replenishments are made gradually. To consider this fact, Taft (1918) proposed to modify the square root formula adding a parameter, to represent the ratio between the demand rate and the production capacity in the same period. This assumption lead to the EPQ model and it has been taken into account by a multitude of researchers after Taft. During the life cycle of the product, the assumption of a constant demand rate is never met. This assumption was relaxed by Donaldson (1977) offering an important special case of dynamic lot sizing (see above), when demand changes with a linear trend. Donaldson established a key property of this optimal replenishment pattern, namely that *"the quantity ordered at a replenishment point, i.e. a point at which actual inventory becomes zero, should be the product of the current instantaneous demand rate and the elapsed time since the last replenishment"* Donaldson (1977). Finally, he used this property to determine for a given demand pattern and horizon length, the best locations in time of a given number of replenishments. Silver (1979) adapted the Silver-Meal heuristic (Silver and Meal 1973) to develop an approximate solution procedure for the positive linear trend, in an effort to reduce the computational load needed in Donaldson's work. Many other researchers dealt with the problem of a linearly changing demand because of its limited complexity. Barbosa and Friedman (1978) presented a continuous-time inventory model with known time-varying demand, and they provided a complete solution for demand functions of the type $D(t) = kt^{\beta}$ with $k > 0$ and $\beta > -2$. For $\beta = 0$, the solution reduces to the classical "square root law", Eq.(2.2), for infinite horizons. More generally, for β integer, the solution can be expressed in a "$(\beta + 2)$ root law". The power form of this model is widely applicable because many real-life demand patterns are well-approximated by appropriately adjusting the parameters k and β. However, the life cycle of many products can be portrayed as a period of growth, followed by a period of relatively level demand and finishing with a period of decline. Ritchie (1980) considered appropriate policies for a linear increase in demand followed by a period of steady demand, and this model was generalized by Hill (1995), who considered a general power function for demand during the growth phase $D(t) = k\left(t/b\right)^{\beta}$ of which a linear increase is a special case ($\beta = 1$). Sana (2008) proposed an Economic Order Quantity model for seasonal goods using a sine function to model the seasonal demand rate. One of the most well-known contributions is the dynamic version of the economic order quantity mentioned above (Wagner and Whitin 1958). This dynamic lot-sizing model, using dynamic programming, is a generalization of the basic EOQ model, so it pursues the goal to minimize the sum of setup costs and inventory holding costs, but it allows the demand for the product to vary over time. The algorithm requires a forecast of product demand over a relevant time horizon, and it then determines the optimal replenishment policy for all periods. Recently Grubbström (2012, 2013) has proposed a dynamic EPQ model with NPV as the objective, in which the assumption of instantaneous replenishments is relaxed, including an algorithm leading to optimality. This model includes the Average Cost approach as an approximation, earlier published by Hill (1997).

A third deficiency of the classical model encountered is that goods may be stored indefinitely to meet future demand. However. in many real-world situations this is not accurate because of the effect of deterioration, which is vital in many inventory systems and cannot be disregarded. Food, blood, photo films, pharmaceuticals and other chemicals, and radioactive substances are examples. Deterioration is defined as decay, damage, spoilage, evaporation, obsolescence, loss of utility or loss of marginal value of a commodity resulting in decreased effectiveness from original (Wee 1993). The earliest work describing the deterioration problem was authored by Ghare and Schrader (1963). They observed that certain commodities shrink with time by a proportion which can be approximated by a negative exponential function of time. Therefore, they considered a constant deterioration rate θ that models the situation in which a constant fraction of the on-hand inventory level deteriorates with time. This type of deteriorating process may be described by the differential equation:

$$\frac{dI}{dt} = -D(t) - \theta I(t) \tag{2.5}$$

where θ is the constant deterioration rate, $I(t)$ the inventory level at time t, and $D(t)$ the demand rate at time t. This formula describes the situation in which the inventory level is depleted simultaneously by the demand rate and by an exponential deterioration process. Assuming $D(t)$ to be constant and equal to D, denoting T to be the moment at which the inventory level reaches zero, and Q the batch size, with the boundary conditions that initial inventory is Q, $I(0) = Q$, and that final inventory at T is zero, $I(T) = 0$, the solution to Eq.(2.5) is given by:

$$I(t) = \frac{D}{\theta}\left(e^{\theta(T-t)} - 1\right), 0 \le t \le T \tag{2.6}$$

The order quantity becomes:

$$Q = I(0) = \frac{D}{\theta}\left(e^{\theta T} - 1\right) \tag{2.7}$$

From (5), the time interval T for a batch of Q units to meet a demand of DT is obtained:

$$T = \frac{1}{\theta}\ln\left(\frac{D}{\theta}Q + 1\right) \tag{2.8}$$

Since the length of all time intervals are the same, we have:

$$I\left(t + kT\right) = \frac{D}{\theta}\left(e^{\theta(T-t)} - 1\right), 0 \le k \le n-1, 0 \le t \le T \tag{2.9}$$

A further development of this model is treated in the following. In the literature many authors have dealt with the problem of deteriorating items using a constant deterioration rate. Examples are Hariga (1996), Dave and Patel (1981), Chang and Dye (1999), Chang (2004), Ouyang, Chang and Teng (2005), Chakrabarti and Chaudhuri (1997), Bose, Goswami and Chaudhuri (1995), and recently Mahata (2011, 2012). The deterioration rate can also be assumed to vary with time according to some function $\theta(t)$. This assumption causes difficult mathematical calculations and closed-form solutions are generally impossible, so algorithms providing a numerical solution must be developed. Covert and Philip (1973) extended Ghare and Schrader's model and obtained an EOQ model for a variable rate of deterioration by assuming a two-parameter Weibull distribution $\theta(t) = \alpha\beta t^{\beta-1}$, where α and β are the scale and shape parameters of the Weibull distribution. It is simple to observe that the case of exponential distribution is a special case of the Weibull distribution with $\beta = 1$. Philip

(1974) generalised Covert and Philip's EOQ model using a three-parameter Weibull distribution $\theta(t) = \alpha\beta\left(t-\gamma\right)^{\beta-1}$, which takes into account the impact of the already deteriorated items that are received into an inventory system as well as those items that may start deteriorating in the future. A few years later Tadikamalla (1978) developed an EOQ model for deteriorating items, using the gamma distribution to representing the time to deterioration. More recently, many authors have dealt with the economic lot size problem with deteriorating items using the Weibull distribution. Examples are Jalan, Giri and Chaudhuri (1996), Chang and Dye (2000), Wu, Lin, Tan and Lee (2000), and Wu (2001). In real industrial situations the supplier often offers the retailer a fixed delay period in paying for the amount of purchasing cost, in order to stimulate the demand of his commodities. In this way, before the end of the trade credit period, the retailer can sell the goods and accumulate revenue and earn interest. A higher interest is charged, if the payment is not settled by the end of the trade credit period. The first basic work on this topic was provided by Goyal (1985). In his model, Goyal established two cases:

Case I: Replenishment period T exceeds the trade credit period t ($T \geq t$). In this case the customer has to pay an interest charge for items kept in stock, for the time that exceeds the trade credit period. A similar notation as the one used above is adopted with C_{tot} now referring to total annual costs, adding the following variables:

I_c interest charges per dollar in stocks per year

I_d interest which can be earned per dollar in a year

The total average cost per year, including the interest payable and the interest earned per year is given by formula (10):

$$C_{\text{tot}} = \frac{K}{T} + \frac{D \cdot t \cdot h}{2} + \frac{D \cdot c \cdot t \cdot I_c}{2} + \frac{D \cdot c \cdot t^2 \cdot I_c}{2T} - D \cdot c \cdot t \cdot I_c - \frac{D \cdot c \cdot t^2 \cdot I_d}{2T} \tag{2.10}$$

By deriving Eq.(2.10) and equating it to zero, he derived the mathematical expression that minimise the total variable cost Eq.(2.11):

$$Q^* = \sqrt{\frac{D\left(2K + D \cdot c \cdot t^2 \cdot \left(I_c - I_d\right)\right)}{h + c \cdot I_c}} \tag{2.11}$$

Case II: The trade credit period *t* exceeds replenishment period *T* ($t > T$). In this case, no interest charges are paid for the items kept in stock. The total variable cost in this case is given by Eq.(2.12):

$$C_{tot} = \frac{K}{T} + \frac{D \cdot T \cdot \left(h + c \cdot I_d\right)}{2} - D \cdot c \cdot t \cdot I_d \tag{2.12}$$

The economic order quantity in this case is:

$$Q^* = \sqrt{\frac{2K \cdot D}{h + c \cdot I_d}} \tag{2.13}$$

This is one of the most studied topics concerning the EOQ problem, so there were several interesting and relevant papers related to trade credits, extending Goyal's model in many directions, and a forerunner is found in (Grubbström 1980, Fig.(2.3)). Some examples are Aggarwal and Jaggi (1995), Teng (2002), Huang (2003), Chung and Huang (2003).

In reality, a supplier is often willing to offer the purchaser a permissible delay of payments if the purchaser orders a large quantity which is greater than or equal to a predetermined quantity. If the order is less than this quantity, the purchaser must pay for the items received immediately (see Chang, Ouyang, and Teng (2003) or Chang (2004), Chung and Liao (2009), Mahata (2011, 2012)). Below, the models of Ghare and Schrader (1963) and Goyal (1985) will be used, combined in Mahata (2012), to demonstrate research opportunities using the NPV combined with Laplace transform methodology.

Harris's model as well as many other inventory models before 1975 do not consider the inflation effect. Inflation can be defined as a general rise in prices, or conversely as a general decrease in purchasing power. To compensate this erosion of purchasing power, the market interest rate includes an inflation premium. These findings make it very important to investigate how time-value of money influences various inventory policies. The first attempt to consider inflation and time value of money in the Lot Sizing field has been reported by Buzacott (1975) that dealt with the EOQ problem with inflation subject to different types of pricing policies in order to investigate how time-value of money affect inventory policies. Misra (1979) developed a discounted-cost model that included internal and external inflation rates for different costs associated with inventories.

In order to accommodate the common industrial policies, some researchers developed EOQ models that incorporate two types of quantity discounts: all-units quantity discounts and incremental quantity discounts, as stated in the framework (Fig.(2.5)). In the former case the supplier provides a discount for all the items sold to the customer, if the quantity purchased exceeds predetermined quantities called price-break quantities. As a consequence, this policy results in discontinuities in the purchase cost function. In the latter case the supplier provides a discount only for the items that exceed a predetermined level, and he sells the remaining items at the usual price. In this case the purchase cost function is continuous. Tersine and Barman (1991) studied the problem of scheduling replenishment orders under the classical EOQ model when both quantity and freight rate discounts are encountered. Carlson, Miltenburg and Rousseau (1996) examined the optimal order quantity under both all-units and incremental-quantity discounts, using a discounted cash flow methodology. Khouja and Mehrez (1996) investigated four different supplier credit policies which included both of these situations and provided closed-form solutions in all cases. Chang(2002) provided a model to determine an optimal ordering policy under a permissible delay of payment and/or cash discount for the customer. Huang and Chung (2003) extended Goyal's model incorporating the cash discount policy for an early payment. They developed two theorems to determine the optimal cycle time, optimal order quantity and optimal payment policy. Ouyang, Chang and Teng (2005) provided the optimal policy for the customer in presence of a permissible delay and cash discount, and they also presented an easy-to-use algorithm to find the optimal order quantity and replenishment time. The basic assumption that shortages are not permitted is restrictive in real industrial situations. Furthermore, the inclusion of a shortage cost and the possibility of backlogging might lead to lower total inventory costs. The risk of shortages is currently a common assumption for most researchers dealing with Lot sizing models. Grubbström and Erdem (1999) derived the EOQ formula including backlogging without reference to the use of derivatives, neither for necessary conditions nor for second-order sufficient conditions, as is basically illustrated by Eq.(2.3). The same approach was extended to the economic production quantity (EPQ) model with shortages by Cárdenas-Barrón (2001). For models where shortages are allowed, complete backlogging, or complete loss of unsatisfied demand are two extreme cases. Deb and Chaudhuri (1987) modified Silver's (1979) procedure by including shortages which were completely backordered. They followed a replenishment policy that allowed shortages in all cycles except the final one. Each of the cycles during which shortages were permitted starts with a replenishment and stocks were built up for a certain length of time which was followed by a period of stockout. Many researchers have turned their attention to models that allow partial backlogging. Examples are Wee (1995), Chang and Dye (1999), Yan and Cheng (1998).

Another relevant aspect is that manufacturing facilities in practice do not function perfectly during all production runs. Process deterioration added to other factors, inevitably generates imperfect quality items. Although this type of situation can be faced more accurately following a stochastic approach, some interesting deterministic models have been developed. These assume that the fraction of defective items is known and constant in each production cycle. Jamal, Sarker and Mondal (2004) considered an EPQ model under two policies. With the first policy, defective items were reworked within the same cycle. With the second policy alternative, the defective items were accumulated until a number of cycles were completed, after which the defective parts were processed. Cárdenas-Barrón (2009) generalised the Jamal et al. (2004) EPQ inventory model with planned backorders, under the first policy. Kevin Hsu and Yu (2009) investigated an inventory model with imperfect quality under a one-time-only discount, where a 100% screening process was performed on the received lot and the defectives were assumed to be sold in a single batch by the end of the screening process. Jaber, Goyal and Imran (2008) assumed that the percentage of defective items per lot diminishes according to a learning curve.

2.4.2 Stochastic models

In a century of history from Harris's model, only a limited number of articles have directly faced the case of EOQ when some parameters are uncertain, an exception being uncertainty in demand mentioned above . This is probably because of two reasons. First, the total inventory cost has a very low sensitivity to inventory cost parameters (Axsäter, 1996). A second reason is the complexity of algebraic operations among random parameters with a probability distribution. However, a stochastic approach is often desirable for dealing with real industrial problems, in which input data are not known a priori and have random properties. A typical example is the EOQ model with products of imperfect quality, in which the production process produces a fraction of defective items. Since it is impossible to know the fraction of defective items a priori, this parameter can be modelled using a probability density function with known or unknown parameters. Porteus (1986) incorporated the effect of defective items into the basic EOQ model, assuming that there was a probability q that the process would go out of control while producing one unit of the product. Rosenblatt and Lee (1986) assumed that the time from the beginning of the production run, until the process goes out of control is exponentially distributed and that defective items could be reworked instantaneously at a cost. In a subsequent paper, Lee and Rosenblatt (1987) considered process inspection during the production run so that the shift to out-of-control state could be detected earlier. Haneveld and Teunter (1998) determined the optimal ordering quantity where demand is modelled by a Poisson process. Salameh and Jaber, (2000) considered a production/inventory situation where items, received or produced, were not of perfect quality, with a known density function. Items of imperfect quality could be used in a less restrictive situation. Papachristos and Konstantaras (2006) extended this model to the case in which withdrawing takes place at the end of the planning horizon. Goyal and Cárdenas-Barrón (2002) developed a simple practical approach that is easier to implement as compared to the optimal approach. Maddah and Jaber (2008) analysed the effect of screening speed and variability of the supply process on the order quantity. Eroglu and Ozdemir (2007) developed an EOQ model with defective items and shortages backordered. Liberatore, (1979) developed a stochastic lead-time generalisation of the EOQ model with backlogging of demand. Hariga and Haouari (1999) presented a general formulation of the inventory lot sizing model with random supplier capacity. Horowitz (2000) considered the effects of inflation on inventory, when the rate of inflation was not known with certainty.

2.4.3 Fuzzy models

A different approach to deal with uncertain parameter is the application of fuzzy set theory (Zadeh 1965). In the classical set theory, the membership of elements in a set is assessed in binary terms according to a bivalent condition — an element either belongs or does not belong to the set. By contrast, fuzzy set theory permits the gradual assessment of the membership of elements in a set; this is described with the aid of a membership function valued in the real unit interval [0, 1]. For this reason fuzzy set theory is usually employed in a wide range of domains in which information is incomplete. However, this methodology requires considerable computational efforts and it is often accused of introducing unnecessary complexity reducing the transparency of results. As a consequence, Fuzzy set theory does not appear to find wide applications in real industrial environments, where managers ask for easy-to-use models. Some examples of Fuzzy EOQ models developed in the past are found among the following references. Vujosevic et al. (1996) considered trapezoidal fuzzy inventory costs, providing four ways of determining the EOQ in the fuzzy sense. Yao and Lee (1998) investigated a computing schema for the EPQ in the fuzzy case, describing demand quantity and production quantity per day with triangular fuzzy numbers. Chang (2004) presented a model with a fuzzy defective rate and fuzzy annual demand. Chen, Wang and Chang (2007) proposed a Fuzzy Economic Production Quantity (FEPQ) model with imperfect products that could be sold at a discounted price, and where costs and quantities were expressed as trapezoidal fuzzy numbers. Further exemplifications can be found in Wang Tang and Zhao (2007), Halim, Giri and Chaudhuri (2008) and in Björk (2009).

2.5 Citation network analysis

In order to identify the most relevant EOQ literature the citation patterns between the papers selected is examined. One of the characteristics of a well-defined community of researchers is to present a network of citations, among their papers, that centers on a core set of works delineating the basic concepts, theories, and methodologies shared by the community itself (Garfield 1979, Kuhn 1970, Merton 1973). The less tightly a paper is linked into a research community's citation network, the greater is the risk that the authors are deviating from the community's norms regarding its core concepts and basic hypotheses.

The central contributors to this research (the "pillars") are analyzed in the following, in particular how tightly they interlinked the set of 219 papers, and the presence of different "schools of analysis". Using the Scopus and the Google Scholar databases, the references for each paper has been downloaded. Then these data have been tabulated by using Excel in order to determine how frequently each paper (i) has cited other papers in the set and (ii) has been cited by other papers within the set. Accordingly, two measures of centrality to determine how tightly linked each paper is to the rest of the literature have been derived: the number of times a given paper cites the older ones in the set of 219 papers ("sent citations") and the number of times a paper is cited by the later ones in the same set ("received citations"). The former represents the authors' positioning of the paper relative to the EOQ/EPQ literature, whereas the latter reflects other authors' perceptions of that paper's contribution to the literature. While both measures have temporal biases (papers that were published earlier have a better chance of getting cited, and those published later have more opportunities to cite other papers), these biases offset each other. Next, a third centrality measure has been created by adding each paper's number of sent and received citations and then normalizing the sum by dividing it by 100 (the number of years covered by the sample, according to Lane et al. (2006). This process provides an index denoting the average annual number of links to and from the EOQ literature. These three measures are listed in descending order in Tab.(2.3), for the pieces of work that are found to be the most tightly linked to the core set.

Paper	Sent Citations *S*	Received Citations *R*	Index Sent+Received (*S*+*R*)/100
Donaldson, W.A. (1977)	0	45	0,45
Ghare, P.M., Schrader, G.F. (1963)	0	44	0,44
Goyal, S.K. (1985)	0	41	0,41
Hariga, M. (1996)	24	16	0,4
Covert, R.B., Philip, G.S. (1973)	1	37	0,38
Dave, U., Patel, L.K. (1981)	0	33	0,33
Aggarwal, S.P., Jaggi, C.K. (1995)	4	29	0,33
Silver E.A. (1979)	2	31	0,33
Jamal, A.M., Sarker, B.R., Wang, S. (1997)	7	24	0,31
Salameh, M. K., Jaber, M. Y. (2000)	5	26	0,31
Mishra, R.B. (1975)	0	29	0,29
Bose, S., Goswami, A., Chaudhuri, K.S. (1995)	18	9	0,27
Chang, H.C., (2004)	13	14	0,27
Manna, S. K., Chaudhuri, K. S. (2001)	21	6	0,27
Rosenblatt, M.J., Lee, H.L., (1986)	0	26	0,26
Manna S.K., Chiang C.(2010)	25	1	0,26
Goswami, A., Chaudhuri, K.S. (1991)	1	24	0,25
Ritchie, E. (1984)	2	22	0,24
Harris, F.W. (1913)	0	23	0,23
Chang, C., Ouyang, L., Teng, J. (2003)	15	8	0,23
Deb, M., Chaudhuri, K.S. (1987)	4	19	0,23
Sana, S. S. (2008)	21	2	0,23
Porteus, E.L. (1986)	1	21	0,22
Goyal, S. K., Cárdenas-Barrón, L. E. (2002)	0	21	0,21
Chakrabarti, T., Chaudhuri, K. S. (1997)	13	8	0,21
Ghosh, S. K., Chaudhuri, K. S. (2006)	21	0	0,21
Liao, H.C., Tsai, C.H., Su, C.T. (2000)	10	11	0,21
Mahata G.C. (2011)	21	0	0,21
Murdeshwar, T.M. (1988)	4	17	0,21
Chang, H.J., Hung, C.H., Dye, C.Y. (2001)	12	8	0,2
Chung, K.J. (1998)	3	17	0,2
Giri, B. C., Goswami, A., Chaudhuri, K. S. (1996)	16	4	0,2
Hill, R.M. (1995)	13	7	0,2

Table 2.3. Most linked papers out of the 219 mapped in the citation network

Fig.(2.6) presents the citation network derived from the relative citation count among the 219 selected papers. Each of these papers is represented by a node, and is marked by a number whose correspondence with the reference can be easily found in Tab.(2.4). Overall, 1296 relations among the papers are represented by a directional arrow. This network is built using the PAJEK software. In order to identify the importance of each paper, the size of each node is made proportional to its number of citations received in the network. Additionally, the century is divided into five periods of equal length, assigning these five different colors. Examining the network, it is easy to identify strong connections between the nodes but it is possible to notice a few clusters concentrated around some central pieces of work. These clusters are densely woven and it is difficult to clearly identify all their relations. By deepening the analysis of the network, four main groups focusing on different modeling aspects are clearly visible:

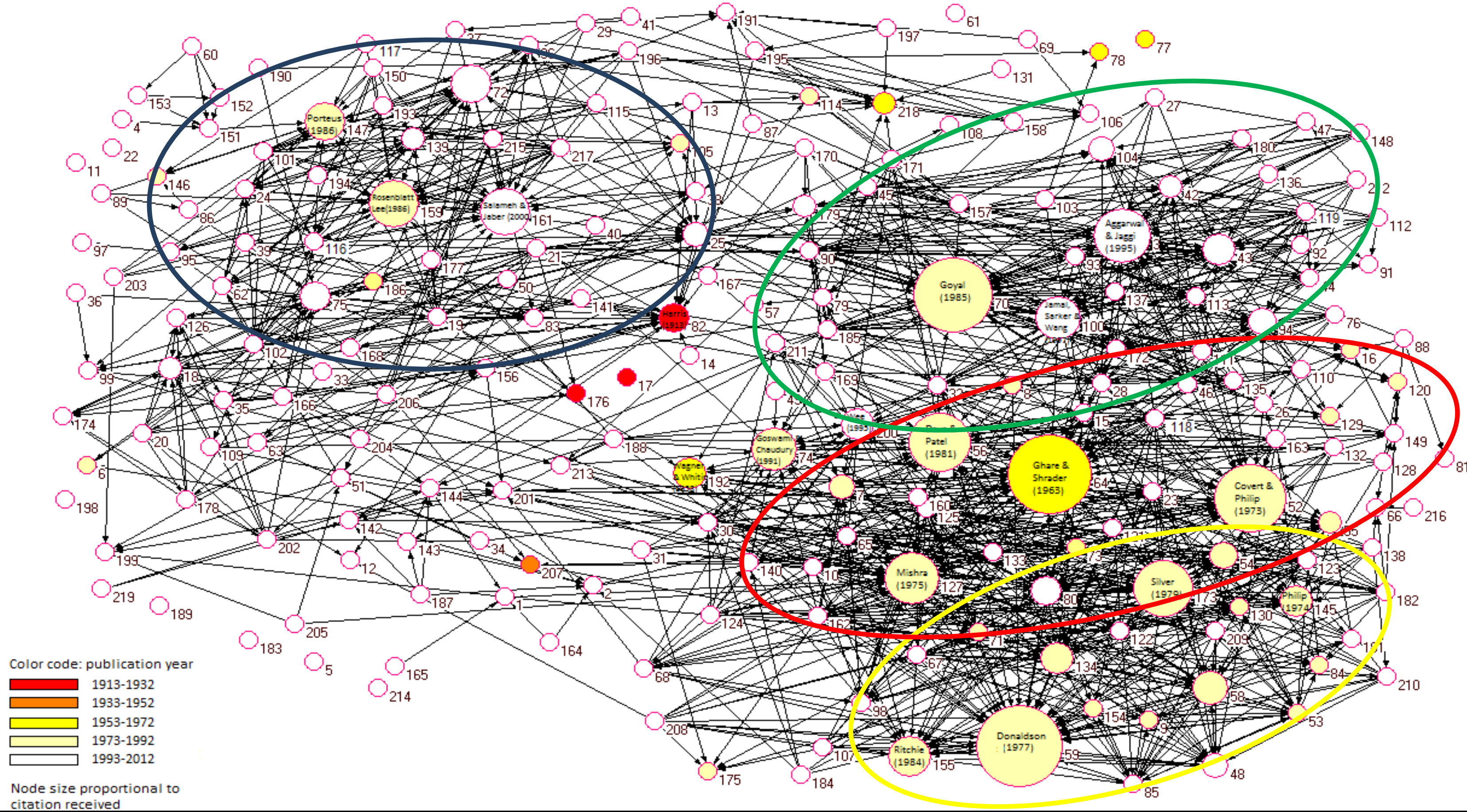
1. GROUP 1: Papers focussed on “imperfect quality items” issues. This cluster incorporates among others Porteus (1996), Rosenblatt and Lee (1986) and Salameh and Jaber (2000).

2. GROUP 2: Papers focussed on “permitted delays in payment” issues. Goyal (1985), Aggarwal and Jaggy (1995), Jamal et al. (1997) are included;

3. GROUP 3: Papers focussed on “deteriorating items” issues - next to Ghare and Shrader (1963) and Covert and Philips (1973), there are Mishra (1975) and Dave and Patel (1981);

4. GROUP 4: Papers focussed on “time varying demand” problems - in this cluster it is possible to find Donaldson (1977), Silver (1979) and Ritchie (1984).

The central parts of these clusters are identified in Fig.(2.6) by four colored ellipses. There are also some papers belonging to more than on cluster, such as Mahata (2011) belonging to Groups 2, 3, and 4.



Cluster Analysis:

GROUP 1 (blue circle): focus on “imperfect quality items”

GROUP 2 (green circle): focus on “permitted delay in payment”

GROUP 3 (red circle): focus on “deteriorating items”

GROUP 4 (yellow circle): focus on “time varying demand”

Figure 2.6. Citation network of the 219 selected papers with cluster analysis

[1]	Abad	2000	[46]	Chung & Liao	2004	[91]	Huang	2004
[2]	Abad	1996	[47]	Chung & Liao	2009	[92]	Huang & Chung	2003
[3]	Aggarwal & Jaggi	1995	[48]	Chung & Ting	1993	[93]	Huang & Hsu	2008
[4]	Alinovi et al.	2012	[49]	Chung & Tsai	1997	[94]	Hwang & Shinn	1997
[5]	Alstrøm	2001	[50]	Chung	2011	[95]	Jaber et al.	2009
[6]	Aucamp & Kuzdrall	1986	[51]	Chung et al.	2011	[96]	Jaber et al.	2008
[7]	Bahari-Kashani	1989	[52]	Covert & Philip	1973	[97]	Jaber et al.	2006
[8]	Baker & Urban	1988	[53]	Datta & Pal	1992	[98]	Jalan et al.	1996
[9]	Barbosa & Friedman	1978	[54]	Dave	1989	[99]	Jamal et al.	2004
[10]	Begum et al.	2010	[55]	Dave	1989	[100]	Jamal et al.	1997
[11]	Best	1930	[56]	Dave & Patel	1981	[101]	Khan et al.	2010
[12]	Beyer & Sethi	1998	[57]	De et al.	2003	[102]	Kevin & W.	2009
[13]	Björk	2009	[58]	Deb & Chaudhuri	1987	[103]	Klein & W.K.	1998
[14]	Bonney & Jaber	2011	[59]	Donaldson	1977	[104]	Khouja & Mehrez	1996
[15]	Bose et al.	1995	[60]	El & A.M.A.	2008	[105]	Lee & Rosenblatt	1987
[16]	Buzacott	1975	[61]	Erdem et al.	2006	[106]	Lee & Yao	1999
[17]	Camp	1922	[62]	Eroglu & Ozdemir	2007	[107]	Lee & Wu	2002
[18]	Cárdenas-Barrón	2001	[63]	Garcia-Laguna et al.	2010	[108]	Li et al.	2007
[19]	Cárdenas-Barrón	2009	[64]	Ghare & Schrader	1963	[109]	Li et al.	2008
[20]	Cárdenas-Barrón	2010	[65]	Ghosh & Chaudhuri	2006	[110]	Liao	2007
[21]	Cárdenas-Barrón	2011	[66]	Giri & Chaudhuri	1998	[111]	Liao	2008
[22]	Carlson et al.	1996	[67]	Giri et al.	1996	[112]	Liao	2007
[23]	Chakrabarti & Chaudhuri	1997	[68]	Giri et al.	2003	[113]	Liao et al.	2000
[24]	Chan et al.	2003	[69]	Glock et al.	2012	[114]	Liberatore	1979
[25]	Chang	2004	[70]	Goyal	1985	[115]	Lin	2010
[26]	Chang	2004	[71]	Goyal	1988	[116]	Maddah & Jaber	2008
[27]	Chang	2002	[72]	Goyal & Cárdenas-Barrón	2002	[117]	Mahapatra et al.	2012
[28]	Chang et al.	2003	[73]	Goyal et al.	1992	[118]	Mahata	2011
[29]	Chang	2004	[74]	Goswami &Chaudhuri	1991	[119]	Mahata	2012
[30]	Chang & Dye	1999	[75]	Grubbström &Erdem	1999	[120]	Mandal & Phaujdar	1989
[31]	Chang & Dye	2000	[76]	Guria et al.	2012	[121]	Mandal	2010
[32]	Chang et al.	2001	[77]	Hadley & Whitin	1963	[122]	Manna & Chaudhuri	2001
[33]	Chang & Lin	2011	[78]	Hadley	1964	[123]	Manna et al.	2007
[34]	Chang et al.	2011	[79]	Halim et al.	2008	[124]	Manna et al.	2009
[35]	Chang et al.	2005	[80]	Hariga	1996	[125]	Manna & Chiang	2010
[36]	Chang et al.	2012	[81]	Hariga & Haouari	1999	[126]	Minner	2007
[37]	Chen et al.	2007	[82]	Harris	1913	[127]	Mishra	1975
[38]	Chiu et al.	2004	[83]	Hayek & Salameh	2001	[128]	Mishra & S.	2008
[39]	Chiu et al.	2010	[84]	Henery	1979	[129]	Misra	1979
[40]	Chiu	2006	[85]	Hill	1995	[130]	Mitra et al.	1984
[41]	Chou	2009	[86]	Hofmann	1998	[131]	Mondal & Maiti	2003
[42]	Chu et al.	1998	[87]	Hojati	2004	[132]	Mukhopadhyay et al.	2005
[43]	Chung	1998	[88]	Horowitz	2000	[133]	Muluneh & Rao	2012
[44]	Chung et al.	2005	[89]	Hou	2007	[134]	Murdeshwar	1988
[45]	Chung & Huang	2003	[90]	Huang	2003	[135]	Ouyang et al.	2005

[136]	Ouyang et al.	2002	[164]	Sana	2011	[192]	Wagner & Whitin	1958
[137]	Ouyang et al.	2009	[165]	Sana	2011	[193]	Wahab & Jaber	2010
[138]	Panda et al.	2007	[166]	San-Jose et al.	2009	[194]	Wahab et al.	2011
[139]	Papachristos & Konstantaras	2006	[167]	Sarkar & Moon	2011	[195]	Wang et al.	2007
[140]	Papachristos & Skouri	2000	[168]	Sarkar et al.	2011	[196]	Wang et al.	2007
[141]	Pasandideh et al.	2010	[169]	Sarkar	2012	[197]	Wang et al.	2010
[142]	Pentico & Drake	2009	[170]	Sarkar	2012	[198]	Warburton	2009
[143]	Pentico et al.	2009	[171]	Sarkar & Chakrabarti	2012	[199]	Wee	1993
[144]	Pentico et al.	2011	[172]	Sarker et al.	2000	[200]	Wee	1995
[145]	Philip	1974	[173]	Silver	1979	[201]	Wee	1999
[146]	Porteus	1985	[174]	Sphicas	2006	[202]	Wee et al.	2009
[147]	Porteus	1986	[175]	Tadikamalla	1978	[203]	Wee et al.	2007
[148]	Qin	2012	[176]	Taft	1918	[204]	Wee & Widyadana	2012
[149]	Ray & Chaudhuri	1997	[177]	Taleizadeh et al.	2011	[205]	Widyadana & Wee	2012
[150]	Rezaei & Salimi	2012	[178]	Teng	2009	[206]	Widyadana & Wee.	2012
[151]	Richter	1996	[179]	Teng	2002	[207]	Wilson et al.	1934
[152]	Richter	1997	[180]	Teng & Chang	2009	[208]	Wu et al.	2000
[153]	Richter & Dobos	1999	[181]	Teng et al.	1999	[209]	Wu et al.	1999
[154]	Ritchie	1980	[182]	Teng et al.	2005	[210]	Wu	2001
[155]	Ritchie	1984	[183]	Teng et al.	2005	[211]	Wu	2002
[156]	Ronald et al.	2004	[184]	Teng et al.	2003	[212]	Xu et al.	2010
[157]	Rong	2010	[185]	Teng et al.	2012	[213]	Yan & Cheng	1998
[158]	Rong	2011	[186]	Tersine & Barman	1991	[214]	Yao & Lee	1998
[159]	Rosenblatt & Lee	1986	[187]	Toews et al.	2011	[215]	Yoo	2009
[160]	Roy & Chaudhuri	2011	[188]	Uthayakumar & Rameswari	2012	[216]	You & Hsieh	2007
[161]	Salameh & Jaber	2000	[189]	Uthayakumar & Rameswari	2012	[217]	Yu & Hsu	2012
[162]	Sana	2008	[190]	Van et al.	1996	[218]	Zadeh	1965
[163]	Sana	2010	[191]	Vujošević et al.	1996	[219]	Zhang	2009

Table 2.4. References for the framework and the citation network

One of the aims of this analysis is determination of the literature pillars in the citation network. In order to achieve this purpose, Tab.(2.5) shows the number of citations received in the network and the number of citations received in the Google Scholar database.

Author	Year	Title	Journal	Citation received in the network	Citation received in Google Scholar
Donaldson, W.A.	1977	Inventory replenishment policy for a linear trend in demand - An analytical solution.	Operational Research Quarterly	45	301
Ghare, P.M., Schrader, G.F.	1963	A model for an exponentially decaying inventory.	Journal of Industrial Engineering	44	681
Goyal, S.K.	1985	Economic order quantity under conditions of permissible delay in payments.	Journal of the Operational Research Society	41	584
Covert, R.B., Philip, G.S.	1973	An EOQ model with Weibull distribution deterioration.	AIIE Transactions	37	385
Dave, U., Patel, L.K.	1981	(T, S1) policy inventory model for deteriorating items with time proportional demand.	Journal of the Operational Research Society	33	88
Silver, E.A.	1979	A Simple Inventory Replenishment Decision Rule for a Linear Trend in Demand .	Journal of the Operational Research Society	31	189
Aggarwal, S.P., Jaggi, C.K.	1995	Ordering policies of deteriorating items under permissible delay in payments.	Journal of the Operational Research Society	29	412
Mishra, R.B.	1975	Optimum production lot size model for a system with deteriorating inventory.	International Journal of Production Research	29	217
Rosenblatt, M.J., Lee, H.L.	1986	Economic production cycles with imperfect production processes.	IIE Transactions	26	583
Salameh, M.K., Jaber, M.Y.	2000	Economic production quantity model for items with imperfect quality.	International Journal of Production Economics	26	339
Goswami, A., Chaudhuri, K.S.	1991	An EOQ model for deteriorating items with shortages and a linear trend in demand.	Journal of the Operational Research Society	24	127
Jamal, A.M., Sarker, B.R., Wang, S.	1997	An ordering policy for deteriorating items with allowable shortage and permissible delay in payment.	Journal of the Operational Research Society	24	363
Harris, F.W.	1913	How Many Parts to Make at Once	Factory, The Magazine of Management	23	547
Ritchie, E.	1984	The EOQ for linear increasing demand - a simple optimal solution.	Journal of the Operational Research Society	22	130
Goyal, S.K., Cárdenas-Barrón, L.E.	2002	Note on: Economic production quantity model for items with imperfect quality - A practical approach.	International Journal of Production Economics	21	139
Porteus, E.L.	1986	Optimal lot sizing, process quality improvement and setup cost reduction.	Operations Research	21	685

Table 2.5. Most cited papers according to the citation count in the network of Fig.(2.6) and in the Google Scholar database.

After a detailed analysis of the data in Tab.(2.5), it is immediate to observe some peculiarities. The ranking of the analyzed papers is made in order of number of citations received in the network, but using the number of citation received in Google Scholar a rather different order would have been obtained. In detail, it is possible to notice two considerable cases: Dave and Patel (1981) has the lowest Google Scholar citation count although it is fifth in this ranking; Porteus (1986) has the highest count, but it appears in the last position of the list. The reason for this apparent inconsistency lies in the fact that a research simultaneously can deal with more than one topic. Thus, a paper that received a large number of citations in the Google Scholar database while only a few in the network, is relevant in different research fields besides the under consideration. Therefore it is cited by many papers that do not appear in the set. On the contrary, a paper that received many citations in the network, but has a low count in Google Scholar, is strongly centered in the EOQ construct. In order to highlight the EOQ pillars, the list has been ranked according to number of citations received in the network.

2.6 Background considerations for a future research agenda

This section attempt to paint a background for a future research agenda. As a first starting point, keywords used in the subset of articles pertaining to the period 1996-2012 are analyzed. Then two areas of importance related to new or recently established aspects of lot sizing, the first focusing on transportation, the second on sustainability are analyzed. A major part of the related literature falls outside of the set of 219 papers, due to novelty and an inability to extract these areas by applying the procedure reported in Tab.(2.1).

2.6.1 Keyword implications

A first background for future research proposals may be found by studying trends in the keywords used in the set of articles chosen from the period 1996-2012 covered by Scopus. All keywords applied in the articles have been analyzed and grouped into five main sets:

Set 1: Keywords related to economic and financial aspects: costs, cost accounting, cost comparison optimization, cost effectiveness, cost benefit analysis, cost minimization models, cost oriented model, cost parameters.

Set 2: Keywords related to quality problems: imperfect production, imperfect production process, imperfect production system, imperfect quality items, imperfect quality, inspection, imperfect reworking, defective items.

Set 3: Reuse and waste disposal aspects: Return policy, reuse, reverse logistics, rework, rework and salvage, rework process, repair, waste disposal, remanufacturing, recovery, product reuse.

Set 4: Social sustainability and impact on human workforce.

Set 5: Environmental impact, environmental problems, green supply chain, carbon emission.

Tab.(2.6) identifies on the one hand a continuous, although variable use over time of terms related to economic and financial aspects (cost accounting, cost minimization models, cost effectiveness) that are still the most important drivers in lot sizing theory, and, on the other, a remarkable increase in the use of keywords related to aspects of imperfect product quality, repair, reuse, waste, and disposal. It also highlights the introduction of environmental impact aspects during the last few years.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Total	Average
Costs, Cost accounting, Cost comparisons optimization, Cost effectiveness, Cost benefit analysis, Cost minimization models, Cost oriented model, Cost parameters	2	2	3	1	1	1	4	7	5	1	6	7	1	6	12	6	6	61	3.59
Imperfect production, Imperfect production process, Imperfect production system, Imperfect quality items, imperfect quality,100% inspection, Imperfect reworking, Defective items	0	0	0	0	0	0	0	2	1	0	0	2	3	10	7	4	7	34	3.40
Return policy, Reuse, reverse logistics, Rework, Rework and salvage, Rework process, Repair, Waste disposal, remanufacturing, recovery, Product reuse	0	2	0	3	0	0	0	0	0	0	0	0	5	6	2	4	9	31	1.94
Social sustainability	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	3	0.38
Environmental impact, Environmental problems, Green supply chain, Carbon emissions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	4	10	3.33

Table 2.6. Count of keywords used in the period 1996-2012.

The last two columns of Tab.(2.6) show the total count of the aforementioned keywords in the respective periods, and their averages. These averages are determined as *Average =TotK / Time interval* , where *TotK* is the total count of the keywords, and *Time interval* represents the length of the interval, in which the keyword is used from its first year until its last year.

2.6.2 Transportation cost considerations in inventory replenishment decisions

Transportation costs are becoming increasingly important in inventory replenishment decisions and, in practice, lot sizing decisions are strongly affected by material handling equipment, transportation flow paths, transportation mode and technical constraints. Companies within a global sourcing context daily experience the cost of transportation as playing a major role in total purchasing costs. A small group of authors recently investigated the transportation cost computation problem in lot sizing decisions (Battini et al. 2012).

As illustrated by Fig.(2.7), transportation costs as a function of batch size can often behave in a discontinuous way, which cannot be differentiated during the whole interval. Moreover, they depend on the number of different vehicle types used in the transportation (for example different containers with different capacities) and in practice, more types of vehicles are available with different capacity and different costs. Furthermore, transportation and handling activities have a great impact on total emissions generated, whereas other activities, such as ordering, warehousing and disposing of waste, have much lower incidence on the total environmental impact.

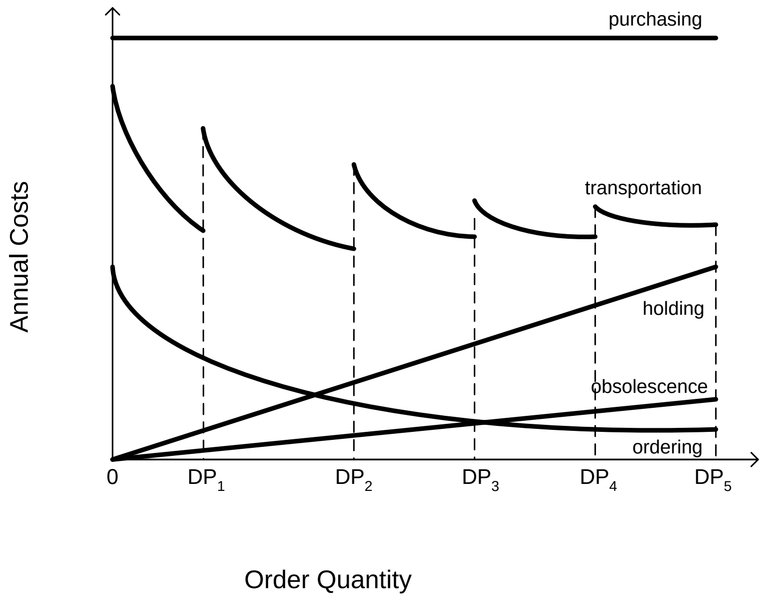


Figure 2.7. Cost function behavior in a purchasing order cycle (Battini et al, 2013).

Vroblefski et al. (2000) proposed a model where transportation costs are considered. They showed that the total cost of the system is a piecewise convex function of the ordering levels with discontinuities at the cost breaks, unlike the traditional model where the total cost is convex over the entire range of ordering levels. Swenseth and Godfrey (2002) incorporate the transportation cost into the total annual logistics cost function. Their model also includes a freight rate per pound for a given shipping weight over a given route. Zaho et al. (2004) considered both the fixed transportation cost and the variable transportation cost in the problem of deciding the optimal ordering quantity and frequency for a supplier–retailer logistic system. A multiple use of vehicles is also considered. They provided an EOQ-modified model and an algorithm to determine the optimal solution that minimizes the whole average cost of the logistic system in the long-run planning horizon. Mendoza and Ventura (2008) extended the Economic Order Quantity model by introducing all-units and incremental quantity discount structures into their analysis. Birbil et al.(2009) provided EOQ models in which the impact of transportation costs is considered. They studied a subclass of problems that also includes the well-known carload discount schedule.

Finally, the impact of transportation costs has a significant influence not only from an economic point of view, but also for its environmental impact, which is explained in the following section. Battini et al. (2013) investigate internal and external transportation costs according to the vendor and supplier position and the different freight vehicle utilization ratios in order to provide an easy-to-use methodology for sustainable lot-sizing. Freight discounts and their effect on lot sizing are also investigated in Burwell, et al. (1997) and further followed up by Chang (2013).

It is possible also to refer to an early basic lot sizing model, in which the inventory of goods-in-transit is considered, cf. (Axsäter and Grubbström 1979). The decision variables would be the lot size, the safety stock level, and the speed (mode) of transportation. A valuable item ties up more capital during transportation than a cheaper one. A more speedy mode of transport would lower capital costs, but direct transportation costs would increase. The length of transport also influences the lead-time and thereby safety stock conditions.

Here, for simplicity, the attention is confined to a simplest case, when only capital holding costs are considered and with no consideration of safety stock consequences. Let K denote the fixed ordering cost, c the economic production/purchase cost per item, ρ the opportunity cost of capital, Q the order quantity, v the velocity of transportation, $\hat{s}$ the transportation distance, and m the weight (alternatively volume) of an item. The direct transportation cost for a batch of weight mQ in the simplest case is assumed to be proportional to weight and to transportation distance $\hat{s}$, $c_{\text{transport}}(v)\cdot mQ\hat{s}$, where $c_{\text{transport}}(v)$ is the cost per distance and weight unit for moving one item at a speed v, which would be expected to be an increasing function of v; in the simplest case proportional, $c_{\text{transport}}(v)=\hat{c}\cdot v$. Assuming one stocking point en route, the total cost per unit will be

$$C_{\text{tot}}=c+\frac{K}{Q}+\frac{Q\rho c}{2D}+\frac{\rho c\hat{s}}{v}+\hat{c}vm\hat{s} \tag{2.14}$$

where the second and third terms are traditional inventory-related costs per item with $h=\rho c$ representing the inventory holding cost parameter, the fourth term being the capital cost per item during transit ($\hat{s}/v$ being time in transit), and the fifth term the direct transportation cost per item. In this simple approach, the optimal choice of Q is independent of the choice of v, and the resulting solution in Q is the traditional one, Eq.(2.2), therefore the optimal solution is:

$$v^{*}=\sqrt{\frac{\rho c}{\hat{c}m}} \tag{2.15}$$

which shows the optimal speed v^{*} to be proportional to the square root of the value density of the item c/m. Gold should be moved by air freight, and brick by sea.

2.6.3 Sustainability issues in lot sizing literature

Sustainability is probably one of the most over-used expressions in recent years, it is a very broad term, formally defined by the Brundtland Report (UN Documents 1987) as *"the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs".* As stressed by the European Union targets (for instance in the Horizon 2020 program), an industrial sector that is economically, socially and environmental sustainable will contribute to EU policy targets and company competitiveness.

The international increasing concern on environmental problems stresses the need to treat inventory management decisions as a whole by integrating economic, environmental and social objectives. Today modern societies have begun to consider environmental and social aspects on top of economic and financial goals. These different aspects contribute to the same target of improving the quality of life of people. In the last three decades new business terms such as recycling, remanufacturing (see Richter 1997, Richter and Dobos 1999), "sustainable development" and ergonomics, the latter having a slightly older history, have been introduced in our economy. Recently, several world class corporations have declared themselves to be committed environmentalists and they have been integrating environmental and ergonomic aspects in the development of their strategies. Consumers are often willing to pay extra for recycled products, recyclable and non-damaging to the environment and human health. They are also demanding more detailed information about the processes used by their suppliers. Social Sustainability is a core element of Sustainability and has considerably grown in importance during the last few years. Social sustainability pursues the goal of creating and maintaining quality of life for people, protecting the mental and physical health of all stakeholders, encouraging community and treating all stakeholders fairly. These elements are essential because a healthy society cannot be developed and maintained, if the population is in poor health. Environmental and social problems are an area of steadily increasing concern in modern society. For this reason, research on environmental and social sustainability has considerably enriched the lot sizing literature during the last three years. Benjaafar et al. (2010) incorporated carbon emission constraints on single and multi-stage lot-sizing models with a cost minimization objective. They considered four different policies based respectively on a strict carbon cap, a tax on the amount of emissions, the cap-and-trade system and the possibility to invest in carbon offsets to mitigate carbon caps. Arslan and Turkay (2010) included environmental and social criteria in addition to conventional economics. In order to consider the social impact in their EOQ model they used working hours as social metric. Hua et al. (2011) extended the EOQ model taking carbon emissions into account under the cap and trade system. Bonney and Jaber (2011) discussed a range of inventory and lot sizing problems that are not considered appropriately in traditional inventory models, for example the effects on the environment from packaging choices, location of stores, and waste. They focussed their attention on the environmental impact of logistic operations, and outlined a hierarchy of the players involved in inventory management. They also suggested some metric categories that could be used to assess inventory performance related to its environmental impact. In the last part of their paper, they formulated a model called "Enviro-EOQ", that considers environmental costs of vehicle emissions, providing a closed-form solution for the optimal lot size. Wahab et al. (2011) formulated a model for a two-level supply chain that determines the optimal production-shipment policy for items with imperfect quality and incorporating the environmental impact by taking into account fixed and variable carbon emission costs. Battini et al. (2012) provided a “Sustainable EOQ model” that from an economic point of view incorporates and investigates the environmental impact of transportation and inventory. In particular internal and external transportation costs, vendor and supplier location and the different freight vehicle utilisation ratios are considered in order to provide an easy-to-use methodology. In the second step of their research (Battini et al. 2013), the authors underline the necessity to investigate the optimal purchasing/production lot size by a multi-objective optimization approach: the optimal lot-sizing decision depends on both costs and emission functions and how these two functions depend on quantity. Recently Bouchery et al. (2012) have proposed a model that reformulates the classical economic order quantity problem into a multi-objective problem. Economic, environmental and social impacts are there considered, using the traditional formulas proposed by Harris’s original work. They developed an interactive procedure allowing to quickly identify the best option among the three solutions. A similar approach is applied also in Andriolo et al. (2013), in which the lot sizing problem in material purchasing is studied from a different perspective: the social impact due to manual handling activities necessary for stock keeping, unit lifting and storing. The ergonomic risk function is here applied to measure the influence on the work conditions of human operators.

There is the need to mention that the consideration of recycling and remanufacturing activities have brought new terminology and distinctions into inventory research. For instance, it is now necessary to distinguish between *recoverable inventory*, having an upward slope for a more or less continuous input flow, and with withdrawals from inventory taking place in batches, on the one hand, and *serviceable inventory*, describing the stock of available refurbished components, on the other. Also extra care is needed when considering holding costs, if the loop has been closed, cf. Teunter and van der Laan (2002).

2.6.4 Methodological developments analyzing cash flows related to inventory

This section attempts to show that a few of the basic models found in the previous analysis, may be tied closely together within the framework of a Net Present Value approach, in which *Laplace transform* methodology plays a central role. As mentioned earlier, applying the Net Present Value (NPV) principle has been regarded to be superior to the Average Cost approach (AC) by several authors, for instance by Trippi and Levin (1974) and Grubbström (1980) and completely essential on occasion (Teunter and van der Laan 2002, Grubbström and Kingsman 2004). Referring to the physically measurable cash flow, rather than costs and revenues, brings the model closer to reality, it is argued. The practical AC model has often been shown to be a good approximation of NPV, when the discount rate ρ is small and the holding cost parameter is interpreted as $h = \rho c$, where c is unit production (or purchase) cost, cf. Beullens and Janssens (2012).

Laplace transform methodology is widely applied in different branches of engineering and statistics, in particular in electrical engineering and it may be applied successfully also in inventory theory, cf. (Grubbström 2007). The details of this analysis are relegated to Appendix I. This use is now illustrated by departing from the original Ghare and Schrader (1963) inventory model with exponential depletion at a rate of θ, cf. Eq.(2.5), this model recently extended by for instance Mahata (2012) to include a finite production rate q combined with trade credits of the Goyal (1985) type. Since this model is extremely rich, there is only space for some basic points in this context.

As demonstrated in the Appendix I, if applying transform theory to Eq.(2.5) and adopting the standard assumption for finite rate models (as in Mahata 2012) that each cycle starts with a production ramp with slope q, lasting Q/q time units, where Q is the batch size, physical inventory level during a cycle will follow

$$I_{\text{cycle}}(t) = \begin{cases} \dfrac{(q-D)}{\theta}\left(1-e^{-\theta t}\right), \; 0 \le t \le Q/q, \\ \dfrac{D}{\theta}\left(e^{\theta(T-t)}-1\right), \quad Q/q < t \le T, \end{cases} \tag{2.16}$$

which is the same as in (Mahata 2012, Eqs (5)-(6)), and it collapses into Eq.(2.7) above when $q \to \infty$. Ccontinuity at $t = Q/q$ requires $q\left(e^{\theta Q/q} - 1\right) = D\left(e^{\theta T} - 1\right)$,showing the relation between *Q* and *T*, collapsing into Eq.(2.7) and Eq.(2.8) above, as $q \to \infty$:

$$Q = \frac{q}{\theta}\ln\left(1 + \left(D/q\right)\left(e^{\theta T} - 1\right)\right),\ T = \frac{1}{\theta}\left(1 + \left(q/D\right)\left(e^{\theta Q/q} - 1\right)\right) \qquad (2.17)$$

In the Appendix I, expressions for the annuity streams related to out-of-pocket inventory holding costs are also derived (as distinguished from capital costs from holding inventories) $\mathrm{AS}_{\text{out-of-pocket}}$ and of sales revenues less production costs $\mathrm{AS}_{\text{profits}}$, both shown to approach Mahata's AC expressions if the discount rate is considered negligible $\rho \to 0$.

In the problem reported by Mahata (2012) generalised from Ghare and Schrader (1963) and Goyal (1985), there are two credits (loans): (i) the supplier is willing to provide the retailer with a full trade credit for payments for a period *M* with the interest I_c, and (ii) a partial trade credit is offered to customers for a period *N* at the interest rate I_e. Making use of an NPV theorem concerning the cash flow associated with a loan, Eq.(A.8) in the Appendix I, expressions for the annuity streams related to the supplier's credit $\mathrm{AS}_{\text{supplier's credit}}$ is derived on the one hand, and to the credit to customers $\mathrm{AS}_{\text{credit to customers}}$, on the other. The supplier's credit is interpreted as paying the supplier at time *M* rather than during the initial production ramp. Concerning the customer credit with which an interest rate I_e is associated, a partial payment is made when items are sold. The customer must then pay off the remaining balance at the end of the offered trade credit period *N*. It is easily shown that the supplier's credit offers an advantage (a positive addition to the annuity stream), when the opportunity cost of capital exceeds the charged interest rate $\rho > I_c$, and vice versa. A first-order Maclaurin expansion in ρ of $\mathrm{AS}_{\text{supplier's credit}}$ (neglecting terms with $I_c\rho$) leads to an average cost expression for the supplier $\mathrm{AC}_{\text{supplier's credit}}$, demonstrating how this average cost depends on the length of the credit period *M* compared to the cycle length *Q*/*q*. It is also shown that $\mathrm{AS}_{\text{credit to customers}}$ has the same sign as $\left(I_e - \rho\right)$, so if the interest rate paid by the customers exceeds the opportunity cost $I_e > \rho$, the credit is favourable, and vice versa, just as expected.

It appears not to be fruitful to further compare this results on credit consequences with those of Mahata, since the capital cost for operations funded by equity are not explicitly considered in Mahata (2012). They are there probably indirectly assumed to be part of the average holding cost expression. Also it appears as if Mahata attaches the credits to items in inventory after depletion.

This sub-section has attempted to show that it is possible to bring together several of the aspects included in inventory model extensions proposed through at least the recent half century, beginning with the NPV formulation by Hadley (1958), the first credit extension by Goyal (1985), and later a second credit extension, in the meantime applying the Taft (1918) extension from EOQ to EPQ, and the extension to include depletions by Ghare and Schrader (1963).

The opportunity for introducing upstream and downstream credits, a common NPV evaluation focussing on cash flows, measurable in reality, and finally to use a simple, but an often neglected opportunity to apply engineering mathematics in the form of transforms, together this should certainly offer new research opportunities. An additional area for methodological research could be in lot-sizing for general multi-echelon systems, relaxing limitations to general assembly systems (Grubbström, Bogataj and Bogataj 2010).

Appendix I

The Laplace Transform of a time function $a(t)$ written $\tilde{a}(s)$ or $£\{a(t)\}$ is defined as $£\{a(t)\} = \tilde{a}(s) = \int_{t=0}^{\infty} a(t)e^{-st}dt$, which transforms the time function $a(t)$ from the time domain into the frequency domain represented by the complex Laplace frequency s. In all normal cases of practical significance, there is a one-to-one correspondence between a time function and its transform, cf. Aseltine (1958). But the NPV of a time dependent cash flow $a(t)$ has the following general form, which simply may be interpreted as the Laplace transform of $a(t)$, when the frequency s is exchanged for the continuous discount rate ρ:

$$\text{NPV} = \int_{t=0}^{\infty} a(t)e^{-\rho t}dt = \left[\int_{t=0}^{\infty} a(t)e^{-st}dt \right]_{s=\rho} = \tilde{a}(\rho) \tag{A1.1}$$

The cash flow may include discrete payments as well as continuous payment streams. In order to compare NPV expressions with average costs per time unit, one may make use of the *annuity stream*, which is the constant flow of cash providing a given NPV. With an infinite horizon, the Annuity Stream is the interest rate times the NPV value:

$$\text{AS}=\rho \cdot \text{NPV} = \rho\,\tilde{a}(\rho) \tag{A1.2}$$

Using Laplace transforms of the cash flows involved thereby opens up the whole of the extensive Laplace transform theory for application. Some applications may be found in Grubbström (2007).

Making use of a few theorems from Laplace transform theory, such as the transform of a time derivative being s times the transform of the function, the transform of a constant being the constant divided by s, the transform of a negative exponential time function $e^{-\theta t}$ being the inverse of the sum of s and the coefficient in the exponent θ, i.e. $1/(s+\theta)$, and the transform of an infinite chain of equal cycles being the transform of the first cycle divided by $\left(1-e^{-sT}\right)$, where T is the length of each cycle. Developing generalizations of the basic model of Ghare and Schrader (1963), the transform of the left-hand member of Eq.(2.5) is made. We have $£\{dI/dt\} = s\tilde{I}(s)$, and of the right-hand member $-£\{D(t)+\theta I(t)\} = -\left(D/s+\theta\tilde{I}(s)\right)$.

But replenishments/production are not included in Eq.(2.5). Assuming the standard case for finite rate models (as in Mahata 2012, originally from Taft 1918) that each cycle starts with a production ramp with slope *q*, lasting Q/q time units, where *Q* is the batch size, the inflow into inventory will have the transform $q\left(1-e^{-sQ/q}\right)/\left(s\left(1-e^{-sT}\right)\right)$, where *T* is the cycle length. Adding this inflow to the right-hand member gives us the equation

$$s\tilde{I}(s) = -\left(\frac{D}{s}+\theta\tilde{I}(s)\right)+\frac{q\left(1-e^{-sQ/q}\right)}{s\left(1-e^{-sT}\right)} \qquad \text{(A1.3)}$$

from which the inventory level $\tilde{I}(s)$ is solved:

$$\tilde{I}(s) = \frac{1}{s\left(s+\theta\right)}\left(\frac{q\left(1-e^{-sQ/q}\right)}{1-e^{-sT}}-D\right) \qquad \text{(A1.4)}$$

This is an infinite sequence of cycles, each cycle having the transform:

$$\begin{aligned}\tilde{I}_{\text{cycle}}(s) &= \tilde{I}(s)\left(1-e^{-sT}\right) = \frac{1}{s\left(s+\theta\right)}\left(q\left(1-e^{-sQ/q}\right)-D\left(1-e^{-sT}\right)\right) = \\ &= \frac{1}{\theta}\left(\frac{1}{s}-\frac{1}{s+\theta}\right)\left(q\left(1-e^{-sQ/q}\right)-D\left(1-e^{-sT}\right)\right)\end{aligned} \qquad \text{(A1.5)}$$

Translating this equation from the frequency domain into the time domain, the time function is expressed by Eq.(2.16). To prove this, we may take the integral $\tilde{I}_{\text{cycle}}(s) =$ $\int_{t=0}^{Q/q}\frac{(q-D)}{\theta}\left(1-e^{-\theta t}\right)e^{-st}dt \quad +e^{\theta T}\int_{t=Q/q}^{T}\frac{D}{\theta}\left(e^{-\theta t}-e^{-\theta T}\right)e^{-st}dt$, which evaluated provides just (A1.5). The one-to-one property of the transform and its corresponding time function then establishes the proof.

Introducing out-of-pocket holding costs corresponding to out-payments proportional to the physical inventory level and using the out-of-pocket holding cost parameter $\hat{h}$, by Eq (A1.2) and (A1.4) the Annuity Stream of this part of the cash flow will be

$$\mathrm{AS}_{\text{out-of-pocket}} = \rho \mathrm{NPV}_{\text{out-of-pocket}} = \rho \hat{h} \tilde{I}(\rho) = \frac{\hat{h}}{(\rho+\theta)} \left(\frac{q\left(1-e^{-\rho Q/q}\right)}{1-e^{-\rho T}} - D \right) \qquad \text{(A1.6)}$$

This expression may be compared with Mahata's AC expression $\left(\hat{h}/(\theta T)\right)\left(qQ/q-DT\right)$, which is the limit of (A1.6) when the discount rate is neglected $\rho \to 0$.

Similarly, the Annuity Stream of sales revenues less production costs found from

$$\mathrm{AS}_{\text{profits}} = \rho \mathrm{NPV}_{\text{profits}} = rD - cq\frac{1-e^{-\rho Q/q}}{1-e^{-\rho T}} = \left(r-c\right)D - c\left(\frac{q\left(1-e^{-\rho Q/q}\right)}{\left(1-e^{-\rho T}\right)} - D \right) \qquad \text{(A1.7)}$$

where the first term shows average profits, if there were no depletion, and the second the annuity stream of expenses due to depleted items. This second term collapses into Mahata's AC expression $\left(c/T\right)\left(pQ/q-DT\right)$ when $\rho \to 0$. As for trade credits, it is possible to make use of the following NPV theorem concerning the cash flow associated with a loan. Let $\mathrm{NPV}_{\text{principal}}$ denote the NPV of the loaned amount and the repayments (the latter with opposite sign and they eventually add up to the loaned amount), but excluding interest payments. It is then straightforward to show that the NPV of the loan also including consideration to interest payments written $\mathrm{NPV}_{\text{loan}}$ may be expressed as

$$\mathrm{NPV}_{\text{loan}} = \left(1-\hat{\rho}/\rho\right)\mathrm{NPV}_{\text{principal}} \qquad \text{(A1.8)}$$

where $\hat{\rho}$ is the interest rate attached to the loan contract, and ρ the discount rate representing the opportunity cost of capital, so $\left(-\hat{\rho}/\rho\right)\mathrm{NPV}_{\text{principal}}$ is the NPV of interest charges. To prove this, the following integral is evaluated. Let the cash flow of loan and repayments be $a(t)$, hence $\mathrm{NPV}_{\text{principal}} = \tilde{a}(\rho)$. Then after subtracting the interest payments on the outstanding loan amount at t from $a(t)$, we have $\mathrm{NPV}_{\text{loan}} =$ $\int_{t=0}^{\infty}\left(a(t)-\hat{\rho}\int_{\tau=0}^{t}a(\tau)d\tau\right)e^{-\rho t}dt = \tilde{a}(\rho)-\hat{\rho}\int_{t=0}^{\infty}\int_{\tau=0}^{t}a(\tau)e^{-\rho t}d\tau dt =$ $\tilde{a}(\rho)-\hat{\rho}\int_{\tau=0}^{\infty}a(\tau)\int_{t=\tau}^{\infty}e^{-\rho t}dtd\tau = \left(1-\hat{\rho}/\rho\right)\mathrm{NPV}_{\text{principal}}$, where the order of integration has been changed in the fourth member.

Eq.(A1.8) is valid for any structure of the loan, i.e. the loaned amount may be distributed in portions over time, and the repayments spread out unevenly, as long as the cumulative cash flow eventually becomes zero. For a standard type of loan with in-payments (the borrowed money) coming earlier than the repayments, $\mathrm{NPV}_{\mathrm{principal}}$ must always be positive. Then, obviously the loan is favourable to take, if $\hat{\rho} < \rho$, and vice versa. When the interest rate of the loan equals the opportunity cost $\hat{\rho} = \rho$, $\mathrm{NPV}_{\mathrm{loan}}$ is zero, so taking the loan or not would be of equal preference.

For the supplier's credit in the problem reported by Mahata (2012), generalised from Ghare and Schrader (1963) and Goyal (1985), the following expression for the annuity stream related to supplier credit payments is developed:

$$\mathrm{AS}_{\text{supplier's credit}} = \rho \cdot \mathrm{NPV}_{\text{supplier's credit}} =$$

$$\frac{c\rho\left(1-I_c/\rho\right)}{1-e^{-\rho T}} \cdot \begin{cases} \left(q\left(1-e^{-\rho M}\right)/\rho - qMe^{-\rho M}\right), & M < Q/q, \\ \left(q\left(1-e^{-\rho Q/q}\right)/\rho - Qe^{-\rho M}\right), & Q/q \le M. \end{cases} \tag{A1.9}$$

A first-order approximation in ρ (and neglecting terms with the product $I_c\rho$) gives the following AC expression (after changing sign):

$$\mathrm{AC}_{\text{supplier's credit}} = -\left[\mathrm{AS}_{\substack{\text{supplier's}\\ \text{credit}}}\right]_{1st\ order} = \frac{\left(I_c-\rho\right)cq}{T} \begin{cases} M^2/2, & M < Q/q, \\ \left(Q/q\right)\left(M-\left(Q/q\right)/2\right), & Q/q \le M. \end{cases} \tag{A1.10}$$

The second credit concerns the customer credit. For this loan, the annuity stream of the related payments amounts to

$$\mathrm{AS}_{\substack{\text{credit to}\\ \text{customers}}} = \rho \cdot \mathrm{NPV}_{\substack{\text{credit to}\\ \text{customers}}} =$$

$$\frac{\rho\left(1-I_e/\rho\right)}{1-e^{-\rho T}} \cdot \begin{cases} \left(-r\alpha D\left(1-e^{-\rho N}\right)/\rho + r\alpha DNe^{-\rho N}\right), & N < T, \\ \left(-raD\left(1-e^{-\rho T}\right)/\rho + r\alpha DTe^{-\rho N}\right), & T \le N, \end{cases} \tag{A1.11}$$

where both expressions to the right are easily shown to be non-positive.

3 THE NEW SUSTAINABLE LOT-SIZING FRAMEWORK

3.1 First considerations

The analysis presented in chapter 2 finds strong evidence that the EOQ literature is a mirror image of the last century: it reflects the evolution of operations management techniques in worldwide industrial systems over the last 100 years. Incremental steps have been made from 1913 till today in an actualization process of the first analytical model developed by Harris, this process aiming at better incorporating aspects of real industrial problems and constraints. Several researchers have added new incremental conditions attempting to reflect real case problems as well as to change the emphasis on different model conditions and constraints.

The work done after Harris has generally focused on:

- Developing new cost and revenue functions for specific applications and for various types of systems in practice;
- Categorizing new input data and factors to be included in the analysis;
- Relaxing the modeling constraints.

The lot sizing literature from the last century, easily demonstrates the impossibility for a single model to describe "perfectly" the reality under study (as with any road map). Efforts to obtain a "perfect model" have often brought researchers to increase model complexity and consequently the time spent for computations. A model may become so complex as to be computationally infeasible to use, and may be accurate only at a particular moment in time (Tukey 1962). In agree with this thinking, Box and Draper (1987) remind us that "all models are wrong, some are useful", meaning that a simple and easy-to-use model could be more effective than a more complex one that require high computational skills. Grubbström (2001) discusses this trade-off between applicability, simplicity and level of technique of scientific models. The trade-off concept always present in mathematical modeling has been fully demonstrated by the Harris EOQ model. Even if we today can benefit from a large and highly connected literature, the basic model of Harris is always attractive for its simplicity and the minimal amount of data needed. For this reason, it is frequently applied by managers today, even 100 years after its creation. Important new challenges are expected for sustainable supply chains in the near future. We need only think of the planning, implementation and management of reverse and sustainable supply networks, in which waste material becomes the raw material input to the echelon following, and when CO_2 emissions must be minimized.

In the light of this considerations, in the following an innovative framework to consider environmental and social aspects connected with the lot sizing decision is presented. This approach provides an easy-to-use method to couple the total cost function with emission consequences, and social aspects linked with material purchasing and handling.

3.2 The new methodological approach

The procedure here proposed consists of two different sets of Lot Sizing decisions: the former is dedicated to the lot sizing issues linked with the material handling within the plant, where product features such as weight, volume and packaging characteristics usually strongly affect manual material handling efficiency and safety; the latter is dedicated to the Lot Sizing problems concerning the purchasing of in-bound materials coming from external suppliers and involving external transportations.

The simultaneous consideration of financial, social and environmental aspects can be performed in different ways. The most used method in the past was the direct accounting, where social and environmental impacts were quantified by a financial point of view, using a direct costing approach. However, the limits of a direct accounting method when externalities need to be quantified, are actually becoming evident in the recent literature (Battini et al, 2012). For this reason, future researches are pushed to find the best way to couple the total cost function quantification with the emission function analysis according to a multi-objective optimization approach. As graphically explained in Fig.(3.2), the Lot sizing problem with sustainability considerations is a typical example of multi-objective optimization (MO) problem. MO plays an important role in engineering design, management, and decision making in general, on the ground that a decision maker needs to make tradeoffs between conflicting design objectives. In this case economic and sustainability goals are the conflicting goals. Tradeoffs occur when improvement of one objective comes at the expense of another objective. For example the packaging cost arises when the item quantity contained in a single Stock Keeping Unit decreases; on the other hand the ergonomic level of the manual handling activity is improved. A generic MO optimization problem involving n conflicting objective criteria expressed as functions of the design variables, can be concisely stated as

$$Minimize\ \{f_1(z), f_2(z), \dots \dots, f_n(z)\}\ ; \qquad (3.1)$$

$$Subject\ to\ z \in \Omega$$

where f_1 (i = 1, n) are the objective functions, expressed in terms of the design variable vector z in the feasible domain Ω for the n-dimensional criteria space. Wilfred Pareto defined "Pareto point" (Pareto 1964, 1971) as a solution where no feasible solutions exist that yield a better objective while keeping the other objective fixed. A non-Pareto solution instead, implies that it is possible to find a better solution that entails no tradeoff. In formula, a design $z \in \Omega$ is a Pareto-optimal solution to the problem posed by Eq.(3.1), if there does not exist any other design $z \in \Omega$ such that

$$f_i(z) \leq f_i(z^*);\ f_k(z) < f_k(z^*)\ \ (i = 1, n\ ; \quad 1 \leq k \leq n)\ . \qquad (3.2)$$

A Pareto-optimal solution is also defined as a "Pareto-efficient solution" according to Steuer (1989) and the set of all efficient points is called the "Efficient frontier". Fig.(3.1) illustrates a generic example of bi-objective problem: the whole set of solutions is identified by the grey empty points, while the optimal ones are the black points.

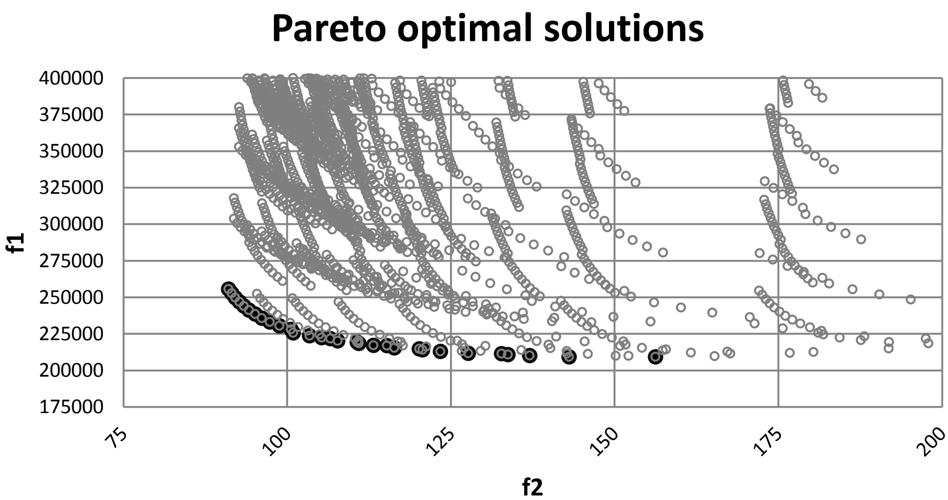


Figure 3.1. Pareto optimal solutions for a generic bi-objective problem

Notice that the Pareto frontier respect the definition given in Eq.(3.2). This approach, referred to as Pareto optimization, has been extensively applied in the literature concerned with multi-criteria design (Stadler and Dauer, 1992; Stadler, 1987, 1988; Osyczka, 1984; Koski, 1994; Grandhi and Bharatram 1993; Grierson and Khajehpour, 2002; Grierson, 2008). Hence, the solution that achieves the optimal balance between tradeoffs can be searched in a limited space (Pareto frontier) without considering the full range of all possible parameters.

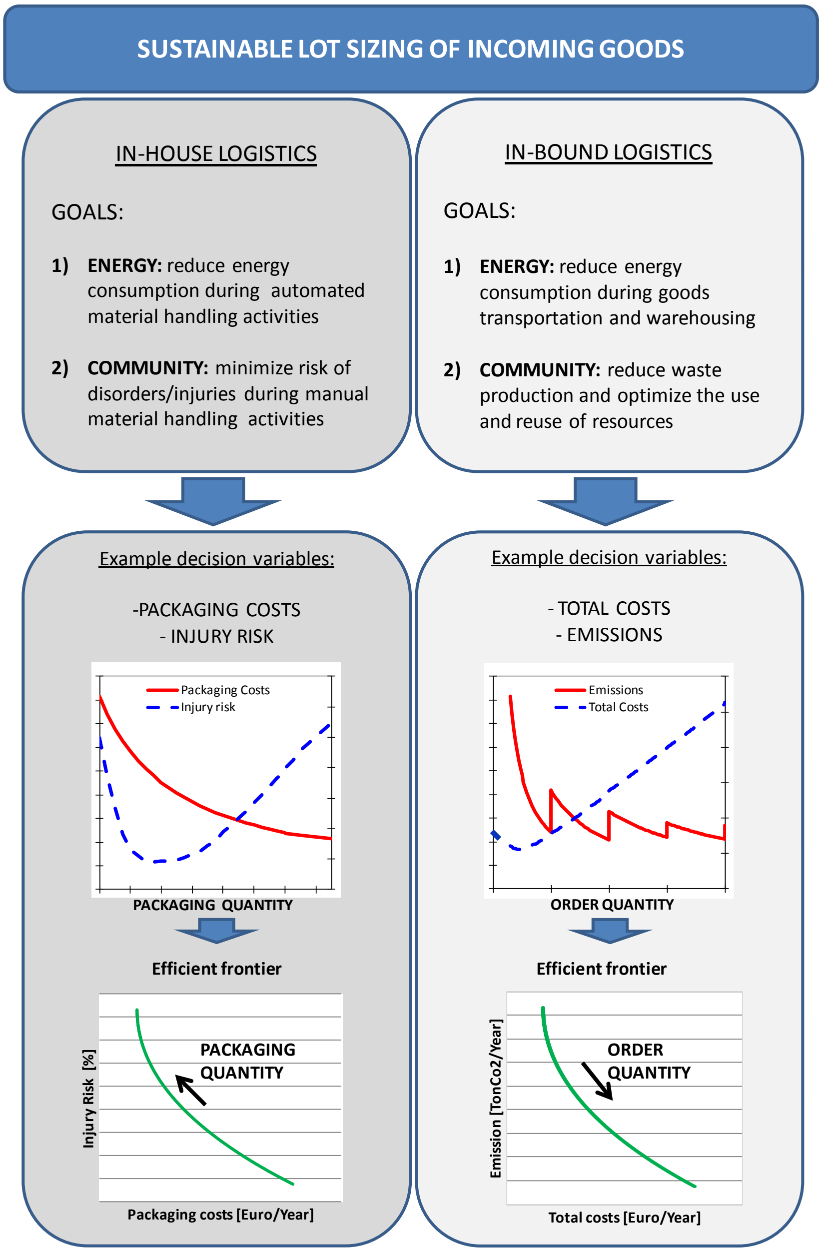


Figure 3.2. Key factors involved in the *Sustainable Lot Sizing* problem.

Fig.(3.2) illustrates the key factors involved in the lot-sizing problem with sustainability issues. Notice that the plots presented in the figure shall be construed as a general and qualitative example, while a deeper analysis will be performed in the following chapters. Anyway, it is possible to find two example of Pareto frontier in the objective space, that highlight the tradeoffs between the economic objective and the sustainability objective for the problem under examination. Logistics decisions may be divided into two main type as explained below:

1) IN-HOUSE LOGISTICS DECISIONS: In this kind of decisions product features, such as weight, volume and packaging characteristics, play an important role since they strongly affect manual material handling efficiency and safety. First of all, it is then necessary to design the most sustainable packaging unit to move on inside the plant. In this case, social criteria directly linked with manual material handling need to be assessed by applying specific approaches not always based on a mathematical computations of quantitative variables. In this context, new research efforts are requested in linking ergonomics aspects with lot sizing decisions, both in production than in purchasing. Ergonomics aspects, in fact, are related to the material handling/lifting activities usually performed by humans in many production systems, and even today they are often not considered in EOQ/EPQ models, or simply included in the cost of re-order. Risk factors related to the development of musculoskeletal disorders, risks of accidents particularly related to loss of balance and falls from heights, and impacts on productivity and quality of service offered to customers in the form of time wasted and stock losses should be considered in this stage. With relation to the product and casing characteristics it is necessary to observe that high values of weight handled determines great exertions and fatigue, therefore the risk for workers arises. On the other hand, small bins and Stock Keeping Units reduce the load weight to be handled but it increase the number of handling operations needed. Besides the determination of maximum load limits, many ergonomics studies have focused on the determination of the rest allowance subsequent to physical exertions. These studies dealt with the intuitive principle according to which when a physical effort is performed, muscles become fatigued and a rest is inevitably necessary. Thus, as an alternative to the injury risk, also the “recovery time” of the operator during handling activity should be used as a “social-sustainable” decision variable.

2) IN-BOUND LOGISTICS DECISIONS: once defined the most sustainable packaging unit in the previous step, it is possible to reconsider our inventory management concepts and include environmental aspects following the sustainability optics. In this case it is necessary to analyze the amount of CO_2 put into the atmosphere caused by deliveries, warehousing, waste disposal/recycling. In this context, of course the impact of transportation activities has a significant influence not only by an economic point of view, but also for the environmental impact. Battini et al. (2012), investigate internal and external transportation costs according to the vendor and supplier position and the different freight vehicle utilization ratio in order to provide an easy-to-use methodology for sustainable lot sizing.

In the light of these considerations, Fig.(3.3) illustrates the new methodological framework here proposed to assess the sustainable lot sizing design according to the 3BL paradigm, and identifies the main decision variables involved according to a Responsible Inventory Management paradigm.

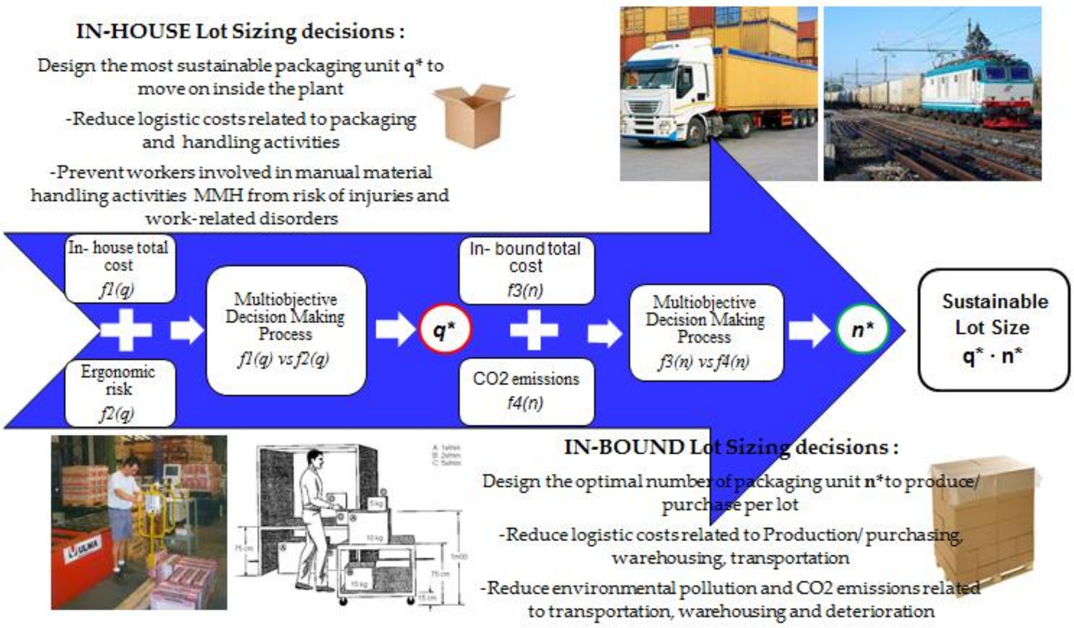


Figure 3.3. Sustainable Lot Sizing framework for incoming materials.

The framework in Fig.(3.3) expects the formulation of four different objective functions, that will be explained in detail in the following chapters. The procedure here identified involves two successive steps, in each of which a trade-off analysis is carried out. The two values for the objective functions (In-house cost vs injury risk , In-bound cost vs Emissions) are computed, and the corresponding point is represented in the space of feasible solutions (see Fig.(3.1)). Then the non-Pareto solutions are removed in order to provide only the efficient frontier. The results of the trade-off analysis are the definition of the best compromise solution for the two decision variables, as explained below:

- *step1:* definition of the optimal number of items per SKU q^*, in order to balance economic and ergonomics goals;
- *step2:* definition of the optimal number of SKU to purchase per lot n^*, in order to balance economic and environmental goals.

It follows that *Step 2* requires the knowledge of the optimized variable q^* that has a fixed value. As a consequence the objective function *f3(n)* and *f4(n)* are discretized on *n*. Notice that since the lot size Q results from Eq.(3.3), the notations $f_i(n)$ and $f_i(Q)$ are completely equivalent.

$$Q = q^* \cdot n \tag{3.3}$$

The most sustainable lot size Q^* is thus given by Eq.(3.4):

$$Q^* = q^* \cdot n^* \tag{3.4}$$

Depending on the specific shape of the Pareto frontier we obtain in a specific real case, it is then possible to define positive or non-positive settings. We will find a positive setting in case it is possible to reduce total annual emissions by increasing the purchasing lot size without significantly increasing cost. This occurs when the region around the cost-optimal solution is relatively flat. Otherwise, when the emission-optimal solution asks the firm to spend too much and it is always less cost-optimal, only Legislation and Direct Cap or a Cap-and-Trade approaches (that means Governmental actions) can force companies in a sustainable direction. The same concepts can be extended to the In-house Logistics case, in which is always the shape of the Pareto frontier that can support or not support a sustainable packaging choice of incoming materials. The methodological framework here proposed needs undoubtedly to evolve and be refined thanks to future research efforts, but actually it aims to provide a first step towards a sustainable Lot Sizing theory.

4 A NEW APPROACH FOR INCLUDING ERGONOMIC PRINCIPLES INTO EOQ MODEL

4.1 The social impact of Lot-Sizing decisions in terms of Ergonomics

As highlighted in chapter 2, the social impact of different inventory management decisions is still poorly addressed with quantitative approaches in the current literature. According to the framework presented in Fig.(3.3) Lot-sizing decisions are divided in two main sets, the first of which consider In-House Logistics where the most influential decision variable is the size of a Stock Keeping Unit SKU, and consequently its weight. One of the aims of this Ph.D. thesis is to provide a quantitative method that is able to quantify the social impact in terms of the ergonomic quality of the purchased SKU, right from the beginning of the analysis.

Ergonomics is a multidisciplinary subject that studies work in relation to the workplace and workers' capabilities. In particular, its purpose is to determine how real settings can be designed or redesigned in relation to human behavior (Wilson, 2000) and how the tasks performed by workers have to be carried out in order to prevent a variety of health disorders and increase productivity and efficiency. Ergonomic aspects are related to the Manual Material Handling (MMH) tasks performed by humans in many production systems. Even today, material handling/lifting activities are not considered in EOQ/economic production quantity (EPQ) models, nor are they simply included in the cost of reorder. Nowadays in fact, companies attempt to optimize the inventory level in order to save money and space in the warehouse, but they seldom consider ergonomic aspects. A report conducted by Denis et al. (2006) in two Québec warehouse superstores of a North American company specializing in the sale of office supplies demonstrated that the disequilibrium between the amount of stock and the available storage space results in the increase of three negative aspects: risk factors related to the development of musculoskeletal disorders; risks of accidents particularly related to loss of balance and falls from heights, and impacts on productivity and quality of service offered to customers in the form of time wasted and stock losses. Industrial companies are involved in accidents and disorders resulting from excessive workloads to which workers are exposed daily. These accidental damages result in significant social, economic, and reputational damage for the companies themselves.

The National Institute of Occupational Safety and Health (NIOSH, United States) estimated that WMSDs are the second major disorder in the top-ten list of health problem in workplaces (NIOSH, 1981). In particular, lower back pain accounts for over 50 billion dollars each year in the United States, including direct medical costs and indirect costs related to the loss of employment and compensation payments. The majority of these costs (75%) can be ascribed to the 5% of workers with temporary or permanent disabilities related to lower back pain (Murrell, 1965; Chaffin, 1972). Recent surveys related to epidemiological data have demonstrated the link between distal upper extremity (elbow, forearm, wrist, hands) disorders and lower back pain with industrial tasks that involve MMH. These disorders could affect subcutaneous tissue, blood vessel, nerves, bones, joints, and muscle-tendon units. Each component of the muscle-tendon unit has its own biomechanical properties, so it is associated with unique disorders. In many situations, symptoms arise from cumulative trauma subsequent to hazardous tasks. For this reason, jobs can be divided into two categories: "safe" and "hazardous". A hazardous job implies that the workers are exposed to potential health risks, such as WMSDs and carpal tunnel syndrome.

The Material Handling Industry of America suggests that the design of production and logistical system, including auxiliary equipment, reduce or eliminate worker injuries whenever possible. However, in many industrial situations such as manual warehousing or picking, packages need to be handled directly by human hands. Thus, the packaging units need to meet ergonomic weight limits and reach requirements for optimal handhold configurations (Rosenau et al., 1996).

4.2 Literature review and Regulations on Ergonomics

According to Moore and Garg (1995), the current in literature highlights four methods to identify hazardous situations:

- Professional opinion from highly qualified job analysts based on subjective evaluations and past experience;
- Evaluation of physiological and/or biomechanical threshold response;
- Analysis of epidemiological data that link tasks and physical variables with some manifestation of increased risk of disorders;
- A combination of the previous three.

Although the professional opinion of specialists (ergonomists, safety professionals, physicians, occupational therapists, etc.) is very desirable and irreplaceable by any model, it is subjective and inevitably influenced by personal bias and background experience. Epidemiological data analysis provides a statistical correlation between jobs and physical disorders, but it does not provide irrefutable responses. Moreover, the vast majority of available data are case reports and case series and they are described qualitatively rather than quantitatively, so it is very difficult to utilize these data to develop semi-quantitative systems. These studies have shown that force, repetitiveness, posture, recovery time, and type of grasp are important risk factors (Moore and Garg, 1995). From a practical point of view, semi-quantitative or quantitative job analysis methodologies are preferable to discriminate between safe and hazardous jobs. These methodologies have limitations and they need to be validated and revised in considerations of real data. The important task variables for MMH tasks are the load lifted/carried, the height from and to the object is lifted, the frequency with which the object is lifted, the distance to which it is carried, and the dimensions and features of the object moved. International regulations such ISO11228 provide guidelines for MMH tasks. In particular, ISO11228-1 provides a method to determine the recommended limits for weight and frequency in lifting and carrying tasks. ISO11228-2 provides a checklist to evaluate the risk for pulling and pushing tasks and a quantitative method to determine the whole body pushing and pulling force limits in relation to the specific characteristics of a worker. ISO11228-3 considers the handling of low loads at high frequency. It provides a checklist and it suggests a detailed method (OCRA) that evaluates frequency, repetitiveness, postures, force, the duration of the repetitive task, and the lack of a recovery period.

Other methods have been developed in the past. In 1981, the NIOSH first developed a semi-quantitative method to analyze jobs and evaluate the risk of two-handed lifting and lowering tasks in the sagittal plane with respect to lower back injury. The lifting equation was widely used by occupational health practitioners because it provided an empirical method for computing a weight limit for manual lifting. The first equation was revised and expanded in 1991 (NIOSH, 1991) to apply to a larger percentage of lifting tasks. The NIOSH equation determines the "Recommended Weight Limit" (RWL), starting from a load constant (LC) multiplied by six multipliers that can take values between 0 and 1. The multipliers are related to asymmetry angle, vertical height of the hands above the floor, horizontal distance of the load, vertical travel distance of the lift, lifting frequency, and coupling classification (ease of grip). The LC assumes different values in relation to gender. The RWL to be lifted is directly derived by Eq.(4.1). The LC assumes different values in relation to gender and age of the worker (see Tab.(4.1)): , whereas multipliers values are determined with the suggested equations or tables (see Tab.(4.2)):

$$RWL = LC \cdot HM \cdot VM \cdot DM \cdot AM \cdot FM \cdot CM \tag{4.1}$$

where LC is the load constant, HM is the horizontal multiplier, VM is the vertical multiplier, DM is the distance multiplier, AM is the asymmetric multiplier, FM is the frequency multiplier, and CM is the coupling multiplier.

LOAD CONSTANT (kg)		
Age	Male	Female
>18	30	20
15-18	20	15

Tab 4.1. Value of the Load Constant according to the NIOSH procedure.

Horizontal Multiplier

H	HM	H	HM
in		cm	
≤10	1.00	≤25	1.00
11	.91	28	.89
12	.83	30	.83
13	.77	32	.78
14	.71	34	.74
15	.67	36	.69
16	.63	38	.66
17	.59	40	.63
18	.56	42	.60
19	.53	44	.57
20	.50	46	.54
21	.48	48	.52
22	.46	50	.50
23	.44	52	.48
24	.42	54	.46
25	.40	56	.45
>25	.00	58	.43
		60	.42
		63	.40
		>63	.00

Asymmetric Multiplier

A	AM
deg	
0	1.00
15	.95
30	.90
45	.86
60	.81
75	.76
90	.71
105	.66
120	.62
135	.57
>135	.00

Vertical Multiplier

V	VM	V	VM
in		cm	
0	.78	0	.78
5	.81	10	.81
10	.85	20	.84
15	.89	30	.87
20	.93	40	.90
25	.96	50	.93
30	1.00	60	.96
35	.96	70	.99
40	.93	80	.99
45	.89	90	.96
50	.85	100	.93
55	.81	110	.90
60	.78	120	.87
65	.74	130	.84
70	.70	140	.81
>70	.00	150	.78
		160	.75
		170	.72
		175	.70
		>175	.00

Distance Multiplier

D	DM	D	DM
in		cm	
≤10	1.00	≤25	1.00
15	.94	40	.93
20	.91	55	.90
25	.89	70	.88
30	.88	85	.87
35	.87	100	.87
40	.87	115	.86
45	.86	130	.86
50	.86	145	.85
55	.85	160	.85
60	.85	175	.85
70	.85	>175	.00
>70	.00		

Coupling Multiplier

Coupling Type	Coupling Multiplier	
	V< 30 inches (75 cm)	V ≥ 30 inches (75 cm)
Good	1.00	1.00
Fair	0.95	1.00
Poor	0.90	0.90

Frequency Multiplier Table (FM)

Frequency Lifts/min (F) ‡	Work Duration					
	≤1 Hour		>1 but ≤2 Hours		>2 but ≤8 Hours	
	V < 30†	V ≥ 30	V < 30	V ≥ 30	V < 30	V ≥ 30
≤0.2	1.00	1.00	.95	.95	.85	.85
0.5	.97	.97	.92	.92	.81	.81
1	.94	.94	.88	.88	.75	.75
2	.91	.91	.84	.84	.65	.65
3	.88	.88	.79	.79	.55	.55
4	.84	.84	.72	.72	.45	.45
5	.80	.80	.60	.60	.35	.35
6	.75	.75	.50	.50	.27	.27
7	.70	.70	.42	.42	.22	.22
8	.60	.60	.35	.35	.18	.18
9	.52	.52	.30	.30	.00	.15
10	.45	.45	.26	.26	.00	.13
11	.41	.41	.00	.23	.00	.00
12	.37	.37	.00	.21	.00	.00
13	.00	.34	.00	.00	.00	.00
14	.00	.31	.00	.00	.00	.00
15	.00	.28	.00	.00	.00	.00
>15	.00	.00	.00	.00	.00	.00

Tab 4.2. Value of the multipliers according to the NIOSH procedure.

Fig.(4.1) shows the geometrical parameters to be considered for the evaluation of the LI according to the normative.

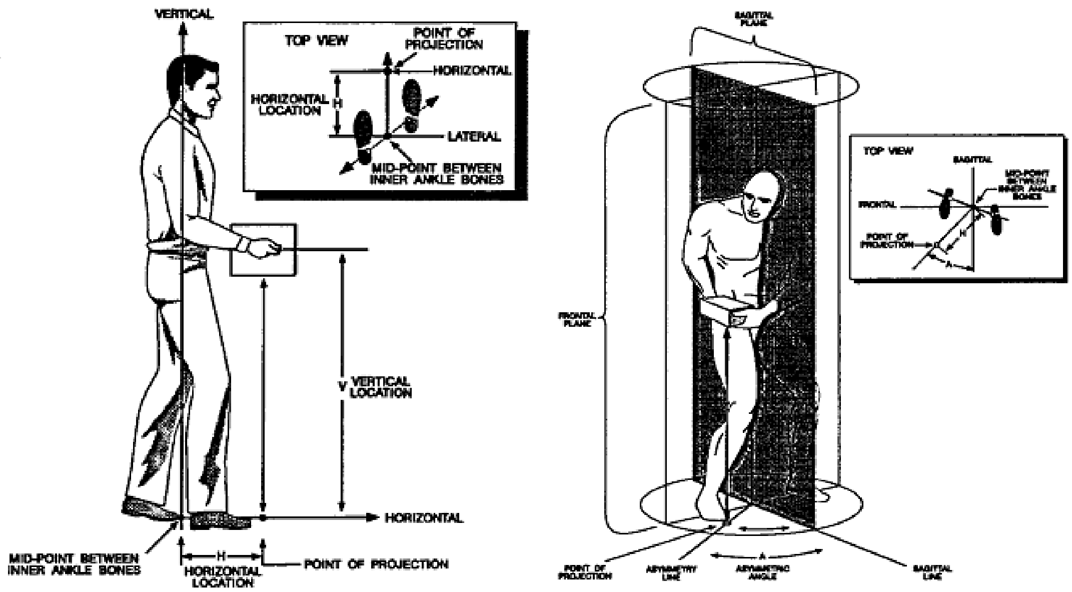


Figure 4.1. Geometrical features for the evaluation of the ergonomic risk according to the NIOSH procedure.

Once the RWL has been computed, it is possible to calculate the Lifting Index (LI) with Eq.(4.2):

$$\mathrm{LI} = \frac{\text{Weight of actual load}}{\text{Recommended weight limit}} = \frac{\mathrm{L}}{\mathrm{RWL}} \tag{4.2}$$

Depending on the value of LI, three different situations are possible:

- LI ≤ 1, the task can be performed without any problem. No redesign is needed;
- 1 < LI ≤ 3, the task could produce some disorder;
- LI > 3, the task is hazardous. A full redesign of the system is needed.

Snook and Ciriello (1991) studied lifting, lowering, pushing, pulling, and carrying tasks. They performed some experiments using male and female subjects, in which they measured oxygen consumption, heart rate, and anthropometric characteristics. The variables considered included gender, task frequency, distance, object size, height, and duration. Using the data collected, they provided some tables for the determination of the maximum acceptable weight and force.

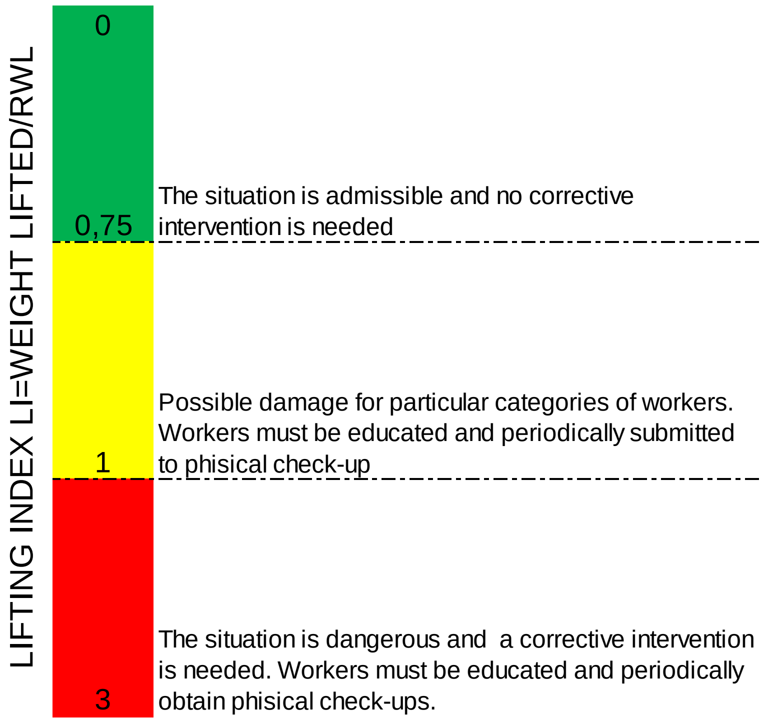


Figure 4.2. Ergonomic evaluation based on the LI (NIOSH).

Moore and Garg (1995) developed a similar methodology called "strain index methodology". The strain index (SI) is a mathematical index derived from the subjective evaluation of six task variables based on physiological, biomechanical, and epidemiological principles: intensity of exertion (force required for a task), duration of exertion, exertion per minute, hand/wrist posture, speed of work, and duration of task per day . Each task variable is rated according to a five-level scale (fewer levels for speed of work and posture) and the SI is the product of all six multipliers. Compared with opportune scales, the SI helps to discriminate between safe and hazardous tasks.

Below in chapter 4.3, the risk of injury for stockers is quantified using the LI as expressed by Eq.(4.2). With regard to the MMH activities performed by the stockers, the most relevant variables that impact on safety and efficiency of the workers are undoubtedly the SKU's size and weight. Thus, an ergonomically conscious determination of the best packaging unit (Rosenau et al., 1996; Hellström and Saghir, 2007) can result in more efficient industrial processing for many points of view: handling, lifting, loading/unloading activities (Chan et al., 2006; Lee and Lye, 2003), material handling devices (Hellström and Saghir, 2007), filling, packing and unpacking (Mollenkopf et al., 2005; Chan et al. 2006; Lee and Lye, 2003; Ge,1996), and warehousing and stocking (Ge,1996). Eq.(4.2) suggests that a high value of the load lifted results in a high risk of injuries for the worker. The weight L of the SKUs used to contain items is determined by the unit weight of the single item uw [kg/item] multiplied by the number of items per packaging unit q [items], according to Eq.(4.3):

$$L = q \cdot uw = \text{[kg]} \tag{4.3}$$

The weight of the unit is so calculated by neglecting the weight of the packaging material. This assumption is accurate in the case of cardboard packaging and when the number of items per unit is sufficiently high. Under these assumptions, the LI equation becomes Eq.(4.4):

$$\mathrm{LI(q)} = \frac{\mathrm{L}}{\mathrm{RWL}} = \frac{q \cdot uw}{RWL} \tag{4.4}$$

The RWL is determined by estimating the multipliers in Eq.(4.1) related to geometric features and frequency involved in lifting\lowering tasks performed by stockers, according to the procedure provided by the NIOSH (1981). For this reason, all the multipliers and therefore the LI are strongly linked to the specific situation under consideration. According to Fig.(4.2), in order to minimize the risk of musculoskeletal disorders for all categories of workers, the weight lifted has to be less than the value of the RWL multiplied by a LI of 0.75. The safety factor of 0.75 outlines the extent of the "Green Area" (Fig.(4.2)), which is the weight limit that assures an acceptable working situation and does not require any improvement action. Note that the boundaries between the areas are not well defined, so it is advisable to stay as far as possible from the limiting value. In a good ergonomic situation, the weight lifted/carried CW in the handling jobs cannot exceed the limit given by Eq.(4.5):

$$CW \leq 0.75 \cdot RWL \tag{4.5}$$

Of course, the best situation to minimize the risk of accident occurs when the SKU is as light as possible, but this would lead to an infeasible solution.

4.3 Modeling the economic impact of the SKUs

From an economical perspective, the number of items per SKU directly impacts the total logistical costs. In particular, "in-house" logistics, which involve all of the decisions that have direct consequence on the activities carried out within the plant, are influenced. Two cost items are a direct function of the number of items per SKU: the packaging cost per year $C_p(q)$ and the handling cost per year $C_{hand}(q)$. Eq.(4.6) models the total "in-house" cost $C_{tot\ IH}(q)$ to be borne by the company every year:

$$C_{tot\ IH}(q) = C_p(q) + C_{hand}(q) \tag{4.6}$$

Traditionally, packaging design has been considered less important than product and production systems design. However, its impact on logistical costs and performance is very relevant and its strategic role inside the supply chain is now acknowledged (Azzi et al., 2012). Packaging design research has attracted considerable attention in the recent past. In the following, some general data about packaging costs and impact are listed, derived from the literature in this field:

- Packaging costs represent approximately 9% of the cost of any product (Làszlo, 1990);
- Packaging materials influence only 10% of the total packaging cost (Stern, 1981);
- Packaging use and disposal is approximately 60% of the total production cost for manufacturing companies (Rauch Associates, 2002; Briston, 1972);
- Packaging materials constitute approximately 65% of the global solid waste (Brody and Marsh, 1997).

In the following model, it has been considered only the unit pack containing the items while the secondary packaging and the shipping packaging, have been overlooked since they have a limited impact on MMH activities. It is a common assumption in the literature that once the packaging material is fixed, part of the cost of a single packaging unit is proportional to its inner volume (Làszlo, 1990; Stern, 1981) because it influences the amount of material necessary for the construction of the packaging unit itself. On the other hand, some handling operations such as filling, closing and palletizing, and/or warehousing are conducted on the SKUs regardless of their size. Starting from this assumption, the cost of a single packaging unit is expressed in relation to the number of items contained, which is directly proportional to the inner volume of the packaging itself. The unit packaging cost is modeled using Eq.(4.7):

$$c_p(q) = \left(c_{fp} + c_{vp} \cdot q\right) \quad (4.7)$$

where $c_p(q)$ is the unit packaging cost (cost of one SKU), q is the number of items per SKU, c_{fp} is the unit fixed cost of packaging, and c_{vp} is the unit variable cost of packaging per item. Through the proper calibration of the two cost parameters c_{fp} and c_{vp} , it is possible to model the unit packaging cost per SKU using Eq.(4.7). As a consequence, the total annual packaging cost can be modeled by Eq.(4.8):

$$C_p(q) = \frac{D}{q} \cdot c_p(q) = \frac{D}{q} \cdot c_{fp} + D \cdot c_{vp} \quad (4.8)$$

where $C_p(q)$ is the total annual cost for packaging and D is the annual demand of the item. Notice that Eq.(4.8) contains a variable part with the number of items per SKU and a fixed part that is not affected by the value of q. The cost of MMH activities in inventory operations varies depending if auxiliary equipment is required. If the load is sufficiently low, the operations can be performed manually; on the contrary, tools that facilitate the handling of loads such as trolleys or jib cranes may be needed.

The annual total handling cost is assessed by Eq.(4.9):

$$C_{hand}(q) = \frac{D}{n \cdot q} \cdot (c_{hw} + c_{he} \cdot x) \cdot (t_h) = \frac{D}{n \cdot q} \cdot (c_{hw} + c_{he} \cdot x) \cdot (t_u \cdot n) = \frac{D}{q} \cdot (c_{hw} + c_{he} \cdot x) \cdot t_u \quad (4.9)$$

where $C_{hand}(q)$ is the total annual MMH cost, D is the annual demand of the item, q is the number of items per SKU, n is the number of SKUs per lot, c_{hw} is the labour cost per hour, c_{he} is the equipment cost per hour, t_h is the handling operation time per lot, t_u is the handling operation time per SKU, and

$$x \quad \begin{cases} 0 \textit{ if operations can be performed manually } (when\ LI < 1) \\ 1 \textit{ if auxiliary equipment are required } (when\ LI \geq 1) \end{cases} .$$

Substituting Eq.(4.8) and Eq.(4.9) into Eq.(4.6), we obtain Eq.(4.10):

$$C_{tot\ IH}(q) = \frac{D}{q} \cdot c_{fp} + D \cdot c_{vp} + \frac{D}{q} \cdot (c_{hw} + c_{he} \cdot x) \cdot t_u \quad (4.10)$$

4.4 A Multi-objective approach for Ergonomic Lot-Sizing

As pointed out above in Fig.(3.3), the most important inventory choice that affects daily "in-house" problems is the determination of the packaging unit to be used. With relation to the product and casing characteristics, it is easy to observe that high values of weight handled result in significant exertion and a risk of injury. On the other hand, small SKUs reduce the weight to be handled, but the number of needed operations and their cost increase. For this reason, this choice must be carefully considered prior to this trade-off. The framework depicted in Fig.(3.3) is here adapted in Fig.(4.3), aiming to link these two areas that normally are not connected in the industry decision making process, by proposing a precise sequence in the problem solving process.

The method here proposed, presents a new lot-sizing procedure for a single-product replenishment problem based on a multi-objective approach that investigates the traditional EOQ framework paired with the social impact of inventory decisions quantified in term of the ergonomics of handling activities. The main difference from previous literature in the field relates to the definition (for the first time) of an ergo-quantity q in accordance with the NIOSH procedure, through the consideration of the LI that evaluates the ergonomic impact of lifting activities. This first step of the proposed framework assures the creation of ergonomic material SKUs to be moved inside the plant. Then, the economic optimization procedure consists of defining the optimal number n of SKUs to purchase in order to minimize the total annual costs.

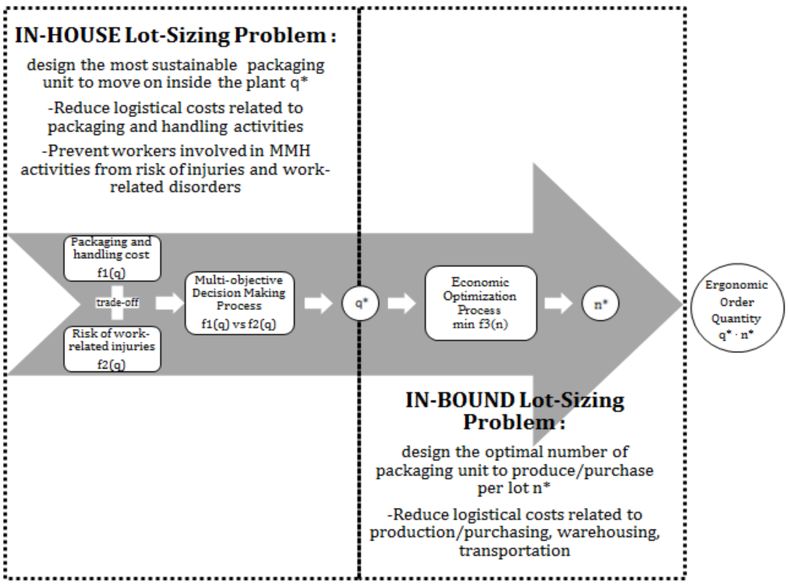


Figure 4.3. Methodological framework for ergonomic lot sizing.

4.4.1 First step: sustainability considerations in the in-house problem

In the first step of the methodology, it is necessary to solve the "in-house" lot-sizing problem, particularly in the simultaneous consideration of economic and social criteria. Following the framework in Fig.(4.3), it is necessary to start from the determination of the most sustainable packaging unit. Using a bi-objective approach, two functions must be considered: the former serves to quantify the economic impact of the choice and the latter serves to evaluate the risk of damage for the worker. The decision variable is thus the SKU's size and it is easy understandable that it directly affects packaging cost, handling cost, and the risk for the workers involved in MMH activities. As in many engineering problems, these two criteria are conflicting, requiring designers to look for good compromise designs by performing tradeoff studies involving the two criteria. This suggests the use of non-dominated optimization to identify a set of feasible designs that are equal-rank optimal, in the sense that no design in the set is dominated by any other feasible design for all criteria, according to the Pareto optimization problem. Thus, let us call $f_1(q)$ the first objective function (the in-house costs) and $f_2(q)$ the second objective function (the risk of injuries) and let us define these quantities as follows:

$$f_1(q) = C_{tot\ IH}(q) = \frac{D}{q} \cdot c_{fp} + D \cdot c_{vp} + \frac{D}{q} \cdot (c_{hw} + c_{he} \cdot x) \cdot t_u \tag{4.11}$$

$$f_2(q) = \mathrm{LI(q)} = \frac{q \cdot uw}{RWL} \,. \tag{4.12}$$

A mathematical analysis of Eq.(4.11) and Eq.(4.12) provides evidence that the total cost function is strictly decreasing with the SKU's size q. Therefore, the optimal solution occurs with the largest SKU possible. On the other hand, the LI is a strictly increasing function over the SKU's size q; the optimality then occurs with the lightest SKU. The best solution from an economic point of view is then the worst from an ergonomic point of view, and vice versa. The two optimal solutions are completely the opposite; the best solution must be chosen as a compromise between the optimal solutions. The decision maker in this case can follow different approaches in the choice of the best SKU's size, according to the company philosophy. A qualitative decision framework is presented below:

Company philosophy	**Profit target**	**Risk of injuries**	**SKU's size**
Pure cost minimization	High	High	q so that LI>>1
Respect of the legislative limit	Medium/High	Medium	q so that LI≤1
Safeguard of the health of employees	Medium	Low	q so that LI≤0.75
High "social responsibility"	Minimum	Very low	q so that LI<<0.75

Table 4.3. Qualitative decision framework based on the "social responsibility" of the decision maker.

Tab.(4.3) describes the decision making process regarding the choice of the best SKU's size. In the light of the previous consideration, it is easy to understand that the higher the profit target, the lower the safeguard of the workers involved. Of course, any quantitative evaluation of the profit reduction must be done for each individual case. Regardless, a quantitative approach to support the decision maker is desirable and fortunately the literature includes different methods to treat multi-objective optimization problems. These methods are divided into three major categories, in relation to the mode of articulation of the preferences of the decision maker:

- Methods with a priori articulation of preferences;
- Methods with a posteriori articulation of preferences;
- Methods with no articulation of preferences.

For a detailed description of the aforementioned methods, see Marler and Arora (2004). In order to solve the multi-objective problem under consideration, it is convenient to use the concept of indifference band (Passy and Levanon, 1984). An indifferent band is the area on the Cartesian coordinate plane where the feasible solutions are all equally desirable to the decision maker. Between any two solutions in the indifference curve there is a trade-off, so that a decrement in the value of one objective function f_i inevitably determines an increment in the other objective function f_j (see Fig.(4.4)). The second concept, which is necessary for our purpose, is the utility function U. In economics, utility is the concept that expresses the decision maker's satisfaction for a solution. In the multi-objective field, an individual utility function is derived for each objective. The utility function U is a mathematical expression that attempts to model the decision maker's preference. There is a certain increment in one objective function that a decision maker is willing to accept for a certain improvement of the other objective. This is called the Marginal Rate of Substitution (Miettinen, 1999). The Marginal Rate of Substitution m_{ij} (Eq.(4.13)), also called the indifference trade-off, is the negative of the slope of the tangent to the indifferent curve at a certain point (Fig.(4.4)) and it therefore provides a local linear approximation of the indifference curve:

$$m_{ij}(x) = \frac{\partial U(f(x))}{\partial f_j} / \frac{\partial U(f(x))}{\partial f_i} \tag{4.13}$$

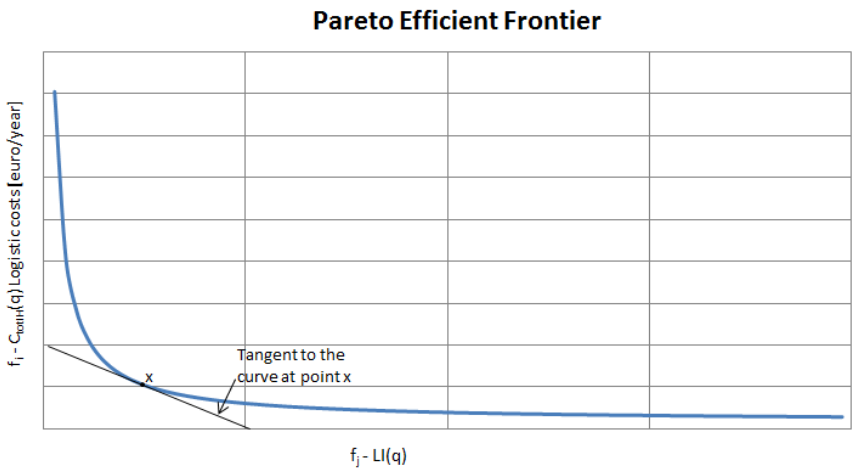


Figure 4.4. Generic Pareto Efficient Frontier for solving the in-house problem.

One of the objective functions is selected as a reference function f_i, and the trade-offs and the marginal rates of substitution are generated with respect to it. Since the reference function must be significant and the most familiar to the decision maker, which in our case is the firm, the total cost of in-house decisions $C_{tot\ IH}(q)$ is considered as the reference function. Under these assumptions, Eq.(4.13) becomes:

$$m_{ij}(q) = \frac{\partial C_{tohIH}(q)}{\partial \mathrm{LI(q)}} \tag{4.14}$$

The decision making process can be performed by generating the entire range of efficient solutions and calculating for each of these the marginal rate of substitution $m_{ij}(q)$. Then, fixing a limiting value of m_{ij}, which is proportional to the social responsibility of the company, the most sustainable solution for the decision maker is obtained. Such a limit value can be defined "*social responsibility index*". This index, in this problem, can be read as the maximum expense that the decision maker is willing to bear to reduce the LI from 1 to 0. If the company is very health conscious, it is willing to accept a significant increment in the total logistical costs in order to improve ergonomics in the workplace. In this case, the social responsibility index is high. On the other hand, if the company is not health conscious, it is not willing to accept considerable increments in its total logistical costs and its social responsibility index is low. After the social responsibility index is defined by calculating the marginal rate of substitution m_{ij}(q) for all the point of the frontier, the point that represents the greatest ergonomic improvement obtainable is obtained, while respecting the expense limit (see Fig.(4.5)). This point represents the most sustainable packaging unit and then the optimal number of items per SKU q^* is defined.

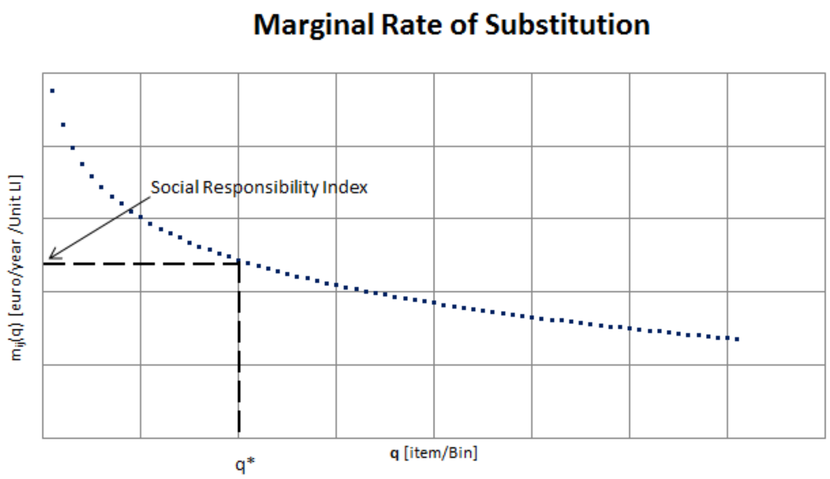


Figure 4.5. Generic marginal rate of substitution and the social responsibility index effect.

4.4.2 Second step: the ergonomic order quantity of in-bound materials

In the second step described in the framework, it is necessary to solve the "in-bound" problem. In the following, the situation where transportation issues are negligible is examined. This assumption is valid when the supplier is located in the same region of the customer, where transportation costs can be included in a unique and constant cost item C_{ord} and emissions due to vehicles utilization are low. Thus, at first instance environmental impact is assumed to be negligible and it will be included in the model only in chapter 5.

Since the SKU's size q^* has been previously defined, the packaging cost per year C_p and the handling cost per year C_{hand} are fixed and they are also invariant with respect to n , therefore these quantities do not affect the "in-bound" problem. It is important to observe that under these hypothesis the only decision variable to optimize is the number of SKUs n to purchase per lot, and the total cost function is discrete. The following sections presents an economical optimization process based on the method developed by Garcia-Laguna et al. (2010) to determine the optimal lot size in case of integer lot. The third objective function $f_3(n)$ introduced in Fig.(4.3) is represented by the total cost associated with the in-bound purchasing decision $C_{totIB}(n)$ and it is described by Eq.(4.15):

$$f_3(n) = C_{totIB}(n) = C_b(n) + C_{ord}(n) + C_{hold}(n) \tag{4.15}$$

where $C_b(n)$ is the purchase cost per year, $C_{ord}(n)$ is the ordering cost per year, $C_{hold}(n)$ is the stock holding cost per year, and $C_{tot\ IB}(n)$ is the total annual cost of the in-bound decision.

The annual purchase cost $C_b(n)$, ordering cost $C_{ord}(n)$, and the stock holding cost $C_{hold}(n)$, can be traditionally determined respectively by the following:

$$C_b(n) = D \cdot c \tag{4.16}$$

$$C_{ord}(n) = K \cdot \frac{D}{n \cdot q^*} \tag{4.17}$$

$$C_{hold}(n) = \frac{n \cdot q^*}{2} \cdot h \cdot c \tag{4.18}$$

where q^* is the number of items per SKU, K is the fixed cost of placing one order, c is the unit purchase cost per item, h is the unit stock holding cost per € per year, including interest and depreciation in stock, n is the number of SKUs per order, n^* is the optimal number of SKUs per order, $n \cdot q^*$ is the lot size, and $n^* \cdot q^*$ is the optimal lot size. In light of Eq.(4.16), Eq.(4.17), and Eq.(4.18), the total cost of the in-bound decision $C_{totIB}(n)$ becomes:

$$C_{totIB}(n) = c \cdot D + K \cdot \frac{D}{n \cdot q^*} + \frac{n \cdot q^*}{2} \cdot h \cdot c \tag{4.19}$$

In the first instance, the optimal solution could be determined by differentiation of Eq.(4.19) with respect to n, according to the original work of Harris (1913):

$$\frac{dC_{totIB}(n)}{dn} = -K \cdot \frac{D}{n^2 \cdot q^*} + \frac{q^*}{2} \cdot h \cdot c = 0 \quad (4.20)$$

$$n^* = \sqrt{\frac{2 \cdot D \cdot K}{h \cdot c \cdot {q^*}^2}} \quad (4.21)$$

Anyway, it is important to emphasize that this process of optimization is performed under the assumption that the variables involved are continuous, therefore the differential calculus for one variable is not applicable when it is restricted to an integer value, as is in our case. In this situation, a simple rounding of the result of Eq.(4.21) may lead to a suboptimal inventory policy.

In the following, the simple procedure developed by García-Laguna et al. (2010) is adapted when the lot size must be an integer quantity. Their method is based on the marginal analysis that is commonly applied in econometrics and engineering fields:

$$Minimize \;\; C_{totIB}(n) = c \cdot D + K \cdot \frac{D}{n \cdot q^*} + \frac{n \cdot q^*}{2} \cdot h \cdot c \quad (4.22)$$

$$Subject\ to \qquad q > 0\ and\ integer \quad (4.23)$$

Taking into account that $C_{totIB}(n)$ is a convex function over the set of the positive integer numbers $n = \{1, 2, 3, \dots\}$, Eq.(4.24) provides the optimal solution if it is unique, or the lower of the solutions, when there are two optimal solutions:

$${n_i}^* = min\left\{n \,\epsilon\, N : n(n+1) \geq \frac{2 \cdot D \cdot K}{h \cdot c \cdot {q^*}^2}\right\} \quad (4.24)$$

Likewise, Eq.(4.25) gives us the optimal solution if it is unique or the larger solution when there are two optimal solutions:

$${n_u}^* = max\left\{n \,\epsilon\, N : n(n-1) \geq \frac{2 \cdot D \cdot K}{h \cdot c \cdot {q^*}^2}\right\} \quad (4.25)$$

The unique positive solutions of the quadratic Eq.(4.24) and Eq.(4.25) are respectively given by Eq.(4.26) and Eq.(4.27):

$$n_i^* = \left\lceil -0.5 + \sqrt{0.25 + \frac{2 \cdot D \cdot K}{h \cdot c \cdot q^{*2}}} \right\rceil \tag{4.26}$$

$$n_u^* = \left\lfloor 0.5 + \sqrt{0.25 + \frac{2 \cdot D \cdot K}{h \cdot c \cdot q^{*2}}} \right\rfloor \tag{4.27}$$

Let us define $x = -0.5 + \sqrt{0.25 + \frac{2 \cdot D \cdot K}{h \cdot c \cdot q^{*2}}}$ and $x + 1 = 0.5 + \sqrt{0.25 + \frac{2 \cdot D \cdot K}{h \cdot c \cdot q^{*2}}}$.

It is easy to understand that $\lceil x \rceil = \lfloor x + 1 \rfloor$ only in the case that x is not an integer number. Consequently, we have that there is a unique optimal solution $n_i^* = n_u^*$ if and only if $-0.5 + \sqrt{0.25 + \frac{2 \cdot D \cdot K}{h \cdot c \cdot q^{*2}}}$ is not an integer number, otherwise there are two optimal solutions, n_i^* and $n_u^* = n_i^* + 1$. The solving procedure discussed above can be summed up in three steps:

Step 1. Calculate $x = -0.5 + \sqrt{0.25 + \frac{2 \cdot D \cdot K}{h \cdot c \cdot q^{*2}}}$ or,

Analogously $x + 1 = 0.5 + \sqrt{0.25 + \frac{2 \cdot D \cdot K}{h \cdot c \cdot q^{*2}}}$;

Step 2. Case A - x is not an integer number: the unique optimal integer solution is given by Eq.(4.26) (or equivalently by Eq.(4.27))

Case B - x is an integer: there exist two different integer solutions, given respectively by Eq.(4.26) and Eq.(4.27)

Step 3. The minimum cost is determined by entering the optimal solution into Eq.(4.22).

4.4.3 Model application

This section presents a case study derived from a real industrial situation. The feeding of assembly lines involves the handling of different type of items. Some of these items are very heavy (big iron/steel components) and require the use of trolleys, transpallets, or fork lifts. Other items are quite small and they can be carried by hand in small Stock Keeping units (screws, fasteners, small plastic parts, small metallic forged items). In this section, the lot-sizing procedure presented above is applied to the latter category of items, in order to evaluate the differences between the optimal solution according to the traditional economical approach (Harris, 1913) and the optimal solution achieved with the new ergonomic conscious approach. The item considered is a small iron forged part with a unit weight uw of *0.028kg*.

These items are stored in a supermarket next to the assembly line and the storage activities involve the stockers in lifting and lowering activities, whose ergonomic evaluation is expressed via the RWL according to the NIOSH approach. Input data and geometrical specifications of the problem are listed below, and they are derived from the observation of the receiving tasks:

- Gender: male;
- Age: >18;
- Starting point of the lift: 10cm;
- Vertical dislocation: 80cm;
- Horizontal distance: 25cm;
- Asymmetric angle: 0°;
- Type of grasp: good;
- Frequency: 1lift/min;
- Duration of tasks: <1h.

The RWL with the input data is:

$$RWL = 30 \cdot 0.83 \cdot 0.88 \cdot 1 \cdot 1 \cdot 1 \cdot 0.94 = 20.39\ kg \tag{4.28}$$

It is assumed that in this case no space constraint exists, thus the quantity for each box is determined only in relation to the weight to be handled. The weight of the carton box is assumed to be negligible. The RWL represents the maximum load to be lifted by a worker and therefore it fixes the maximum number of items per SKU, which, in this case, is given by Eq.(4.29):

$$q_{max} = \left\lfloor \frac{RWL}{uw} \right\rfloor = 726\ items/bin \tag{4.29}$$

The project data and the cost parameters are listed below:

D	*200000 items/year*
K	*60 €/order (phone calls, e-mail, practices, receiving, load-unload)*
C	*0.3 €/item*
h	*0.15 1/year*
c_{fp}	*0.37 €/SKU*
c_{vp}	0.0018 *€/item·SKU*
c_{hw}	*25 €/working hour*
t_u	*1min/SKU*

The “social responsibility index” is assumed to be 1000 [€/unit LI].

First, the procedure focuses on the in-house problem, according to the framework in Fig.(4.3). The reference function to be used in the multi-objective optimization is the total cost of the in-house decisions. Assuming that all the activities must be carried out only by hand, without any supporting equipment, the total cost is given by Eq.(4.30):

$$C_{tot\ IH}(q) = \frac{20000}{q} \cdot 0.37 + 20000 \cdot 0.0018 + \frac{20000}{q} \cdot 25 \cdot 1 \tag{4.30}$$

The second objective function in the multi-objective problem is Eq.(4.31):

$$\mathrm{LI} = \frac{\mathrm{L}}{\mathrm{RWL}} = \frac{q \cdot 0.028}{20.39} \tag{4.31}$$

The two objective function patterns are shown below in Fig.(4.6).

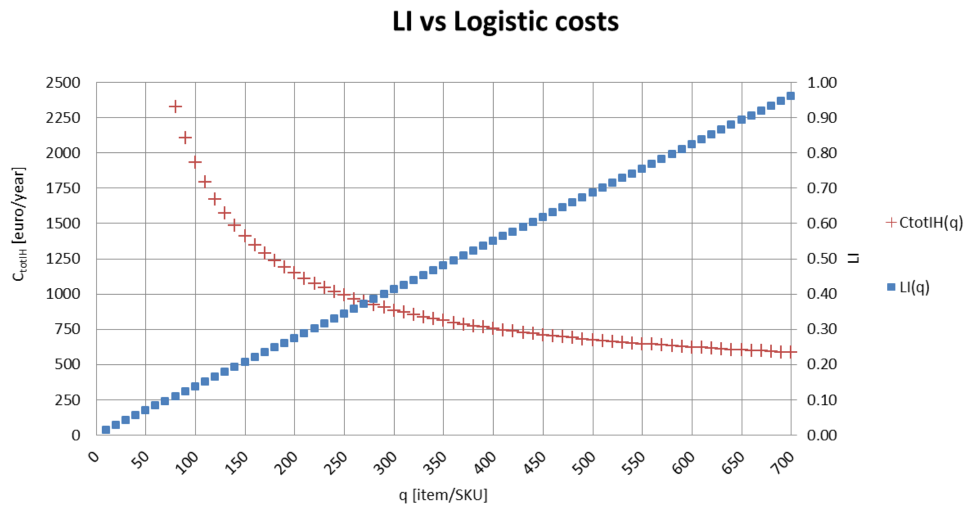


Figure 4.6. Total cost of in-house logistics decisions vs. LI.

Fig.(4.7) shows the set of efficient solutions of the problem:

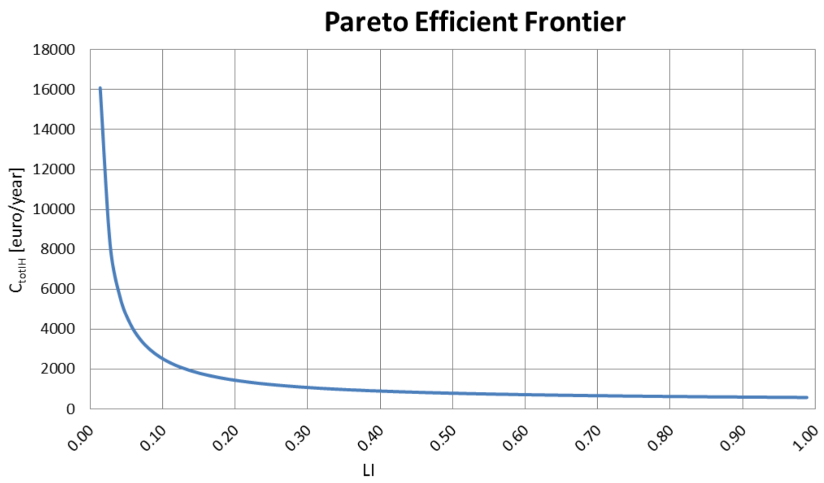


Figure 4.7. The Pareto Efficient Frontier.

The decision making process presented in Section 4.4 involves the calculation of the marginal rate of substitution $m_{ij}(q)$ for all the efficient solutions, via the application of Eq.(4.14). This calculation can be replaced by its approximation:

$$m_{ij}(q) = \frac{\partial C_{tohIH}(q)}{\partial \mathrm{LI(q)}} \cong \frac{\Delta C_{tohIH}(q)}{\Delta \mathrm{LI(q)}} \tag{4.32}$$

where $\Delta C_{tohIH}(q)$ and ΔLI(q) are the deltas in Eq.(4.30) and Eq.(4.31), moving from one point of the set of efficient solutions to the adjacent one. The results are shown in Fig.(4.8). Pointing out that the social responsibility Index is 1000 [€/unit LI], it follows that the intersection of the curve with this limit value occurs at

$$q^* = 330 items/bin$$

which is the most sustainable packaging unit.

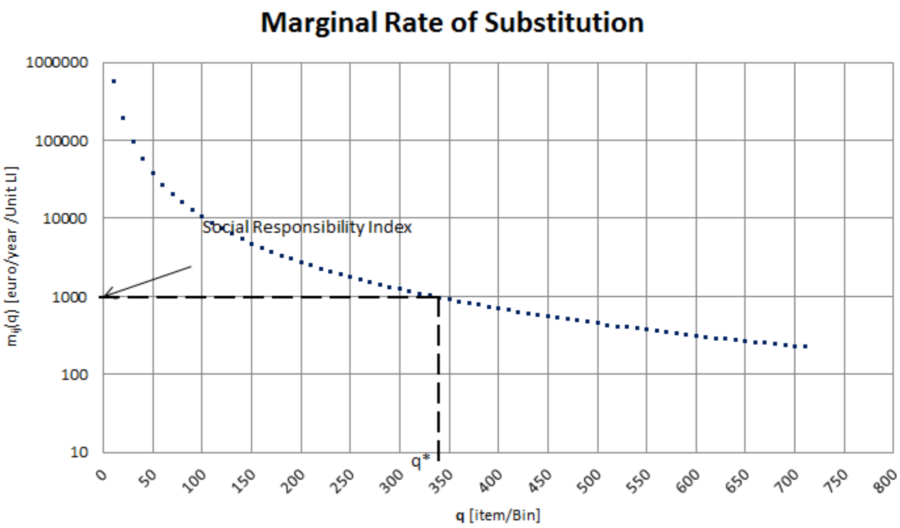


Figure 4.8. The marginal rate of substitution.

Then, the weight of the most sustainable SKU, the LI, and the total in-house cost become, respectively:

$$\mathrm{L} = 330 \cdot 0.028 = 9.34\mathrm{kg} \tag{4.33}$$

$$\mathrm{LI} = \frac{\mathrm{L}}{\mathrm{RWL}} = \frac{9.34}{20.39} = 0.453 \tag{4.34}$$

$$C_{tot\ IH}(q) = 836.77€/year \tag{4.35}$$

Now, the problem focuses on the in-bound decisions and the optimal number of SKUs to be purchased per lot is determined using the simple three-step method presented in Section 4.4.2.

Step 1. $$x = -0.5 + \sqrt{0.25 + \frac{2 \cdot 200000 \cdot 60}{0.15 \cdot 0.3 \cdot 330^2}} = 69.48$$

Step 2. Since x is not an integer number , the unique optimal integer solution is given by $n^* = n_i{}^* = \lceil x \rceil = 70$ bins

Step 3. The minimum cost is

$$C_{totIB}(n^*) = 0.3 \cdot 200000 + 60 \cdot \frac{200000}{330 \cdot 70} + \frac{330 \cdot 70}{2} \cdot 0.15 \cdot 0.3 = 61039.23€/\text{year}$$

where 60000 $€/year$ is the purchase cost that is invariant respect the lot size, while the variable part due to ordering cost C_{ord} and stock holding cost C_{hold} is 1039.23 $€/year$. Fig.(4.9) shows the variable costs on the number of SKUs per lot.

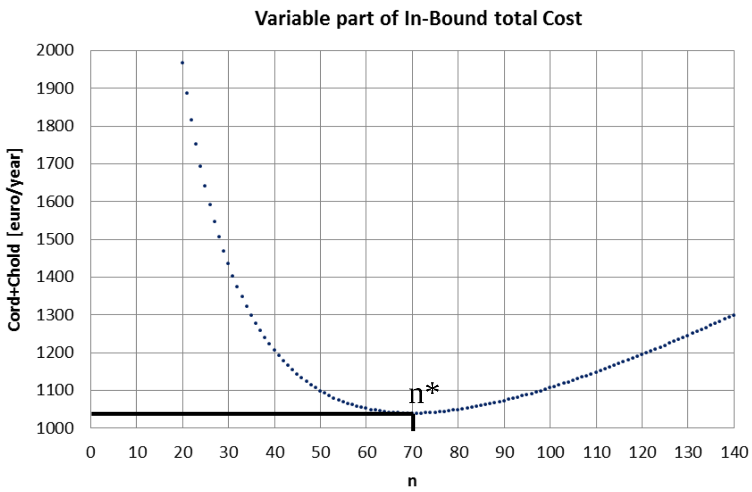


Figure 4.9. The variable part of the total in-bound cost.

The most sustainable lot size is finally:

$$Q^* = n^* \cdot q^* = 330 * 70 = 23100 \; items/lot \qquad (4.36)$$

The optimal lot size according to the Harris formula (1913) is given by Eq.(4.21):

$$Q^* = \sqrt{\frac{2 \cdot D \cdot K}{h \cdot c}} = 23094 \; items/lot \qquad (4.37)$$

Let us observe that the new model is fully in accordance with the traditional lot-sizing literature since the difference in the result is only due to the discretization of the lot-sizing problem under consideration: in fact, thanks to the definition of an ergonomic

SKU at first instance, it is possible to re-think the EOQ model in terms of the optimal number of ergonomic SKUs to purchase. Fig.(4.10) shows the result of the application of this new method: the items that were traditionally purchased in large metallic baskets are now supplied using small easy-to-handle plastic casing, with a strongly improved ergonomic impact.

Figure 4.10. Result of the new approach: before and after the application of the method.

In this example, the effort required by the company to make this sustainable choice amounts to only 1.4% of total annual in-bound cost (836.77 € out of a total annual in-bound cost of 61039,23 €).

4.5 Ergonomic lot-sizing model with a direct costing approach

As stated in chapter 4.1, a different approach to deal with the social impact of Lot sizing problem is the direct costing, where social issues are quantified in terms of financial expenditure for the firm. Such a method can be attractive for its quick applicability, and it grants the advantage of providing a closed-form solution for the problem. In this chapter, the ergonomic impact of MMH tasks is translated in financial terms using the "Energy expenditure method", through the quantification of the time wasted for the rest of the workers involved in the receiving and handling tasks. Besides the determination of maximum load limits in fact, many studies have focused on the determination of the rest allowance subsequent to physical exertions. These studies dealt with the intuitive principle according to which when a physical effort is performed, muscles become fatigued and a rest is inevitably necessary. Garg et al. (1978) provided a collection of formulas to determine the metabolic rates for MMH operations. They provided a method to determine metabolic energy expenditure rate for a series of task that involves lifting, lowering and carriage of loads in relation to the body weight of the subject performing these activities, distance, frequency, body postures, and gender. The aforementioned method (reported in Appendix II) is based on the assumption that a job can be divided into simple tasks, and that the average metabolic energy consumption can be determined as the sum of the energy demands of each task and the maintenance of body posture averaged over time. Physiological tests performed on a sample of the US population by Chaffin (1972) have stated that the maximum aerobic power of a normal young male is 16 Kcal/min for a highly dynamic job. For an entire work shift (eight hour) Chaffin suggests a physical work capacity limit of 5.2Kcal/min (33% of the maximum aerobic power). When this limit is exceeded a rest allowance becomes necessary. Literature presents several works concerning the determination of rest allowance consequential to physical exertions. Among others let us mention Murrel (1965), Rohmert (1973), Eliezer E. Kamon (1982). These works determine rest allowance time as percentage of the time of the task with knowledge of the metabolic requirements of a job.

This paragraph develops a model for calculating the full costs of a single-product replenishment problem based on the traditional EOQ framework and in which the social impact of the material lot size is considered in term of ergonomics of handling activities, through the consideration of rest allowance related to the effort performed. In particular the decision variables is the number of SKUs n to purchase per lot, and the optimization takes into account also the rest allowance subsequent to n handling operations in the receiving phase.

The main difference from previous literature in the field relates to the definition (for the first time) of an ergo-quantity q in accordance with the NIOSH procedure, in order to assure the creation of ergonomic material bins. Then, the optimization procedure consists in defining the optimal number n of bins to purchase in order to minimize the total annual cost. In this case, handling costs quantification and down time costs estimation in function of the recovery time required to the operator during handling tasks have been included. As stated in Appendix II, the number of items per stock keeping unit and therefore the weight of the box lifted/carried, strongly influences the intensity of exertion. The metabolic rate for the MMH operations is quantified using the model provided by Garg et al. (1978). Following Harris' assumptions, a constant demand rate, instantaneous replenishment are considered and no shortage are permitted. Next to the traditional costs, the Handling Operation Cost C_{hand} is introduced, that reveals the annual expenditure for manual material handling tasks, considering the number of repetition for each series of task and the rest allowance subsequent to the physical effort performed. Rest allowance is calculated according to the Rohmert's formula (Rohmert, W. 1973):

$$t_r = t_h \cdot 1.9 \cdot t_h^{(0.145)} \cdot \left(\frac{\bar{\dot{E}}_{job}(q)}{4.2} - 1\right)^{1.4} \quad (4.38)$$

Where $\bar{\dot{E}}_{job}(q)$ is the average metabolic expenditure in Kcal/min for a given job involving a SKU with q items inside it (see Appendix II), the parameter 4.2Kcal/min is the basic cost of work that does not require rest allowance and t_h is the MMH job duration. The Down Time cost C_{dt} is introduced in order to considers the annual expenditure due to the rest allowances resulting from the execution of a given job. During the rest period in fact, the worker is unproductive and assembly line cannot be feeded. The notation used in the model is stated below:

q	*number of items per bin*
n	*number of bins per order*
$n \cdot q$	*lot size*
w	*unit weight per item*
RWL	*Recommended Weight Limit (NIOSH)*
D	*annual demand*
K	*fixed cost of placing one order*
c	*unit purchase cost per item*
h	*unit stock holding cost per € per year including interest and depreciation in stock*
c_h	*labor cost per hour*
c_{dt}	*down time cost per hour*
t_u	*unit time for handling operation*
t_h	*time for handling operations on the entire lot* $t_h = t_u \cdot n$

t_r *resting time consequent to n handling activities on the entire lot*

C_p *purchase cost per year*

C_{ord} *ordering cost per year*

C_{hold} *stock holding cost per year*

C_{hand} *handling operation cost per year*

C_{dt} *down time cost per year*

C_{tot} *the total annual variable cost*

The total annual cost Eq.(4.39) consists of five elements: purchasing cost C_p, stock holding cost C_{hold}, ordering cost C_{ord}, handling operation cost C_{hand} and down time cost C_{dt}.

$$C_{tot} = C_p + C_{ord} + C_{hold} + C_{hand} + C_{dt} \tag{4.39}$$

The annual purchasing cost, ordering cost and stock holding cost, can be determined respectively by Eq.(4.40), Eq.(4.41), Eq.(4.42):

$$C_p = D \cdot c \tag{4.40}$$

$$C_{ord} = K \cdot \frac{D}{n \cdot q} \tag{4.41}$$

$$C_{hold} = \frac{n \cdot q}{2} \cdot h \cdot c \tag{4.42}$$

The impact of MMH tasks in inventory operations is given by Eq.(4.43) and Eq.(4.44):

$$C_{hand} = \frac{D}{n \cdot q} \cdot C_h \cdot (t_h + t_r) = \frac{D}{n \cdot q} \cdot C_h \cdot (t_u \cdot n + t_r) \tag{4.43}$$

$$C_{dt} = \frac{D}{n \cdot q} \cdot c_{dt} \cdot (t_r) \tag{4.44}$$

In the light of previous formulas Eq.(4.45) becomes:

$$C_{tot}(n, q) = c \cdot D + K \cdot \frac{D}{n \cdot q} + \frac{n \cdot q}{2} \cdot h \cdot p + \frac{D}{n \cdot q} \cdot C_h \cdot (t_h + t_r) + \frac{D}{n \cdot q} \cdot c_{dt} \cdot t_r$$

$$= c \cdot D + \frac{n \cdot q}{2} \cdot h \cdot p + \frac{D}{n \cdot q} \cdot (K + (C_h + c_{dt}) \cdot t_r) + \frac{D}{q} \cdot C_h \cdot t_u \tag{4.45}$$

The expression of total annual cost highlights the relation between the total cost $C_{tot}(n,q)$ with the variables n and q. It is easy to understand that the bi-dimensional curve that links the total annual cost with the lot size, as proposed in the traditional model by Harris (1913), is replaced by a tri-dimensional surface reporting the total cost $C_{tot}(n,q)$ upon two different variables. Although the simultaneous optimization on n and q of the total cost function C_{tot} is possible, it can lead to excessive workload and therefore to unacceptable ergonomic situations. The reason lies in the fact that in the expression of handling cost C_{hand} Eq.(4.43), the increased cost of rest allowance deriving from a greater load lifted/carried, can be lower than the economic benefit deriving from the reduction of the number of job performed per lot. As a consequence the maximum load of the container must be determined as a priority. Using the NIOSH approach, the "Recommended Weight Limit" (RWL) for the container is directly derived by Eq.(4.1). Once computed the RWL, it is possible to calculate the Lifting Index (LI) with Eq.(4.2). In this model, in order to reduce the risk of musculoskeletal disorders, the weight lifted is assumed to take a value smaller than the RWL multiplied by a Lifting Index (LI) of 0.75. The safety factor 0.75 outline the limit for the "Green Area" (Fig.(4.2)), that is the weight limit which promise an acceptable working situation and does not require any improvement action. In a good ergonomic situation the weight lifted/carried *CW* in the handling jobs, cannot exceed the limit given by Eq.(4.46):

$$CW \leq 0.75 \cdot RWL \tag{4.46}$$

By the knowledge of the unit weight per item, the maximum number of item *q* per bin is easily computable with Eq.(4.47):

$$q \leq \frac{0.75 \cdot RWL}{w} \tag{4.47}$$

In certain situations the most restrictive constraint is space. Especially in assembly lines, the space available in the supermarket or on the shelf next to the line is highly limited, therefore the boxes must be fixed a priori. The number of items per SKU is thus given approximately by Eq.(4.48):

$$q \leq \frac{\mathrm{F}}{f} \tag{4.48}$$

where F is the inner volume of a standard bin or Stock Keeping Unit (in cubic meters) and f is the size of one item unit (in cubic meters). However because of the geometric peculiarities of each item, the exact number of items per box can be defined only by experimental tests. The subsequent verification of of the LI is then required. In the light of previous formulas the number of item per bin q is determined by the most constraining between Eq.(4.47) and Eq.(4.48). As a consequence of the earlier determination of the variable q, the total cost C_{tot} can be optimized on n.

4.5.1 Case studies

In this section two different case studies derived from a real industrial situation are presented. The feeding of assembly lines involves the handling of different type of items. Some of these are very heavy (big iron or steel components) then the necessity of trolley, transpallet or fork lift arise. Others are very small and they can be carried by hand (screws, fasteners, small parts). The model here presented, is applied to the latter category of items, in order to evaluate the differences between the optimal solution according to the traditional economical approach (Harris 1913) and the optimal solution achieved with the new ergonomic conscious approach. The model implementation, calculation, and graph are carried out using the software Matlab.

Example 1: Electronic capacitor

These items are stored in a supermarket next to the assembly line where the space constraint is very restrictive. For this reason, they are contained in standardized bins whose dimensions were previously established. The nominal size of the standard bin is 600x400x147mm.

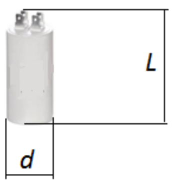


Figure 4.11. Geometrical features of the item

D *120,000 Units/Year*

K *60€/order (phone calls, e-mail, practices, receiving, load-unload)*

c *4.30 €/Unit*
h *0.25* $year^{-1}$
W *60g /Unit*
C_h *30 €/h*
t_h *1min (Lifting from pallet, carriage across the warehouse, lowering in shelf, return)*
BW *75kg (body weight of the male worker)*
V *1.3m/s (walking speed)*
c_{dt} *250 €/h*
Tare *2.2kg (weight of the standard bin)*

Geometric features

Capacitor size d=40mm; L=70mm
Bin size 600x400x147mm (inner size 544x354x109)

Considering the size of the items and the geometrical features of the standard bin, the maximum number of items per box is:

q=13 row x 5 items x 2 layer = 130items/box

The gross weight of a box CW (casing + items) is determined by Eq.(4.49) :

$$CW = \ q * W + Tare = 10kg \tag{4.49}$$

Using the approach developed by NIOSH (1991) as described above, the maximum weight allowed is calculated. By the evaluation of the tasks performed by workers during the receiving and warehousing phases, RWL is determined by Eq.(4.50):

$$RWL = 30 \cdot 0.78 \cdot 0.86 \cdot 1 \cdot 1 \cdot 0.9 \cdot 0.96 = 17kg \tag{4.50}$$

The ergonomic evaluation of the condition under consideration can be done by calculating the Lifting Index *LI* with Eq.(4.51):

$$LI = \ \frac{CW}{RWL} = \frac{10}{17} = 0.5882 < 0.75 \tag{4.51}$$

The LI reveals a very good ergonomic condition, therefore no corrective actions are required. Using the model proposed by Garg et al. (1978) the metabolic rate for the handling job performed is:

$$\bar{\dot{E}}_{\mathrm{job}}(q) = 7.23kcal/min \tag{4.52}$$

The rest allowance required after the handling job depends on the number of repetition of the job per lot Eq.(4.38). Fig.(4.12) presents the rest allowance t_r upon the number of boxes per lot n, for the case under consideration.

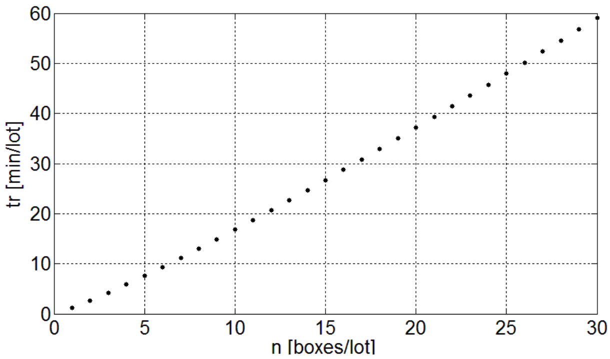


Figure 4.12. Rest allowance t_r upon n.

Fig.(4.13) presents the total annual cost $C_{tot}(n)$ in two different cases: the former (continuous line) is the traditional model of Economic Order Quantity (Harris, 1913), in which only stock holding cost C_{hold} and ordering cost C_{ord} are considered. The latter (dotted line) shows the total cost including the ergonomic impact of MMH tasks through the consideration of rest allowances in handling operation cost C_{hand}, and down time cost C_{dt}. In both cases the purchase cost is neglected.

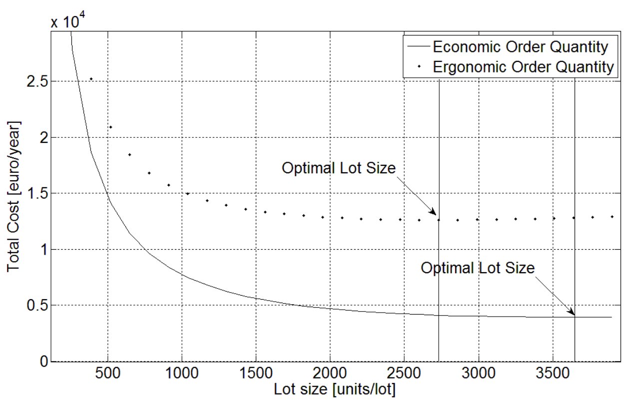


Figure 4.13. Total cost for EOQ and Ergo-EOQ (Electric Capacitors)

The optimal solutions for the two models are different. The consideration of ergonomic impact of the operations leads to a sensible reduction of the Lot Size as follows:

	Optimal Lot size [units/lot]	Optimal Lot size [SKUs/lot]
EOQ (Harris 1913)	3,660	-
Ergo-EOQ	2,730	21

Table 4.4. Optimal solution for EOQ and Ergo-EOQ (Capacitors)

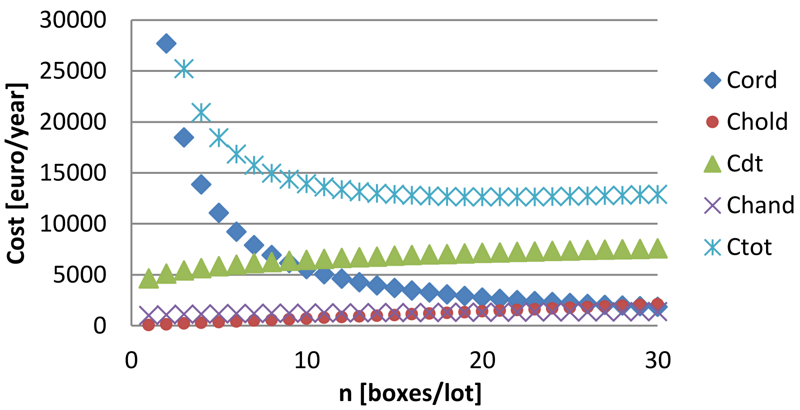


Figure 4.14. Cost functions according to variation in the number of boxes/bins ordered.

C_{tot}	12,620.95 €/year
C_{ord}	2,637.36 €/year
C_{hold}	1,467.38 €/year
C_{hand}	1,324.54 €/year
C_{dt}	7,191.67 €/year

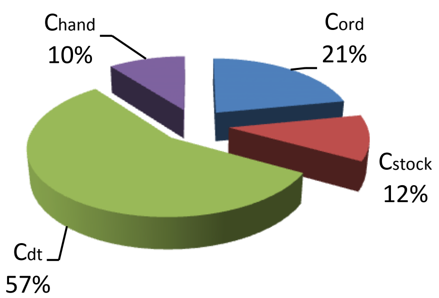


Figure 4.15. Total cost distribution for the optimal solution

Example 2: small metallic parts (screw M10x30)

It is assumed that in this case no space constraint exists, thus the quantity for each SKU is determined only in relation to the weight to be handled. The weight of the carton box is assumed to be negligible.

D   *100,000 Units/Year*

K   *60€/order*   *(phone calls, e-mail, practices, receiving, load-unload, weighing)*

c 0.226 €/Unit

h 0.22 $year^{-1}$

W 27g/Unit

C_h 30 €/h

t_h 2min (Lifting from pallet, weighing, carriage across the warehouse, lowering in shelf, return)

BW 75kg (body weight of the male worker)

V 1.3m/s (walking speed)

c_{dt} 250 €/h

The ergonomic weight of the box in an acceptable condition, according to NIOSH can be determined by Eq.(4.53):

$$CW = RWL \cdot 0{,}75 = 12.8kg \tag{4.53}$$

The maximum number of item per box is:

$$q = \frac{CW}{W} = 474\ unit/box \tag{4.54}$$

According to Garg et al. (1978) the metabolic rate for the handling job performed with a box of 12.8kg is:

$$\bar{\dot{E}}_{job}(q) = 6.365kcal/min \tag{4.55}$$

In this case the handling operations involve also weighing. The duration of the job is then longer than the other case, consequently a greater rest is expected according to Eq.(4.38). The rest allowance upon n required after the handling job is reported in Fig.(4.16).

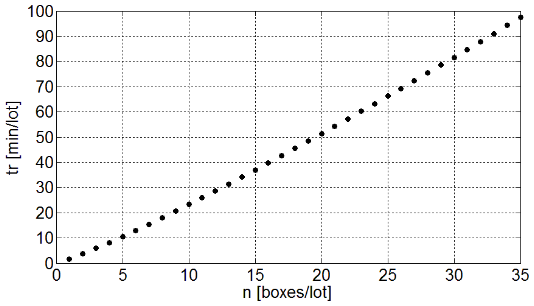


Figure 4.16. Rest allowance t_r upon n.

Fig.(4.17) reports the total cost for the traditional EOQ model (continuous line), and the total cost with MMH cost and ergonomic impact (dotted line).

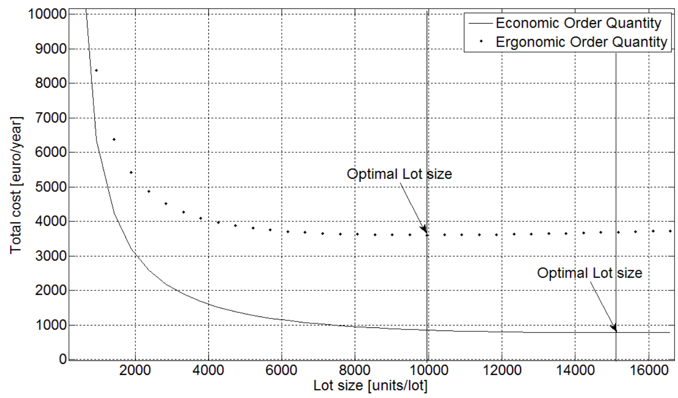


Figure 4.17. Total cost for EOQ and Ergo-EOQ (Screws)

Due to a longer duration of handling job t_h, the ergonomic impact on the total cost is heavier than in the other case, then the optimal solution with consideration of ergonomics is farther from the optimal solution provided by the traditional EOQ model. The results are shown in Tab.(4.5):

	Optimal Lot size [units/lot]	Optimal Lot size [SKUs/lot]
EOQ (Harris 1913)	15,535	-
Ergo-EOQ	9,954	21

Table 4.5. Optimal solution for EOQ and Ergo-EOQ

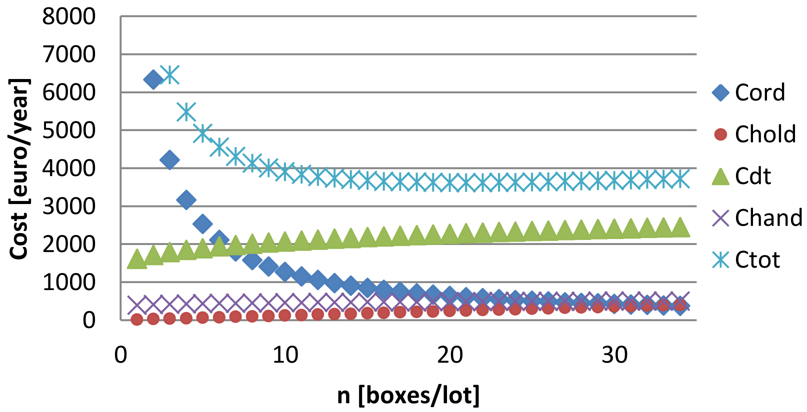


Figure 4.18. Cost functions according to variation in the number of boxes/bins ordered.

C_{tot}	3,620.08 €/year
C_{ord}	602.68 €/year
C_{hold}	247.49 €/year
C_{hand}	2,286.44€/year
C_{dt}	483.47 €/year

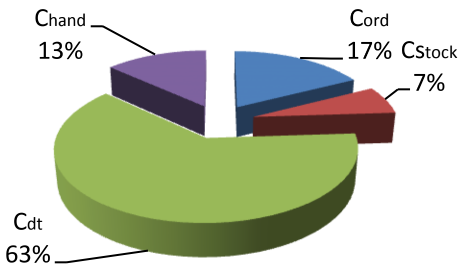


Figure 4.19. Total cost distribution for the optimal solution

The model is here applied to understand the real effect of social sustainability considerations in EOQ theory when a direct accounting method is applied. The results show that the difference between a traditional EOQ approach and social-sustainable EOQ is really interesting and the Ergo-EOQ is capable to define a value of *n* lower than the EOQ. Anyway, the limits of a direct accounting method when social aspects need to be quantified are also evident.

Appendix II

This section reports the formulas used in the model for the determination of the energy expenditure rate developed by Garg et al. (1978) . The Average energy expenditure rate of the job can be computed with the following formula:

$$\bar{\dot{E}}_{job} = \frac{\sum_{i=1}^{ni} \dot{E}_{pos} \cdot t_i + \sum_{i=1}^{n} \Delta E_{task}}{T} \quad \text{(A2.1)}$$

Where:

$\bar{\dot{E}}_{job}$ *Average energy expenditure rate of the job (Kcal/min)*

$\dot{E}_{pos}$ *Metabolic energy expenditure rate due to maintenance of* i_{th} *posture (Kcal/min)*

t_i *Time duration of* i_{th} *posture (min)*

ni *Total number of body posture employed in the job*

ΔE_{task} *Net metabolic energy expenditure of the* i_{th} *task in steady state (kcal)*

n *Total number of tasks performed in the job*

T *Time duration of the job (min)*

The total average metabolic average consumption is determined as the sum of the energy consumptions for each task that compose the job and for the maintenance of body postures, averaged over the total time of the job. This formula derives from the assumption that a job can be divided into simple activity, each of them has its metabolic cost that can be calculated with the proper formulas, as reported below. According to Garg et al. (1978) the net metabolic energy expenditure is influenced by: gender, body weight, load weight, vertical heights of lifting/lowering, lateral movements of arms in horizontal plane, speed of walking and carrying load, postures and time duration of the task. Other variables, such as age, training, size of load, speed of performing a task, temperature and humidity, have a smaller influence compared to the others aforementioned, so they are neglected in the model.

Maintenance of body postures:

Sitting $\dot{E} = 0.023 \cdot BW$ (A2.2)

Standing $\dot{E} = 0.024 \cdot BW$ (A2.3)

Standing, bent position $\dot{E} = 0.028 \cdot BW$ (A2.4)

Net metabolic cost of tasks:

Stoop lift (kcal/lift) for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.325 \cdot BW \cdot (0.81 - h_1) + (1.41 \cdot L + 0.76 \cdot S \cdot L)(h_2 - h_1)] \quad \text{(A2.5)}$$

Squat lift (kcal/lift) for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.514 \cdot BW \cdot (0.81 - h_1) + (2.19 \cdot L + 0.62 \cdot S \cdot L)(h_2 - h_1)] \quad \text{(A2.6)}$$

Arm lift (kcal/lift) for $0.81 < h_1 < h_2$

$$\Delta E = 10^{-2}[0.062 \cdot BW \cdot (h_2 - 0.81) + (3.19 \cdot L + 0.52 \cdot S \cdot L)(h_2 - h_1)] \quad \text{(A2.7)}$$

Stoop lower(kcal/lower) for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.268 \cdot BW \cdot (0.81 - h_1) + 0.675 \cdot L \cdot (h_2 - h_1) + 5.22 \cdot S \cdot (0.81 - h_1)] \quad \text{(A2.8)}$$

Squat lower(kcal/lower) for $h_1 < h_2 \leq 0.81$

$$\Delta E = 10^{-2}[0.511 \cdot BW \cdot (0.81 - h_1) + 0.701 \cdot L \cdot (h_2 - h_1)] \quad \text{(A2.9)}$$

Walking (kcal)

$$\Delta E = 10^{-2}[51 + 2.54 \cdot BW \cdot V^2 + 0.379 \cdot BW \cdot G \cdot V] \cdot t \quad \text{(A2.10)}$$

Carrying loads held against things or against waist (kcal)

$$\Delta E = 10^{-2}[68 + 2.54 \cdot BW \cdot V^2 + 4.08 \cdot L \cdot V^2 + 11.4 \cdot L + 0.379 \cdot (L + BW) \cdot G \cdot V] \cdot t \quad \text{(A2.11)}$$

Lateral movement of arms of 180 degrees, both hands (kcal/task)

$$\Delta E = 10^{-2}[0.11 \cdot BW + 0.726 \cdot L] \quad \text{(A2.12)}$$

Lateral movement of arms of 90 degrees, standing one or both hands (kcal/task)

$$\Delta E = 10^{-2}[3.31 + 0.629 \cdot L + 0.143 \cdot S \cdot L] \quad \text{(A2.13)}$$

Forward movement of arms, standing one or both hands (kcal/task)

$$\Delta E = 10^{-2} \cdot X \cdot [3.57 + 1.23 \cdot L] \tag{A2.14}$$

Where:

$\dot{E}$ *Metabolic rate (Kcal/min)*

ΔE *Kcal for walking, carrying and holding. For the other tasks, units are kcal/task*

BW *Body weight (kg)*

G *Grade of the walking surface (%)*

h_1 *Vertical height from floor (m); starting point for lift, end point for lower*

h_2 *Vertical height from floor (m); end point for lift, starting point for lower*

L *Weight of the load (kg)*

S *Gender; 1 for males, 0 for females*

t *Time (minutes)*

X *horizontal movement of arms (m)*

5 ENVIRONMENTALLY SUSTAINABLE LOT-SIZING MODEL AND MONETARY INCENTIVE COMPUTATION

5.1 The Environmental problem in the modern global purchasing scenario

The international growing concern on environmental problems stresses the need to treat inventory management and material purchasing decisions by integrating economic and environmental objectives. The increasing externalization of the EU productions in the eastern Europe and in the far east countries caused transportation issues have become very important in inventory replenishment decisions and, in practice, companies within a global sourcing context daily experience the cost of transportation as playing a major role in total purchasing costs. Furthermore, transportation activities have also a great impact on total emissions generated, along with other activities, such as ordering, warehousing and disposing of waste.

In this chapter, the material purchasing strategy is investigated by applying a bi-objective optimization model, in which the optimal purchasing lot size decision depends on two objective functions, costs and emissions, under a set of transportation constraints. These aspects deal with the “In-bound” logistics decisions according to the framework developed in chapter 3 (Fig.3.3). The emissions generated by the material purchasing order are here analyzed from the beginning to the end of the order life. Of course the transportation activity of the material quantity represents the most relevant issue by an environmental point of view, while the economic value of the inventory in hand, both during transportation lead time and both during the storage time, represents a very burdensome cost item.

The demonstration of the effect in providing monetary incentives for the deployment of low carbon purchasing strategies is then discussed and motivated by a mathematical point of view. The discussion is finally supported by a parametric analysis in which different input parameters and different efficient frontier shapes are analyzed and compared according to variations in product size, obsolescence risk and purchasing price.

5.2 Theoretical background

By an academic point of view, research on sustainability issues has considerably enriched the inventory management literature during the last four years. In particular, there are some recent studies closely related to the research activity presented in this Ph.D. thesis. In the research agenda proposed by Bonney and Jaber (2011), the authors briefly present an illustrative model that includes vehicle emissions cost into the economic order quantity (EOQ) model. Emissions associated with the storage of products are not taken into account. The order quantity is thus larger than the classical EOQ. Hua et al. (2011) extend the EOQ model to take carbon emissions into account under the cap and trade system. Analytical and numerical results are presented and managerial insights are derived. Benjaafar et al. (2013) incorporate carbon emission constraints on single and multi-stage lot-sizing models with a cost minimization objective. Four regulatory policy settings are considered, based respectively on a strict carbon cap, a tax on the amount of emissions, the cap-and-trade system and the possibility to invest in carbon offsets to mitigate carbon caps. Insights are derived from an extensive numerical study. An interactive procedure that allows the company to quickly identify the most preferred option is proposed by the authors. Jaber et al. (2013) include emissions from manufacturing processes into a two-echelon supply chain model. A different way to include sustainability criteria into inventory models is proposed in the paper of Bouchery et al. 2012, in which the authors apply a multi-objective formulation of the EOQ model abandoning the traditional approach of using a single objective function.

Anyway, the aforementioned paper considers a modeling structure equal to the classical cost function of the EOQ model and the multi-objective optimization results presented are valid as soon as the criteria are modeled by using general strictly convex functions. Interesting modeling question arises when the company need to consider also different travelling distances, different transportation mode and transportation modality practical constraints (for example in size and capacity of vehicle/containers). In practice, the traditional EOQ is strongly affected by material handling equipment, transportation flow path and transportation mode technical constraints (Tersine, 1994 and Choi and Noble, 2000; Battini et al, 2013).

The present thesis, is complementary to the existing literature aiming to better reflect real cost and emission functions arising when a company needs to purchase materials in a global supply chain environment, in which expanded travelling distance is present and different type of transportation modality are used.

The model here presented is the conceptual evolution of the work by Battini et al., 2013, in which the authors provided a "sustainable EOQ model" that incorporates the environmental impact of transportation and inventory holding in the total cost function using a direct accounting approach. According to the focus of this Ph.D. thesis, the material purchasing strategy is analyzed by applying a multi-objective optimization approach (Pareto 1964, 1971; Grierson, D.E., 2008) in which the optimal lot-sizing decision depends on a bi-objective model with two different objective functions (costs and emissions). In order to better reflect real industrial situations, transportation capacity constraints are here considered. The mathematical formulation of the two conflicting objective functions is here provided an discussed, analyzing how costs and emissions evolve over purchasing quantity under different supply chain scenario. The total cost consists of purchasing, ordering, holding, obsolesce and transportation costs. On the other hand, emissions depend on the amount of equivalent CO_2 generated during transportation, warehousing and waste management of the obsolete products, according to the Life Cycle Assessment already provided in Battini et al. 2012. Different shape of the efficient Pareto frontiers are here analyzed and compared according to variations in four influencing parameters: product weight and density, product obsolescence risk, product unitary purchasing price starting from a set of fixed input data (i.e. the annual demand, the travelling distances and the mix of transportation modes used). The model here proposed permits to introduce, for the first time, a mathematical definition of the "Monetary Incentive" necessary to push managers from cost-efficient solutions towards emission-optimal solutions. Finally, an illustration of the effect in providing monetary incentives for the deployment of low carbon purchasing strategies is discussed and motivated by a mathematical point of view.

5.3 Including environmental impact into Lot-Sizing

In this section the "In bound" issues of the lot sizing problem are discussed and analyzed using a bi-objective model considering a typical global supply chain purchasing problem, where total purchasing costs and total greenhouse gas emissions are taken into account (see Fig.(3.3)). The model is firstly applied to an example case in order to help the reader comprehension of the methodology. Then, the application is extended to different scenarios where a set of input data are fixed (the annual demand, cost and emission parameters, the travelling distances and the mix of transportation modes used) while four product features (weight, product density, obsolescence risk, purchase price) assume different values. The parametric analysis thus developed, permits to analyze the different shapes of the Pareto efficient frontiers according to variations in these key parameters and conclude that the effect in providing “carbon reduction incentives” to company will be highly beneficial to push managers in reducing emissions in purchasing strategies, though more responsible lot sizing strategies (in order to saturate containers and other handling units).

5.3.1 Mathematical formulation

The mathematical formulation that follows tries to capture economic and environmental trade-offs of lot sizing in material purchasing according to the first results obtained in Battini et al, 2013. The model here developed considers the single-product replenishment problem and applies a bi-objective optimization approach by modelling the lot sizing problem for incoming goods to be purchased by a company in accordance with two distinctive objective functions: the total annual cost function and the total emission function. The assumption of the model are listed in the following: the product demand is deterministic, the product price is exogenous and the buyer decides only the order size. The process of delivering and storing a purchasing lot of materials (from the beginning to the end of the order life) consume an amount of energy for the transportation and warehouse operations and produce an amount of emissions that will be considered in the analysis. First, the notations used in the model are presented:

INDICES:

i container/vehicle type

j transportation mode

DECISION VARIABLES AND COST FUNCTIONS:

Q decision variable [units/purchasing order]

$C(Q)$ total average annual cost of replenishment [€/year]

$E(Q)$ total annual emission generated by the replenishment [CO_{2eq}/year]

Q_c* optimal order quantity for the cost function [units/purchasing order]

Q_e* optimal order quantity for the emission function [units/purchasing order]

INPUT PARAMETERS:

D annual demand [units/year]

p unit purchase cost [€/unit]

p' unitary scrap price [€/unit]

b space occupied by a product unit with sale packaging [m^3/unit]

a weight of a unit stored in the warehouse [ton/unit]

O fixed ordering cost per order [€/order]

h holding cost [€/unit]

β obsolescence annual risk: that is the annual frequency of incurring in an inventory obsolescence event [obsolescence events/year]

y full load-vehicle/container capacity [units or m^3]

v average freight vehicle speed [km/year]

d_j distance travelled by transportation mode j [km]

$c_{f,j}$ fixed transportation cost coefficient for transportation mode j [€/km]

$c_{v,j}$ variable transportation cost coefficient for transportation mode j [€/km m^3]

$c_{ef,j}$ fixed transportation emission coefficient for transportation mode j [$kgCO_{2eq}$/km]

$c_{ev,j}$ variable transportation emission coefficient for mode j [$kgCO_{2eq}$/km m^3]

c_{eh} warehouse emission coefficient [$kgCO_{2eq}/m^3$]

c_{eo} waste collection and recycling emission coefficient [$kgCO_{2eq}$/ton]

n_i number of full load-vehicle/container i [units]

y_i full load-vehicle/container i capacity [units]

L_{tot} maximum load capacity of a container [kg]

V_{tot} maximum volumetric capacity of a container [m^3]

k range of order quantity Q_s between the two discontinuity points DP_k and DP_{k+1}

DP_k Discontinuity Point for range k, defined as $\sum_i n_i * y_i$

S freight vehicle utilization ratio in %

Unlike prior models already discussed in section 5.2, transportation and obsolescence cost are here considered explicitly and modeled according to their true discontinuity nature. Let us introduce the first objective function $f_3(Q)$ (according to the framework in Fig.(3.3)), that quantifies the average annual cost of replenishment and it is expressed as follows:

$$f_3(Q) = C(Q) = p \cdot D + C_o(Q) + C_h(Q) + C_{obs}(Q) + C_t(Q) \tag{5.1}$$

In detail, the terms included in this formulation are defined as follows (from Battini et al, 2013). The ordering cost, associated only to the buyer fixed cost of processing the order, and the holding cost are calculated according to traditional models:

$$C_o(Q) = \frac{D}{Q} \cdot O \tag{5.2}$$

Holding cost now considers both the traditional holding cost of carrying inventory in the warehouse and the cost associated to hold inventory during the transportation activity that is not as function of Q, as expressed by the following formula (derived from Axsäter and Grubbström ,1979):

$$C_h(Q) = \frac{Q}{2} h + Q\left(\frac{d}{v}\right)\left(\frac{D}{Q}\right) h \tag{5.3}$$

Where v is the freight vehicle speed expressed in km/year and d is the transportation distance. To make the application of this formulation less time-consuming as stressed in Bouchery (2012), a simple but plausible formulation for obsolescence cost is here introduced (as already presented in Battini et al, 2013). The inventory stored in the warehouse present a risk of incurring in an obsolescence event during the year. An obsolesce event comes from a specific cause (i.e. a change in the product design or in product technical specifications) and makes immediately unusable the inventory on hand. For this reasons, the obsolescence annual risk rate β is used. At the end of each year, the remaining stocks are sold by the buyer to a specific waste treatment company for disposal at the unitary scrap price p', lower than p. This formulation is very general, therefore it permits to treat the cases where the owner has to pay the waste treatment company for the disposal service. In such a situations, p' becomes negative.

$$C_{obs}(Q) = \frac{Q}{2}(p - p') \cdot \beta \tag{5.4}$$

Due to the relevance of transportation cost on the optimization of the order quantity (Zhao et al, 2004; Birbil et al., 2009), its formulation includes both fixed and variable costs and it presents Discontinuity Points DP_k when the vehicle capacity is saturated. Thus, the transportation costs are expressed with the sum of a fixed portion (in €/km since it does not increase with the order quantity but only with the travelled distance) and a variable portion (in €/km m^3) which depend on the quantity transported and on the vehicle saturation. The vehicle saturation S_j depends on the quantity transported, on vehicle capacity y_i and on the number of vehicle used in the order cycle n_i:

$$S_j = \frac{Q}{\sum_i n_i y_i} \tag{5.5}$$

Under the following constraints:

$$\sum_i n_i y_i \geq Q \tag{5.6}$$

$$y_i = \min\left(\frac{L_{tot}}{a}; \frac{V_{tot}}{b}\right) \tag{5.7}$$

Where Eq.(5.7) aims to take into account the saturation in weight or in volume. As discussed in previous studies (Zhao et al, 2004 and Birbil et al., 2009), the transportation cost is not a describable with a continuous function and it cannot be differentiated during the whole interval. Moreover, the value *n* depends on the number of different vehicle types used in the transportation (for example different containers with different capacities). In practice, in a global supply chain scenario, more types of vehicle are available with different capacities and different costs, hence it is necessary to accurately evaluate all discontinuity points and ranges between them and apply a step by step approach, as already adopted in literature. To simplify the problem, when DP_k is the Discontinuity Point *k*, obtained after the accurate evaluation of all capacity saturation ranges of different kind of container applied in the same purchasing cycle, it is possible to assert that in general:

$$S_j = \frac{Q}{\sum_i n_i y_i} = \frac{Q}{DP_k} \tag{5.8}$$

And then express the transportation cost for each kind of transportation mode j used, as follows (Battini et al, 2013):

$$C_t\left(Q, d_j, S_j\right)_j = \left[\left(c_{f,j} \cdot d_j \cdot \sum_i n_i\right) + \left(c_{v,j} \cdot d_j \cdot DP_k\right)\right] \cdot \frac{D}{Q} \tag{5.9}$$

Concluding, the first function to optimize in the “In bound” problem is finally expressed as follows (considering the whole mix of transportation modes used in the material supply from vendor to buyer):

$$\begin{aligned} f_3(Q) = C(Q) = p \cdot D + \frac{D}{Q_s} \cdot O + \frac{Q}{2} \cdot h + \left(\frac{v}{d}\right) \cdot D \cdot h + \frac{Q}{2}(p - p') \cdot \beta \\ + \left[\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k\right)\right] \cdot \frac{D}{Q} \end{aligned} \tag{5.10}$$

The second objective function $f_4(Q)$ is introduced, which measures the average total emission quantity generated during the annual purchasing activity. It can be expressed by the sum of the emissions generated in the following three steps: material order transportation, warehousing and waste collection and treatment of the obsolete items. Thus, by an environmental point of view, only three terms must be considered and homogeneously expressed in tons of CO_{2eq}.

$$f_4(Q) = E(Q) = E_h(Q) + E_{obs}(Q) + E_t(Q) \tag{5.11}$$

The first term computes the average quantity of equivalent carbon emissions generated by warehousing during the time unit of one year:

$$E_h(Q) = c_{eh}\left(\frac{Q}{2} \cdot b\right) \tag{5.12}$$

c_{eh} is the average emission coefficient of a warehouse expressed in €/m^3 of warehouse space occupied by inventory (this coefficient differs in case we use or not a temperature controlled warehouse), and b measures the volume in m^3 occupied by a product unit stored in the warehouse (considering also packaging materials).

The inventory stored in the warehouse present a risk of obsolescence at the end of the year, expressed by the obsolescence annual risk rate β. Obsolete goods at the end of the year are sold by the buyer to a specific waste treatment company for recycling at the disposal price *p'*, lower then *p*. Anyway, in this case only the emissions generated during the waste collection and treatment process are considered. Therefore:

$$E_{obs}(Q) = \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} \tag{5.13}$$

c_{eo} is the carbon emission cost coefficient for obsolete inventory waste collection and recycling, expressed in €/ton and a is the weight of an obsolete unit stored in the warehouse in tons/unit. Finally, due to the reasons described above and to the discontinuity nature of the transportation cost function, also the emission function linked to the transportation activity will be described by a discontinuous function as follows:

$$E_t\left(Q, d_j, S_j\right)_j = \left[\left(c_{ef,j} \cdot d_j \cdot \sum_i n_i\right) + \left(c_{ev,j} \cdot d_j \cdot DP_k\right)\right] \cdot \frac{D}{Q} \tag{5.14}$$

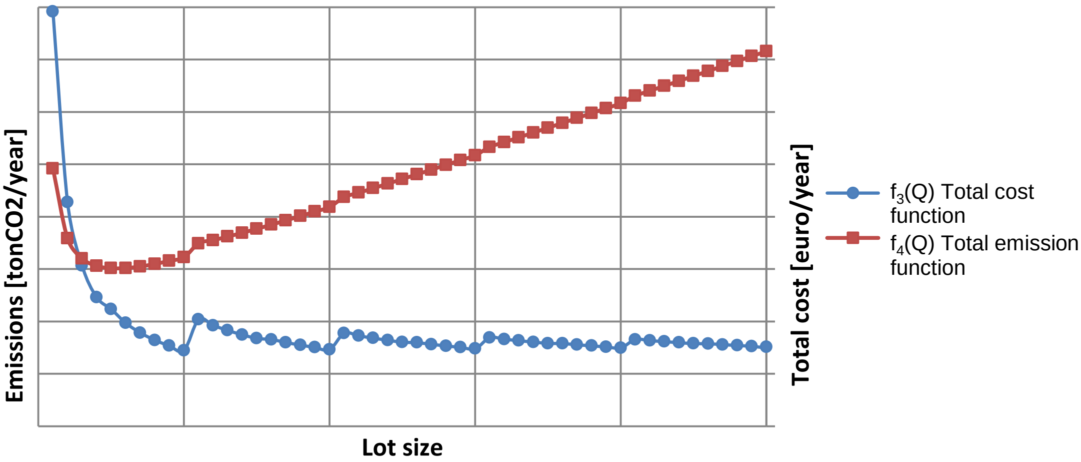
Thus, the second objective function to optimize is finally expressed as follows (considering the whole mix of transportation modes used in the material supply from vendor to buyer):

$$f_4(Q) = E(Q) = c_{eh}\left(\frac{Q}{2} \cdot b\right) + \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} + \left[\sum_j \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k\right)\right] \cdot \frac{D}{Q} \tag{5.15}$$

According to a generic Pareto design optimization problem (Pareto 1964, 1971), involving the two conflicting objective functions introduced above in Fig.(5.1), can be concisely stated as:

$$\mathit{Minimize}\ \{f_3(Q), f_4(Q)\} \tag{5.16}$$

A more detailed description of the multi-objective optimization process is reported in section 3.2.



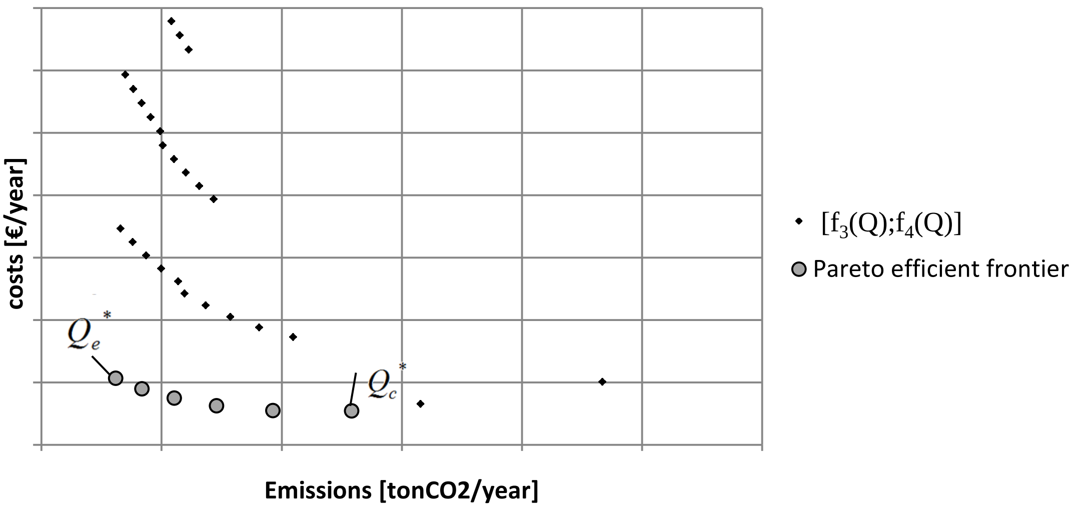


Figure 5.1. Total costs function and emissions function examples (above); set of points [f_3(Q); f_4(Q)] and Pareto efficient frontier (below)

5.3.2 Monetary incentive definition

The effect of using monetary and fiscal incentives to promote and push managers towards sustainable choices is already known in the worldwide context. Let us think to the large set of monetary incentives used by several EU Governments and their effect on the effective capital cost of solar energy technologies to the user. Let us suppose now to provide companies with monetary incentives in order to justify a sustainable purchasing of goods from overseas countries in order to optimize vehicle capacity utilization (with larger purchasing orders) and reduce empty mileage.

If Q_c^* is the single objective minimum of the objective function $f_3(Q)$ (the cost-optimal purchasing solution) and Q_e^* is the single optimal solution of $f_4(Q)$ (the emission-optimal purchasing solution) we can call EF the efficient frontier of the lot sizing problem here proposed, then:

$$EF = \left[Q_c^*, Q_e^* \right] \tag{5.17}$$

There exist $Q_{\min} < Q_{\max}$ such that $Q^* \in \left[Q_{\min,} Q_{\max} \right]$. As a consequence, the shape of *EF* strongly affect the possibility to move from a cost-optimal to an emission-optimal solution. It is now possible to define the following three measures, all related to the *EF* shape:

$$\Delta Q = Q_{\max} - Q_{\min} = \left| Q_e^* - Q_c^* \right| \tag{5.18}$$

$$\Delta C = f_3(Q_e^*) - f_3(Q_c^*) \tag{5.19}$$

$$\Delta E = f_4(Q_c^*) - f_4(Q_e^*) \tag{5.20}$$

The first one expresses by a quantitative point of view the extension of the efficient frontier curve in the space and in other words the distance between the emission-optimal solution and the cost-optimal solution.

By computing the rate $\Delta C / \Delta E$ it is possible to express the expected marginal increment in annual cost per ton CO_{2eq}. in order to move towards the emission optimal solution instead of a cost optimal solution (Fig.(5.2)).

The solution of the multi-objective problem under consideration, can be achieved using the concept of indifference band (Passy and Levanon, 1984). An indifferent band is the area on the Cartesian coordinate plane where the feasible solutions are all equally desirable to the decision maker. Between any two solutions in the indifference curve there is a trade-off, so that a decrement in the value of one objective function f_i inevitably determines an increment in the other objective function f_j.

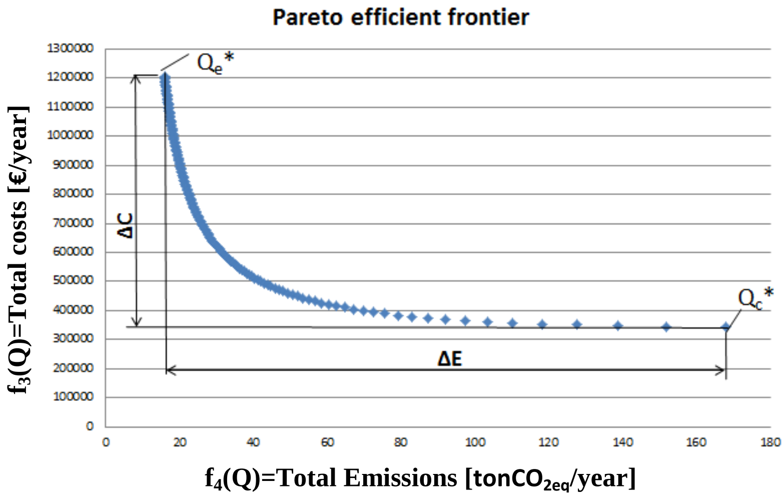


Figure 5.2. Pareto efficient frontier example

If a monetary incentives are given for the deployment of low carbon purchasing strategies, a certain increment in the first objective function *$f_3(Q)$* can be accepted by the decision maker for a certain improvement of the other objective *$f_4(Q)$*. This is called the Marginal Rate of Substitution (for a more detailed discussion see Miettinen, 1999). The Marginal Rate of Substitution m_{ij}, also called the indifference trade-off, is computed by Eq.(5.21)

$$m_{34}(Q) = \text{Monetary Incentive} = \frac{\partial f_3(Q)}{\partial f_4(Q)} = \frac{\partial C}{\partial E} \tag{5.21}$$

In this case, $f_3(Q)$ is chosen as reference function, so the marginal rates of substitution are generated with respect to it and they are expressed in €/tonCo_{2eq}. In a specific situation with certain initial data, it is necessary to generate the entire range of efficient solutions, and for each couple of optimal solutions, the marginal rate of substitution $m_{34}(Q)$ has to be calculated. Then, analyzing the values thus obtained it is possible to determine the "carbon reduction incentive" required for the deployment of low carbon strategies. Under these assumptions, the rate ΔC/ΔE can be considered as the incentive to be provided in order to move towards the emission optimal solution from the cost optimal solution, without reducing the profit for the firm.

Fig.(5.3) shows that the monetary incentive can be interpreted by a mathematical point of view as the derivative of the cost function respect to the emission function, that is the marginal increment in cost over the marginal reduction in emission. For example, to move from the starting point to a certain point 1 the expected incentive 1 must be determined through the slope of the tangent line to the graph at that point (as the marginal rate of substitution).

The more flat the efficient frontier is, the lower the increment in the necessary incentive is. On the other hand, the steeper the path in rising the efficient frontier is, the higher is the necessary incentive to push managers towards a sustainable purchasing lot size.

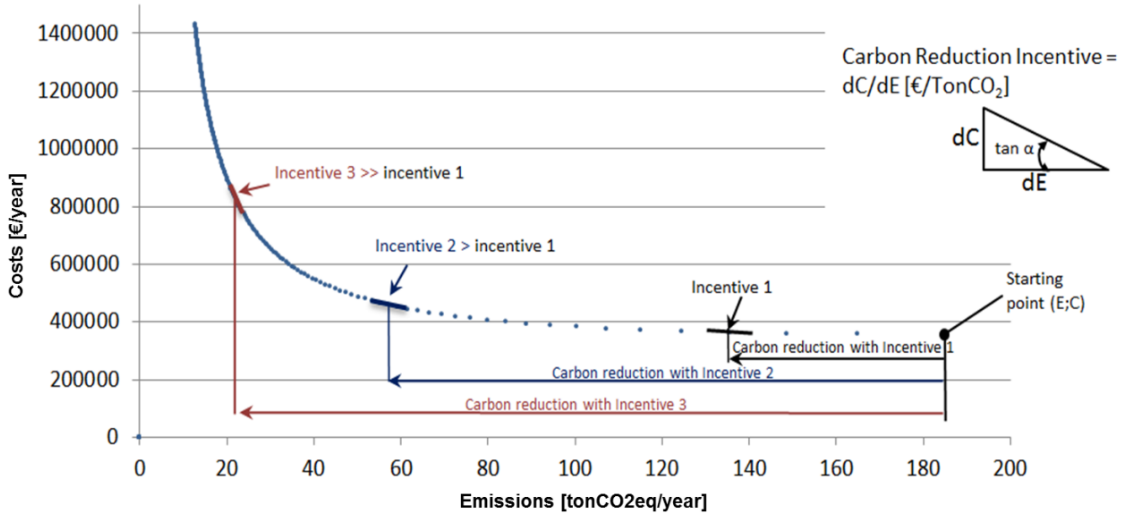


Figure 5.3. Monetary Incentive provision to reduce emissions starting from the cost-optimal lot-sizing solution.

In order to take advantage of the incentives without sacrificing the profit for the firm, the best compromise solution is obtained when the value of the marginal cost equals the Carbon Reduction Incentive provided (see Fig.(5.4)).

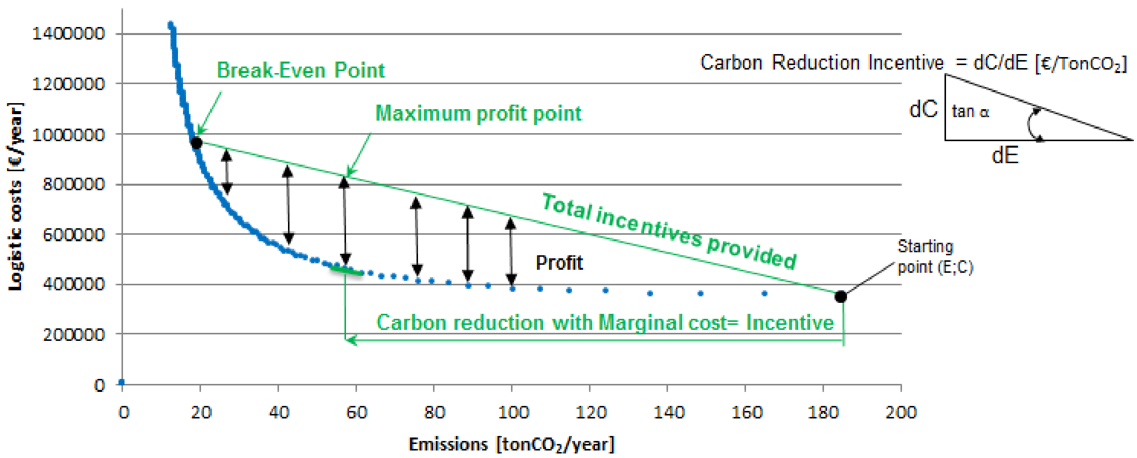


Figure 5.4. Carbon reduction incentive effect.

This solution is the so called “Maximum profit point”, where the profit for the decision maker is maximized, while having significantly reduced CO_2 emissions. This effect arises because while the slope of the Pareto frontier increases moving from the cost optimal solution towards the emission optimal one, the CRI is kept constant all along the Frontier according to the current regulations (see for example the CRC energy efficiency scheme of the UK government *https://www.gov.uk/government/policies*).

Fig.(5.4) identifies the "Break-even Point". At the "Break-even Point" the curve of the total incentive provided intersects the Pareto frontier, meaning that the incentives provided reward completely the In-Bound cost increase, allowing to obtain the best results in carbon emission reduction without generating additional profit. The choice between which of the two points to keep as objective, depends on the environmental responsibility of the decision maker.

Notice that the same reasoning can be performed considering the effect of a carbon tax (Benjaafar et al. (2013)), or the payment for the carbon price according to the European Emission Trading System (ETS) of the EU. In such situations, for each ton of CO_2 emitted, the firm has to pay a fixed additional cost. Therefore, the reduction in carbon emissions generates savings that can be considered equivalent to an economic incentive. For this reason, the curve of total incentive provided in Fig.(5.4) can be seen as the total amount of expense saved thanks to the reduction of emissions. Consequently, the “Break-even point” and the “Maximum profit point” assume the same meaning of the case discussed before.

In 5.3.4 a parametric analysis is performed in order to discuss the effect of applying different input parameters (linked to the product physical specifications) on the efficient frontier shape and monetary incentive amount.

5.3.3 Model application

The numerical application here presented is directly inspired by a real industrial case in order to illustrate the above analytical model and provide clarification in the correct sequence order in which the methodological steps should be performed. Let consider an Italian company which purchase a series of product, homogeneous in term of weight, volume and price, and let us suppose that these products are PC tablets produced by a Far East supplier located in Hong Kong. Let consider the possibility to purchase the products in analysis by adopting a rail-ship intermodal transport with only a final short handling by truck. The cost and emission functions reported in Eq.(5.10) and Eq.(5.15) are computed in relation to the set of discontinuity points DP_i identified according to the different handling units used in the purchasing network (container 1: ISO 20 feet and container 2: ISO 40 feet). Transportation costs can be easily derived from the Italian Ministry of Transport Report (2012) and carbon footprinting coefficient can be calculated using the Ecoinvent database in SimaPro Software (www.simapro.co.uk).

Constant Input Data	***Value***	***Constant Input Data***	***Value***
D	40,000	$c_{v,road}$ *[€/km*m³]*	0.01
O [€/order]	400	$c_{f,rail}$ *[€/km]*	0.6
d [km on road]	100	$c_{v,rail}$ *[€/km*m³]*	0.007
d [km by train]	500	$c_{f,ship}$ *[€/km]*	0.48
d [km by ship]	14,000	$c_{v,ship}$ *[€/km*m³]*	0.003
Inner volume container1 [m^3]	33.2	c_{eh} *[$kgCO_{2eq}$/ m^3*year]*	24
Load Capacity container1 [tons]	21.75	c_{eo} *[$kgCO_{2eq}$ / ton]*	77.004
Inner volume container2 [m^3]	67.2	$c_{ef,road}$ *[$kgCO_{2eq}$/km]*	2.20017
Load Capacity container2[tons]	26.70	$c_{ev,road}$*[$kgCO_{2eq}$ /ton*km]*	0.154398
v_{road} *[km/year]*	525,600	$c_{ef,rail}$ *[$kgCO_{2eq}$ /km]*	1.28017
v_{rail} *[km/year]*	788,400	$c_{ev,rail}$ *[$kgCO_{2eq}$ /ton*km]*	0.0392892
v_{ship} *[km/year]*	219,000	$c_{ef,ship}$*[$kgCO_{2eq}$ /km]*	0.06443
$c_{f,road}$ *[€/km]*	0.8	$c_{ev,ship}$*[$kgCO_{2eq}$ /ton*km]*	0.0088875

Table 5.1. Input data used in the application case

By applying the model described in 5.3.1 and the definition of Incentive provided in 5.3.2, under a regulatory policy based on a carbon incentive provision by the Government, a company should assess the sustainable lot sizing problem by performing the following consecutive computational steps:

Step1) Calculate the two objective functions defined in 5.3.1 according to different purchasing lot size, than build the Efficient Frontier curve and analyze its shape by building the graph reported in Fig.(5.5).

Step 2) Analyze the carbon reduction percentage achievable according to different levels of monetary incentives and different amount of product package density (see Fig.(5.6)) until obtaining an abacus as the one reported in Fig.(5.10).

Step 3) Understand for a specific product package density which is the major emission reduction achievable in practice by beneficing of the maximum incentive provided by the Government (see Fig.(5.7)). Finally understand how far the sustainable solution is from the maximum emission reduction achievable by applying an emission optimal purchasing lot size.

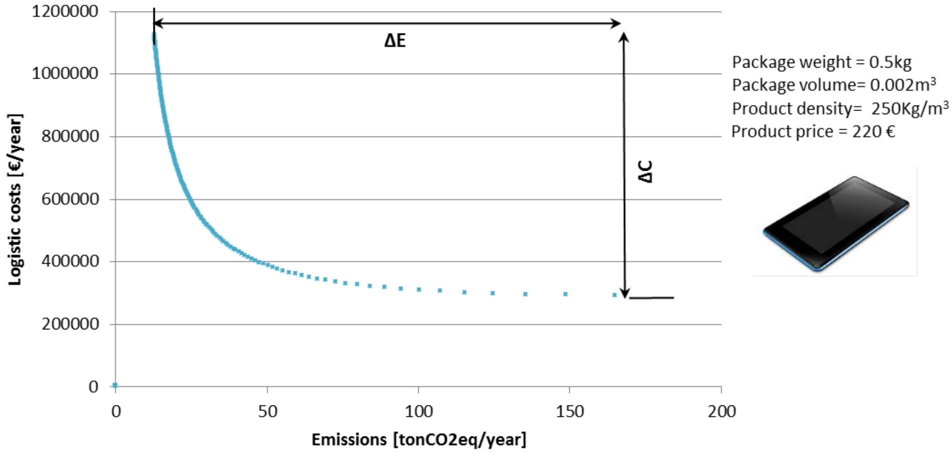


Figure 5.5. Step 1: Construction and analysis of the Efficient Frontier curve according to the product purchasing price and product physical specifications

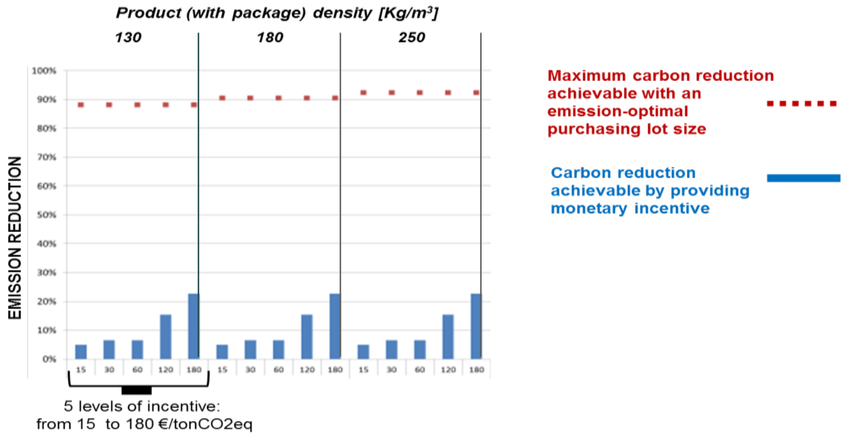


Figure 5.6. Step 2: Analysis of the emission reduction achievable by different monetary incentives (from 15 to 180 €/tonCO_{2eq}) and according to different product density

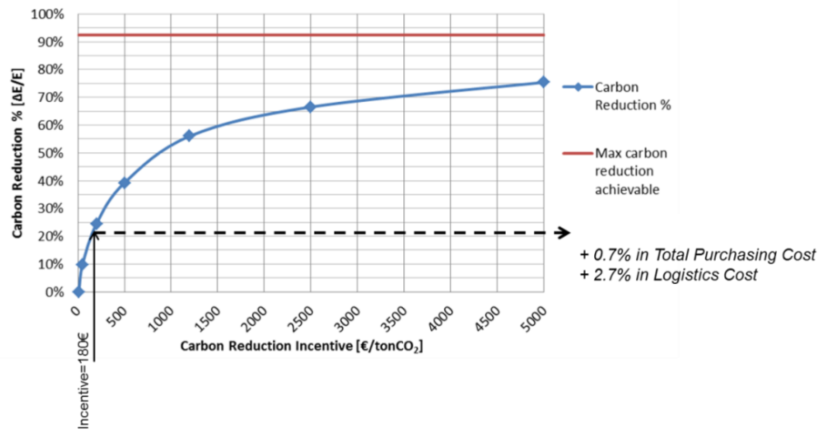


Figure 5.7. Step 3: Analysis of the emission reduction achievable by different monetary incentives and comparison with the maximum emission reduction when applying the emission-optimal lot sizing solution.

The abacus of Fig.(5.10) shows the maximum carbon reduction achievable by purchasing a lot size equal to Q_e^*instead of Q_c^* (dotted line). The incentive ($\Delta C / \Delta E$) necessary to a company to fully payback the effort done to reduce emissions to the minimum amount could be really high and higher the product price, higher the incentive necessary to move from the cost-optimal solution towards the emission optimal solution. In the example provided in Fig.(5.6) with a carbon incentive ranging from 15 to 180 €/tonCO_{2eq}. and three different product density, it is possible to payback a sustainable purchasing strategy and obtaining from 5 to 23 percent reduction in emission. By purchasing a product with a density equal to 250 kg/m3 while receiving a monetary incentive of 180 €/tonCO_{2eq}. it is possible to reduce annual emission by 23% that is about 40 tonCO_{2eq} per year less, with a total monetary annual incentive of about 7,200 €. According to *Step 3*, by coupling the graphical analysis reported in Fig.(5.5) and Fig.(5.7), it is possible finally to derive that the major cost incurred by the company without a monetary incentive provision is about the 2.7% higher than the annual logistic cost and about the 0.7% higher than the total annual purchasing cost hired by the company.

5.3.4 Parametric analysis

In this section a parametric analysis is presented, directly inspired by the real industrial case presented overhead. The product set considered in the following parametric analysis can be easily assimilated in practice to different kind of electrical and electronic equipment. All constant input parameters used in the analysis are summed up in the already shown Tab.(5.1), while the input parameters subject to variations are reported in Tab.(5.2). Tab.(5.3) lists all the dependent variables in the model, with relation to the input data. Firstly, notice that the product density ρ (with package included) has been varied, in order to generate different situations for the type of products under consideration. This variable presents a range that was established after observations of different electronic equipment (i.e. DVD reader, TV, radio, computer, etc.), considering weights and volumes of the products packaged. Using this parameter, the volume of packaging is calculated accordingly, depending on weight, as reported in Tab.(2.3). The range of volume lies between 0.005 m^3 and 0.267 m^3. The saturation of the two types of container can be achieved by volume or by weight, depending on the characteristics of the product (see Tab.(5.2) and Tab.(5.3)).

Variable Input Data	***Set of values***
p [€/unit]	[1 ; 10 ; 20 ; 40 ; 70 ; 110 ; 160 ; 220 ; 290 ; 370]
β [%]	[0.05 ; 0.15 ; 0.3]
a [tons/unit]	[0.0005 ; 0.001 ; 0.005 ; 0.01 ; 0.02]
Density ρ [kg/m^3]	[75 ; 100 ; 250 ; 500 ; 750 ;1000]

Table 5.2. Variable Input data

Dependent Variables	***Relation with variable Input Data***
b [m^3/unit]	*a/ (ρ*1000)*
p' [€/unit]	*0.5* p*
h [€/unit]	*0.25* p*
y_1 [units/contanier1]	*Min (Inner volume container1/b; Load Capacity container1/a)*
y_2 [units/container2]	*Min (Inner volume container2/b; Load Capacity container2/a)*

Table 5.3. Dependent Variables

It is necessary to observe that with low product density (ρ <250Kg/m^3), both types of containers are saturated by volume, while with high density (ρ > 750Kg/m^3) both are saturated by weight. For intermediate situations instead, the container1 is saturated by volume, while container 2 is saturated by weight. A set of 900 different scenarios have been created combining the input data, and for each situation the values of $Q_c{}^*, Q_e{}^*$,

ΔQ , ΔC and ΔE have been calculated, as described in section 5.3.1. Finally, the computation of the rate $\Delta C / \Delta E$ has been carried out, in order to express the expected marginal increment in annual cost per tonCO_{2eq}. in order to move towards an emission optimal solution instead of a cost optimal solution.

The output values thus obtained, were studied through the Analysis of Variance (ANOVA) in order to observe the variance in the mean values of these dependent variables, partitioned into components attributable to the variation of the each input parameters.

However, as in many engineering problems, when two or more independent variables are involved in a problem formulation, the "main effect" of each of the independent variables is probably not enough. In fact, the effect of one independent variable on the dependent variable of interest, may not be the same at all levels of the other independent variable. In order to find these interaction, the independent variables here considered are "crossed" with one another so that there are observations at every combination of levels of two independent variables. This statement prompt us to deepen the analysis, through the development of the “interaction plot” for ΔQ and “main effects” plots for ΔC and ΔE (Fig.(5.8)). This figure helps to understand the causality between the different sources of variation and the output considered and allows us to formulate some general findings:

- The main effect of β is almost negligible, even if, generally, an increment in the annual product obsolescence risk lead to a slight increment in ΔC. As a consequence, this parameter is excluded from the subsequent analysis;
- The increase of the product weight a, results in the quick reduction of both ΔC and ΔE, due to an optimization in the transportation vehicle saturation;
- The trend of the outputs in relation to the price p is evident in Fig.(5.8): low values of the product price p determine lower values of ΔC and ΔE, while their increase also increases the gap between the two optimal lot sizing solution $Q_c{}^*$and $Q_e{}^*$ and thus ΔC and ΔE become higher.
- As the volume occupied by a product unit (with sale packaging) b decreases, the product density obviously increases and ΔC and ΔE decreases.

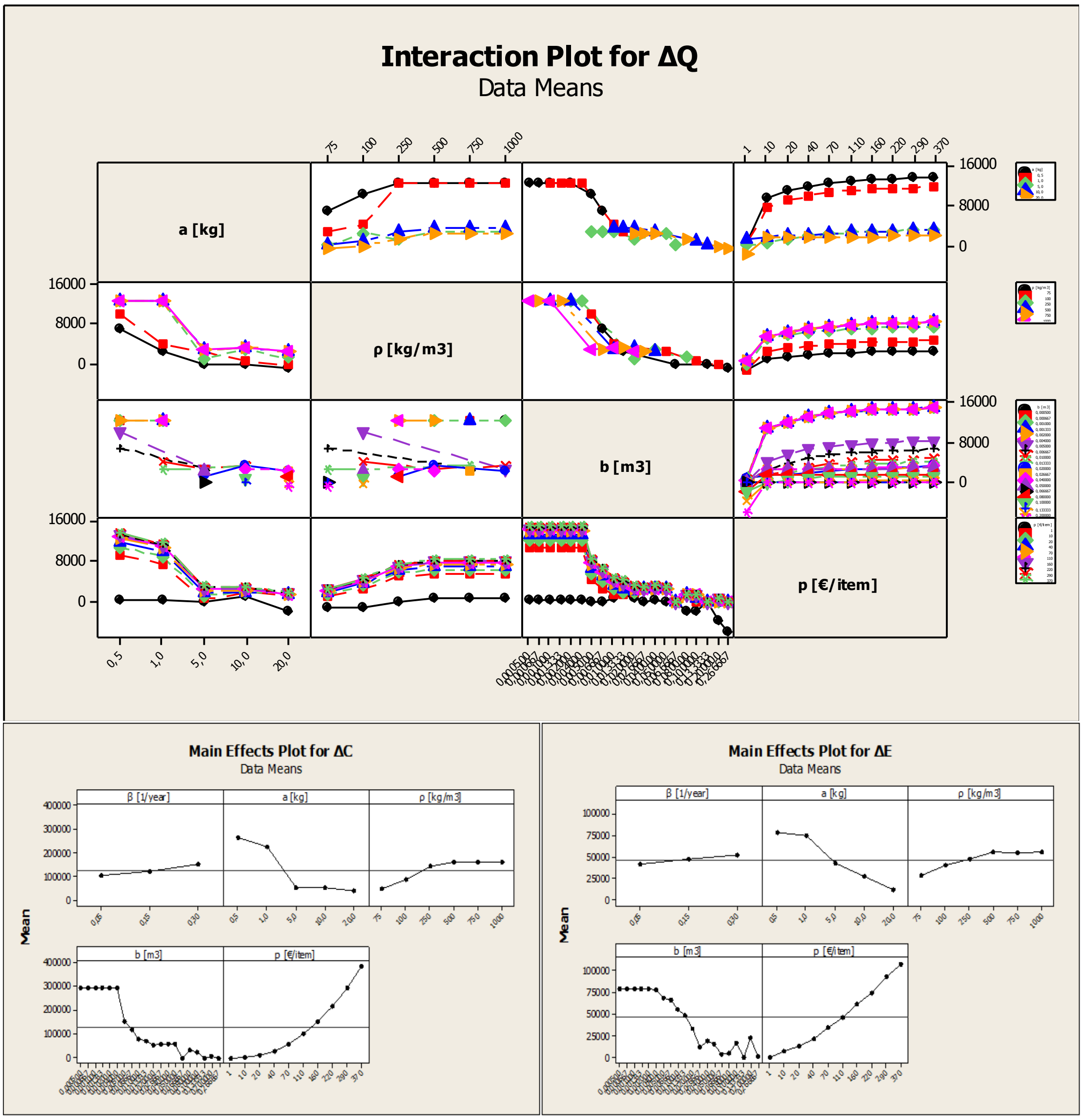


Figure 5.8. Interaction Plot of the standardized effects for ΔQ (units) and Main Effects plots for ΔC and ΔE according to variations in the product obsolescence annual rate, weight, density, volume, price.

Fig.(5.9) shows the trend of the Pareto efficient frontiers for 5 different values of product weight. Note that the scales are the same for all the graphs, in order to facilitate a visual comparison of the different frontier shapes. From first glance, it is immediately notice that as the product weight increases, the width of the frontiers reduced, then the number of Pareto optimal solutions for the problem under consideration decreases. Moreover, the efficient frontiers move towards higher values of the total emissions but at the same time the total annual costs decrease. Consequently, they move towards the right lower part of the Cartesian plane. At equal weight instead, as the product price increases, the efficient solutions move towards higher values for both costs and emissions.

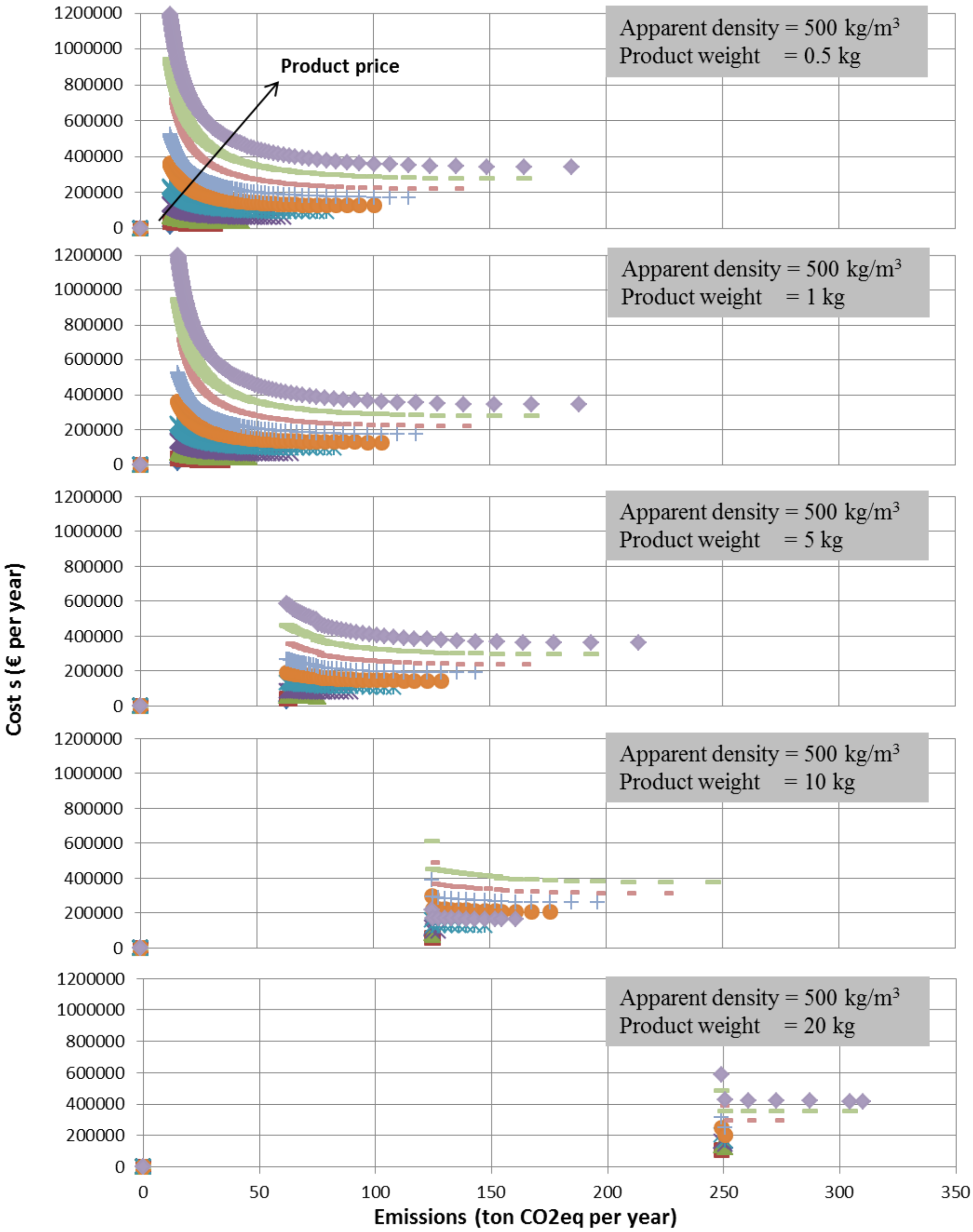


Figure 5.9. Sensitivity analysis of the Efficient Frontier according to variations in the product unitary price (with different colors) and in the product weight (from top to down).

Thus, Fig.(5.9) makes evident that the convenience of applying a sustainable lot sizing approach in a specific material purchasing case is only dependent on the efficient frontier shape: the frontier becomes larger when the price p increases and smaller when the weight increases, moving from left to right.

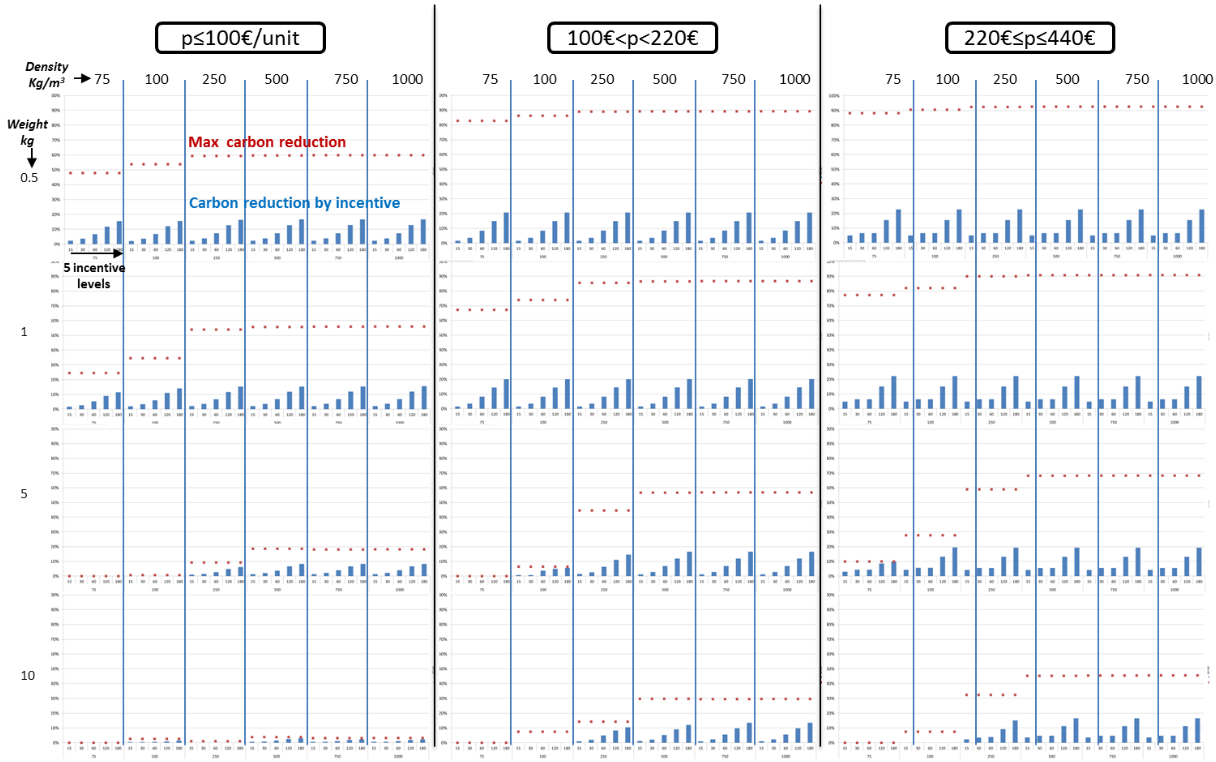


Figure 5.10. Abacus with the emission reduction achievable by different monetary incentives (bar chart) in comparison with the maximum emission reduction (dotted line) with variation in product price (from 1 to 440€), product weight (from 0.5 to 10 kg) and product density (from 75 to 1000 kg/m3).

Finally in the abacus reported in Fig.(5.10) (here the purchasing price ranges from 1 to 440 €/unit) it can be easily noticed that in the down-left portion of the abacus (i.e. for high product weight and low purchasing price) the cost optimal solution and the emission optimal solution are quite the same and vehicle saturation can be easily reached. On the contrary in the up-right portion of the abacus (i.e. with high unitary purchasing price and low product weight) the emission optimal solution is consistently far from the cost optimal solution and in order to avoid the presence of low saturated vehicle in transportation it is necessary to provide high monetary incentive. In this case, governmental actions are not sufficient to justify a “responsible” decision and only horizontal cooperation between different buyers and haulage sharing practice can become effective in reducing emission and avoiding low saturation percentage. All other intermediate situations represented in the Fig.(5.10) could be effectively assessed by providing different kind of financial and fiscal incentives to companies in order to help them paying pack the extra-cost.

By the way, the results of the parametric analysis conducted above suggest that regulatory policies based on a carbon reduction incentive should be set up according to the type of product purchased and in particular on its physical characteristics (weight and volume of the packaging unit) and on its purchasing price.

In conclusion, according to this analysis it is evident that carbon reduction incentives should be defined according to the type of product purchased and in particular to its physical characteristics (weight and volume dimension) and on its purchasing price. However, when a company is purchasing homogeneous products with high unitary purchasing price and low product weight (or volume) the emission optimal solution is consistently far from the cost optimal solution, so governmental actions could be not sufficient to justify a “responsible” decision. In such situations, only horizontal cooperation between different buyers and haulage sharing approaches can become effective in reducing emission.

6 HORIZONTAL COLLABORATION TO ACHIEVE SUSTAINABILITY IN MATERIAL PURCHASING

6.1 The “Haulage Sharing” approach

Global warming is a rising concern in academic and industrial researches and the whole community is aware that the freight transport industry is responsible for large amounts of carbon dioxide emissions contributing to global warming. Governmental initiatives are increasing in order to favor the companies that are able to operate in the global supply chain setting in a responsible way. In 2010, the freight transport sector was responsible for 2.8 GtonCO_{2eq} including international shipping (IEA, 2009), i.e. for more than 10% of global fossil-fuel based CO_2 emissions. As reported above in 5.2, recent works have highlighted and investigated the importance of transportations in inventory management. Battini et al. (2014) provide a “sustainable EOQ model” that incorporates and investigates according to an economic point of view the environmental impact of transportation and inventory. In particular, internal and external transportation costs, vendor and supplier location, and different freight vehicle utilization ratios are considered in order to provide an easy-to-use methodology. Chen et al. (2013) discuss a carbon-constrained EOQ model and investigate the applicability of a variety of Governmental regulations including carbon caps, carbon tax, cap and offsets and cap and trade. The main commonality in the aforementioned studies is the transportation strategy: a single buyer takes alone the decision of how much and when purchase a specific item from a specific vendor, according to his own cost trade-off. Nowadays, a new approach allows a change in the point of view of the problem by considering two different buyers and a cooperative approach in sharing the transportation vehicle and the transportation mode. This approach is the so called “Haulage Sharing”. In the present economic circumstances, an increase in high-mix, low-volume production and the extension of travelling paths results in lower-loading ratios and long-distance transportation (Kuse, 1998). The environmental impact of running empty commercial vehicles is very high. Worldwide Governmental Officials estimate large percentage of vehicles running with low saturation in their countries due to low purchasing quantities purchased “on demand”. In Italy, for example, according to the data reported from the Ministry of Transport, a 25 per cent of lorries and 15 per cent of vans are travelling empty, that means with a very low saturation level (www.mit.gov.it). That's over

500,000 empty lorries and vans travelling the UK's roads every day, releasing an incredible 36 million tons of CO_2 into the atmosphere every year for no good reason. By grouping different buyer's orders where possible, and by minimizing empty vehicles in the transportation path, an immediate reduction of the harmful CO_2 released into the atmosphere by freight transportation can be immediately achieved. Haulage Sharing can be easily included in the so-called "Horizontal Cooperation", which is defined by the European Union (2001) as concerted practices between companies operating at the same level in the market. Horizontal cooperation in logistics is mainly gaining momentum in Western Europe. Through close collaboration, *"the partnering aim at increasing productivity, e.g. by optimizing vehicle capacity utilization, reducing empty mileage and cutting costs of non-core/supporting activities to increase the competitiveness of their logistics networks"* (Cruijssen et al. 2007). According to the survey of Cruijssen et al. (2007), horizontal cooperation decreases empty hauling, provides a better usage of storage facilities, reduces purchasing costs (e.g. vehicles), can offer better quality of service at lower costs, e.g. in terms of speed, frequency of deliveries, geographical coverage, reliability of delivery times and enables individual companies to tender with large shippers on larger contracts. According to Leitner et al. (2011), the overlapping of transportation networks based on similar source and sink regions are both prerequisite and indication of possible cooperation synergies.

Leitner et al. (2011) highlight that the most forms of horizontal cooperation require a neutral coordinator whose tasks and duties are similar to the current service offered by a Logistic service provider. Anyway, more intense the cooperation between the partners is, the higher the resulting consolidation potential in terms of cost and emission savings is. In published literature, a few studies assess the evaluation and design of cooperative purchasing scenario by a quantitative point of view and the only examples available regard the development of Vehicle Routing Problem models (Wasner and Zapfel, 2004; Yang and Odani, 2006). Onoyama et al. in 2008 developed a genetic algorithm for planning a long-distance transportation network consisting of several mutual sub-networks such as "parts-collection networks" covering parts suppliers and depots (distribution centers) and a "long-distance transportation network" covering depots and factories. Current published works in "haulage sharing" and "cooperative logistic networks" do not yet consider multi-objective problems in which two competitive functions, costs and emissions, need to be modeled and investigated together.

In the following a three step methodology is proposed, allowing the decision maker for quickly identify the feasibility and profitability of a logistics cooperation modality, as the Haulage Sharing approach, in terms of costs and savings both in monetary value and in CO_2 emissions. The proposed method is a new combination of multi-objective analysis techniques and it is complementary to the existing literature on sustainable purchasing and lot sizing. The two examples here discussed show that horizontal cooperation could be highly beneficial in increasing the sustainability of the freight transportation sector, while reducing the total logistics costs.

6.2 The models: individual planning vs haulage-sharing

The mathematical formulation of the individual planning approach (single-product, single-buyer replenishment problem) with the associated indices and decision variables, have been extensively explained in paragraph 5.3.1, then the formulations in the following refer to the model presented by Eq.(5.1) to Eq.(5.16). A deficiency of the classical EOQ model is that goods may be purchased by a single buyer instead using cooperation between two or more buyers in order to better use and saturate the transportation facilities available in the common delivery path. The following model instead, introduces a new assumption: haulage-sharing in goods transportation is possible between two buyers when they are purchasing and transporting materials between two common points (origin and destination) through a common delivery path. Fig.(6.1) depicts the basic principle of the two models here provided.

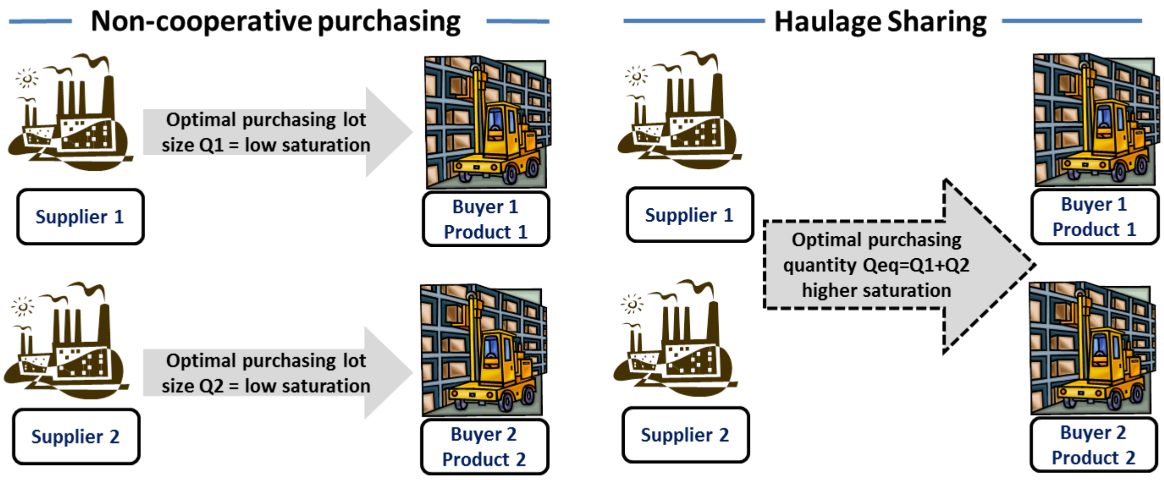


Figure 6.1. Comparison between the two approaches: individual planning on the left and Haulage Sharing on the right

The following initial assumptions need to be considered before introducing the haulage-sharing model by an analytical point of view:

i) Two different buyers are taken into consideration, each buyer purchase a specific product with specific characteristics in term of weight, size and density. These characteristics jointly with the product purchasing price and the annual average demand strongly affect the possibility to saturate containers and other handling units during each order transportation with the direct consequence that the transportation vehicle are not fully saturated.

ii) The two buyers purchase from suppliers located in the same geographical region and also the buyers are located in the same geographical region. Thus, the travelling paths during product transportation are assumed to be equal.

iii) A haulage sharing fixed cost could arise due to the new management activities and new transaction costs. In this model the haulage sharing cost is assumed to be negligible, compared to the total annual costs.

iv) A global scenario and a multi-mode transportation are here considered. Thus, the transportation activity highly contributes to the total annual costs and to total emissions generated.

The mathematical formulation that follows tries to capture economic and environmental trade-offs in material purchasing lot sizing when two different buyers are cooperating in sharing transportation facilities. The new notations are presented in the following:

DECISION VARIABLES:

Q_1 decision variable for buyer 1 [units/purchasing order]

Q_2 decision variable for buyer 2 [units/purchasing order]

$Q_{eq} = Q_1 + Q_2$ total purchasing quantity [Equivalent Product units/purchasing order]

INPUT PARAMETERS:

D_1 annual demand of buyer 1 [units/year]

D_2 annual demand of buyer 2 [units/year]

b_1 space occupied by the product unit purchased by buyer 1 [m^3/unit]

a_1 weight of the product unit purchased by buyer 1 [ton/unit]

ρ_1 apparent density of the product unit purchase by buyer 1 [kg/ m^3]

b_2 space occupied by the product unit purchased by buyer 2 [m^3/unit]

a_2 weight of the product unit purchased by buyer 2 [ton/unit]

ρ_2 apparent density of the product unit purchase by buyer 2 [kg/ m^3]

Firstly, it is necessary to establish a basic assumption in order to achieve that for each purchased transportation load the ratio between the quantities of the two products is always fixed and constant. Since this ratio is fixed, it is possible to define an Equivalent Product whose features are given by the average of the features of the two purchased products weighted on the annual demands. Q_{eq} is the total number of purchased "equivalent product" units per order by a haulage sharing approach.

$$\frac{D_1}{Q_1} = \frac{D_2}{Q_2} = n_{load} = \frac{D_{eq}}{Q_{eq}} \tag{6.1}$$

$$Q_2 = Q_1 \cdot \frac{D_2}{D_1} \tag{6.2}$$

$$Q_{eq} = Q_1 + Q_2 = Q_1 \cdot \left(1 + \frac{D_2}{D_1}\right) \tag{6.3}$$

The weight of an Equivalent Product unit becomes:

$$a_{eq} = \frac{a_1 \cdot Q_1 + a_2 \cdot Q_2}{Q_{eq}} = \frac{a_1 + a_2 \cdot \frac{D_2}{D_1}}{\left(1 + \frac{D_2}{D_1}\right)} \tag{6.4}$$

The volume of an Equivalent Product unit is:

$$b_{eq} = \frac{b_1 \cdot Q_1 + b_2 \cdot Q_2}{Q_{eq}} = \frac{b_1 + b_2 \cdot \frac{D_2}{D_1}}{\left(1 + \frac{D_2}{D_1}\right)} \tag{6.5}$$

The unitary price of an Equivalent Product unit is:

$$p_{eq} = \frac{p_1 \cdot Q_1 + p_2 \cdot Q_2}{Q_{eq}} = \frac{p_1 + p_2 \cdot \frac{D_2}{D_1}}{\left(1 + \frac{D_2}{D_1}\right)} \tag{6.6}$$

The holding cost of an Equivalent Product unit is:

$$h_{eq} = \frac{h_1 \cdot Q_1 + h_2 \cdot Q_2}{Q_{eq}} = \frac{h_1 + h_2 \cdot \frac{D_2}{D_1}}{\left(1 + \frac{D_2}{D_1}\right)} \tag{6.7}$$

The apparent density of an Equivalent Product unit is:

$$\rho_{eq} = \frac{a_{eq}}{b_{eq}} = \frac{a_1 + a_2 \cdot \frac{D_2}{D_1}}{b_1 + b_2 \cdot \frac{D_2}{D_1}} \tag{6.8}$$

It is now possible to express the two objective functions $f_I(Q)$ and $f_{II}(Q)$ for the equivalent product defined above:

$$f_I(Q_{eq}) = C(Q_{eq}) = p_{eq} \cdot D_{eq} + 2 \cdot \frac{D_{eq}}{Q_{eq}} \cdot O + \frac{Q_{eq}}{2} \cdot h_{eq} + \left(\frac{v}{d}\right) \cdot D_{eq} \cdot h_{eq} + \left[\sum_j \left(c_{f,j} \cdot d_j \cdot \sum_i n_i + c_{v,j} \cdot d_j \cdot DP_k \right)\right] \cdot \frac{D_{eq}}{Q_{eq}} \tag{6.9}$$

$$f_{II}(Q_{eq}) = E(Q_{eq}) = c_{eh}\left(\frac{Q_{eq}}{2} \cdot b_{eq}\right) + \left[\sum_j \left(c_{ef,j} \cdot d_j \cdot \sum_i n_i + c_{ev,j} \cdot d_j \cdot DP_k \right)\right] \cdot \frac{D_{eq}}{Q_{eq}} \tag{6.10}$$

As in the case of single buyer and single product problem, the next step is the multi-objective optimization of the two objective functions, as indicated below:

$$Minimize \left\{ f_I(Q_{eq}), f_{II}(Q_{eq}) \right\} \tag{6.11}$$

6.2.1 Generalization of the cooperative model to n partners

Although in practice an horizontal collaboration is easily practicable between two partners, in some cases the partner involved may be more than two. This section provides a generalization of the assumptions made before, in order to consider a situation in which *n* partners pool their transportations. The first assumption presented above Eq.(6.1) is still required to ensure the collaboration among the *n* partners along the time. With more generality it becomes:

$$\frac{D_i}{Q_i} = n_{load} = \frac{D_{eq}}{Q_{eq}} \tag{6.12}$$

for i = 1,2,3,...n

where:

$$Q_{eq} = \sum_{1=1}^{n} Q_i \tag{6.13}$$

$$D_{eq} = \sum_{1=1}^{n} D_i \tag{6.14}$$

The quantities to purchase per lot for each item Q_i are expressed by:

$$Q_i = Q_{eq} \cdot \frac{D_i}{D_{eq}} \tag{6.15}$$

The features of the Equivalent Product are given by the average of the features of the *n* purchased products weighted on the annual demands as follow:

$$a_{eq} = \frac{\sum_{1=1}^{n} a_i \cdot Q_i}{Q_{eq}} \tag{6.16}$$

$$b_{eq} = \frac{\sum_{1=1}^{n} b_i \cdot Q_i}{Q_{eq}} \tag{6.17}$$

$$p_{eq} = \frac{\sum_{1=1}^{n} p_i \cdot Q_i}{Q_{eq}} \tag{6.18}$$

$$h_{eq} = \frac{\sum_{1=1}^{n} h_i \cdot Q_i}{Q_{eq}} \tag{6.19}$$

$$\rho_{eq} = \frac{a_{eq}}{b_{eq}} = \frac{\sum_{1=1}^{n} a_i \cdot Q_i}{\sum_{1=1}^{n} b_i \cdot Q_i} \tag{6.20}$$

Once defined the features of the two equivalent product, the two objective functions $f_I(Q)$ and $f_{II}(Q)$ are applicable without any modification respect to Eq.(6.9) and Eq.(6.10).

6.3 New three-step methodology and numerical applications

Multi-objective optimization has been applied in many fields of science, including engineering, economics and logistics, where optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives. The final aim is to help in finding a single solution that satisfies the subjective preferences of one or more decision makers (Miettinen et al, 2008). The two models presented respectively in paragraphs 5.3.1 and 6.2 are here incorporated in a new methodology with the final aim to support managers' decisions when a haulage sharing approach need to be evaluated and compared with the traditional approach. The method here presented consists of three subsequent steps that allow the decision maker to quickly identify, in an interactive way, a subset of feasible solutions and finally help him to reach the best choice according to his subjective preferences (Miettinen et al, 2008). The three steps are explained in the following:

- *Step1*: Definition of the Efficient Frontier for the non-cooperative case and for the cooperative one. The set of Pareto optimal solutions is built using the two analytical models presented above in order to allow a graphical comparison between a non-cooperative transportation system and a haulage-sharing approach. The non-cooperative optimal solutions must be determined among all the combination of solutions for the two buyers taken by themselves.
- *Step2:* Quantification of the trade-offs in costs and emissions for the system made up by the two partners as a whole
- *Step*3*:* Quantification of the trade-offs in costs and emissions for the two partners separately and the forecast future average inventory levels in the two partners' warehouse.

6.3.1 Numerical applications of the Haulage sharing approach

Two different numerical cases are here presented to illustrate the method and provide some interesting observations. The two examples are directly inspired by real industrial cases coming from the electrical equipment sector:

1) *Case 1:* in the first case two European buyers purchase high-price products, with medium-high size and low annual demand, from Far East countries. The two

buyers are not able to saturate transportation units alone. Together, by applying a cooperative logistics strategy they can reach a consistent increment in the vehicle saturation percentage. The two products can be easily assimilated to real electrical equipment as for example: LCD TV32” and LCD TV 50”.

2) *Case 2:* in the second case the two European buyers purchase low-price products, with small-size and a medium annual demand, from Far East countries. The two buyers are able to saturate only the smallest handling unit alone. Together, by applying a cooperative logistics strategy, they can reach a consistent increment in the vehicle saturation percentage and use larger handling units for transportation. The two products can be easily assimilated to real electrical equipment as for example: DVD reader and Hard Disk drive.

The two cases consider both the buyer company located in the North-East part of Italy (i.e. Venice) and closed to intermodal terminals. Let consider the possibility to purchase the products in analysis from a vendor located overseas (i.e. in Hong Kong) by adopting a rail-ship intermodal transport with only a final short handling by truck.

Common input data	***Value***
O [€/order]	400
d [km on road]	100
d [km by train]	500
d [km by ship]	14,000
Inner volume container1 [m^3]	33.2
Load Capacity container1 [tons]	21.75
Inner volume container2 [m^3]	67.2
Load Capacity container2[tons]	26.70
v_{road} *[km/year]*	525,600
v_{rail} *[km/year]*	788,400
v_{ship} *[km/year]*	219,000
$c_{f,road}$ *[€/km]*	0.8
$c_{v,road}$ *[€/km*m^3]*	0.01

Common input data	***Value***
$c_{f,rail}$ *[€/km]*	0.6
$c_{v,rail}$ *[€/km*m^3]*	0.007
$c_{f,ship}$ *[€/km]*	0.48
$c_{v,ship}$ *[€/km*m^3]*	0.003
c_{eh} *[$kgCO_{2eq}$/ m^3*year]*	24
c_{eo} *[$kgCO_{2eq}$ / ton]*	77.004
$c_{ef,road}$ *[$kgCO_{2eq}$/km]*	2.20017
$c_{ev,road}$*[$kgCO_{2eq}$ /ton*km]*	0.154398
$c_{ef,rail}$ *[$kgCO_{2eq}$ /km]*	1.28017
$c_{ev,rail}$ *[$kgCO_{2eq}$ /ton*km]*	0.0392892
$c_{ef,ship}$*[$kgCO_{2eq}$ /km]*	0.06443
$c_{ev,ship}$*[$kgCO_{2eq}$ /ton*km]*	0.0088875

Table 6.1. Common input data set used in the two numerical cases

All constant input parameters used in the two numerical applications are summed up in Tab.(6.1) . In the table, transportation costs are derived from the Italian Ministry of Transport report (2013) and carbon footprinting coefficient are calculated using the Ecoinvent database by the SimaPro Software (www.simapro.co.uk).

Numerical case 1

In order to start solving the *Step 1*, the Tab.(6.2) reports on the input data set of the two buyers used in the application case 1 and the Tab.(6.3) shows the parameters computed to define the Equivalent Product specifications.

Input data: buyer 1	***Value***	***Input data: buyer 2***	***Value***
D_1	5,000	D_2	10,000
a_1 *[kg/unit]*	10	a_2 *[kg/unit]*	20
Apparent Density ρ_1 *[kg/m³]*	300	*Apparent Density* ρ_2 *[kg/m³]*	300
p_1 *[€/unit]*	250	p_2 *[€/unit]*	400

Table 6.2. Specific Input data for the two buyers: case 1

Equivalent Product specifications	***Value***
D_{eq}	15,000
a_{eq} *[kg/unit]*	16.67
Apparent Density ρ_{eq} *[kg/m³]*	300
p_{eq} *[€/unit]*	350

Table 6.3. Equivalent product specifications: case 1

By applying the two bi-objective models presented in above and by putting them in direct comparison it is possible to observe the Pareto efficient frontiers shape in the two cases: non-cooperative purchasing and haulage sharing. Fig.(6.2) reports the Pareto efficient frontiers for the two isolated buyers and for the combination of all the possible solutions adopted by the two buyers without cooperation.

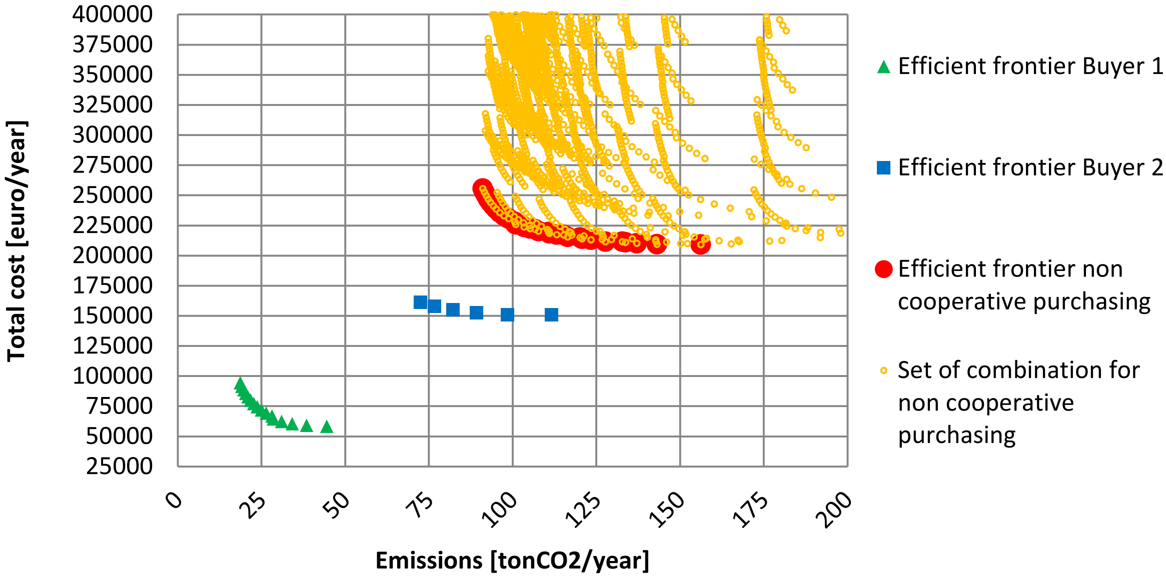


Figure 6.2. Step 1: Pareto efficient frontiers creation according to a non-cooperative transportation approach.

From Fig.(6.3) it can be noticed that the Efficient Frontier for the whole traditional system (buyer 1+ buyer2) without cooperation is positioned in an upper position respect to the haulage-sharing case. Thus, the haulage-sharing efficient frontier is dominating the non-cooperative curve. The cost optimal solution with haulage sharing brings to a consistent save in emissions due to a higher transportation vehicle saturation. In correspondence of the optimal economical solutions in the two situations, the vehicle saturation increases from an average of about 50% in the non-cooperative case to 66% in the haulage-sharing case. Examining the emission-optimal solution, it is possible to note that despite the saturation in the classical situation (buyer 1 and buyer 2 by their own) is already very high, haulage sharing provides more goods results for both the objective functions.

After these general statements, it is now interesting to understand how much it is possible to force the CO_2 emission reduction by moving from right to left in the graph of Fig.(6.3). The haulage-sharing efficient frontier shape is, in fact, shorter and more flat than the other that means that it is beneficial to sustainable lot sizing decisions, which could push to increase the purchasing product quantities in order to fully saturate containers. As described in Fig.(6.3), by purchasing the cost-optimal quantity with haulage sharing the partners spend about 194,711€/year (logistic costs), while by purchasing the emission-optimal quantity the total costs increases until reaching about 200,636€/year; that is always less if compared with the non-cooperative solution (209,171€/year). Thus, by a haulage-sharing approach the effort in moving from the right end point to the left end point of the Pareto curve is more justified and Governmental actions (incentives or carbon taxes) no more necessary.

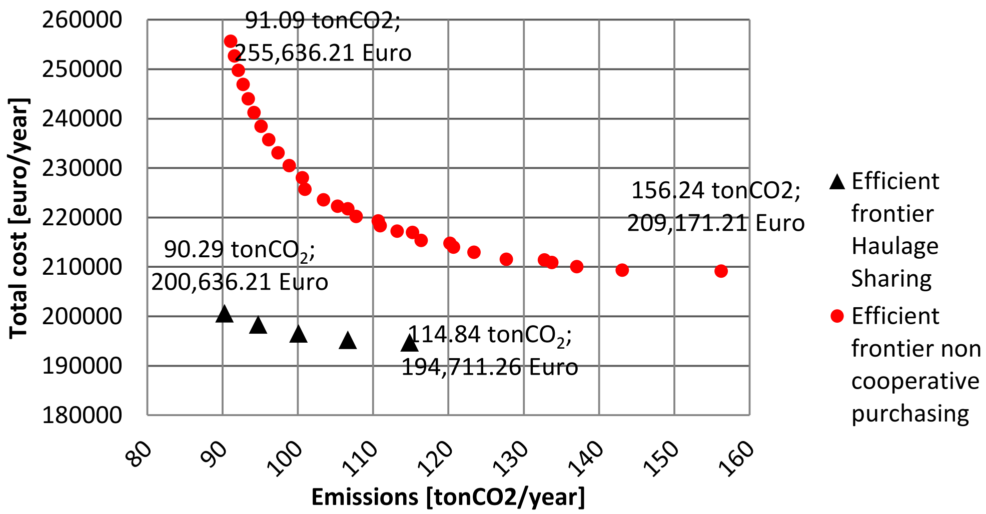


Figure 6.3. Step 1: Pareto efficient frontiers according to a non-cooperative transportation system made up by the 2 buyers and according to a haulage-sharing approach.

According to the *Step 2* of the procedure, the analysis is then focused on the system as a whole in order to further compare the results on costs and emissions obtained in a year of period with haulage sharing with the no-cooperative system (209,171€/year), as reported in Tab.(6.4). The annual cost saving provided by a haulage-sharing is always positive for the whole system even when we force the purchasing system towards higher reduction in emissions and higher vehicle saturation. Of course, as shown in Fig.(6.4), more we reduce emissions more we increase the required total logistic cost and more we reduce the saving provided by the haulage sharing respect to the traditional procedure, arriving to a minimum cost saving of 4%, which is associated to an emission saving of about 42% (about a half of the emissions generated in the non-cooperative case). Anyway, even when the cost saving is higher (about the 7% in total logistic costs) the reduction in emissions is consistent: about 26.5% less.

The same concept could be also described in terms of vehicle saturation level: Tab.(6.4) clearly shows that the haulage sharing solutions increases vehicle saturation in any case from a minimum of 66.2% until a maximum of 99.3% of saturation at lower annual logistics costs. By a no-cooperative approach the two partners should spend 27% more to obtain almost the same saturation level (99.2%).

	Haulage Sharing				***No-cooperative system***			
	Optimal purchasing lot size	Total cost [Euro/year]	Total emissions [tonCO_2/year]	Saturation Level [%]	Optimal purchasing lot size	Total cost [Euro/year]	Total emissions [tonCO_2/year]	Saturation Level [%]
Cost-optimal solution	800 Eq. Items (267 item 1 + 533 item 2)	194,711.2	114.8	**66.2%**	500 item 1 + 500 item 2	209,171.2	156.2	**50.2%** item 1 **49.6%** item 2
Emission-optimal solution	1200 Eq. Items (400 item 1 + 800 item 2)	200,636.2	90.2	**99.3%**	2000 item 1 + 1000 item 2	255,636.2	91.0	**99.2%** item 1 **99.2%** item 2

Table 6.4. Step 2: Economic and environmental optimal solutions in comparison for the whole system made up by the two partners together.

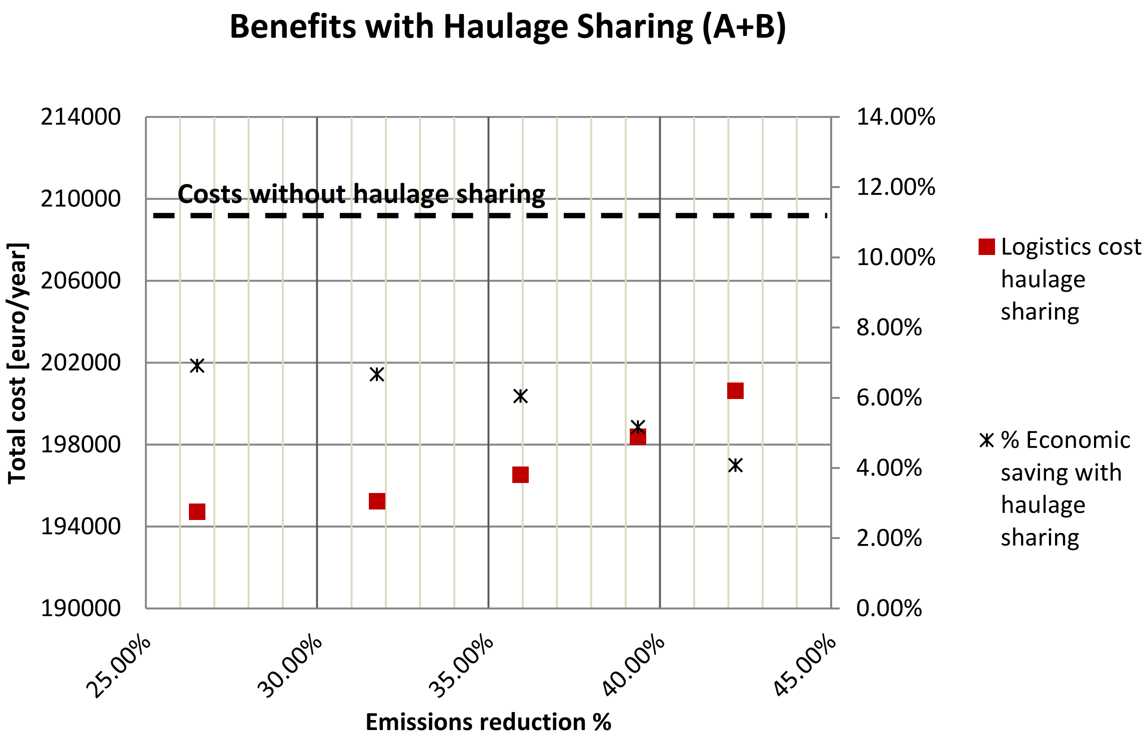


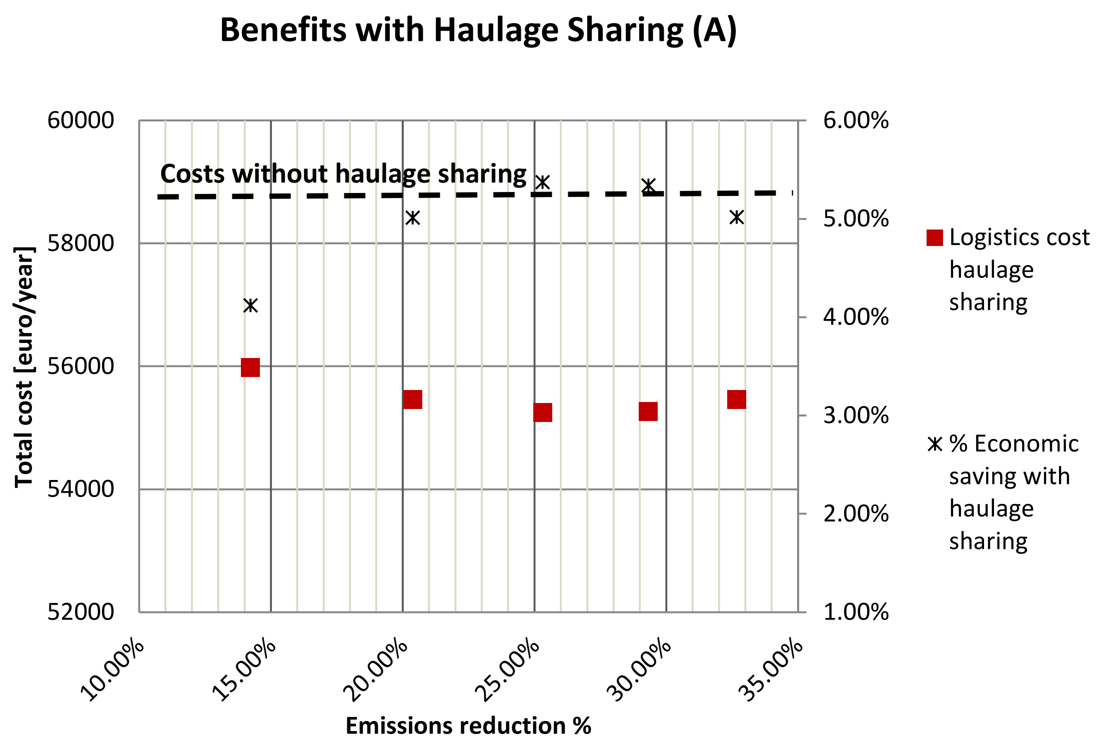
Figure 6.4. Step 2: Annual costs and % savings obtained by a haulage sharing approach for the entire system made up by the two partners together.

Finally, the third step of the procedure aims to analyze the situation by the point of view of the two single partners involved in the horizontal cooperation. Thus, it is necessary to correctly subdivide inventory costs and savings accordingly to the product effectively purchased by the two partners. For instance it is necessary to estimate the average stock level (direct function of *Q/2)* in the partners' warehouses, according to the assumption of having a constant demand rate *D* (Harris, 1913).

	Haulage Sharing			***No-cooperative system***		
	Optimal purchasing lot size	Average stock level partner1	Average stock level partner2	Optimal purchasing lot size	Average stock level partner1	Average stock level partner2
Cost-optimal solution	800 Eq. Items (267 item 1 + 533 item 2)	133.5 items	266.5 items	500 item 1 + 500 item 2	250 items	250 items
Emission-optimal solution	1200 Eq. Items (400 item 1 + 800 item 2)	200 items	400 items	2000 item 1 + 1000 item 2	1000 items	500 items

Table 6.5. Step 3: Comparison of the average stock level in the partners' warehouses

Tab.(6.5) shows the outcomes and provides an analytical proof that haulage sharing solutions are capable of increasing the saturation level of containers without considerable increasing the inventory levels at the two partners warehouses. For example, by applying the cost-optimal solution with haulage sharing, the partner 2 will increase the inventory level of only 6.8% respect to the non-cooperative system while partner 1 will not be affected by an increment in inventory. In Fig.(6.4) the haulage sharing approach is always preferable and beneficial to the entire system made up by two different buyers. Now it is necessary to understand costs and savings for the two partners distinctly. In doing this, it must be considered that the annual transportation cost will be divided proportionally to the demand rate of each partner, but inventory holding costs will be divided accordingly to the monetary value of the purchased product, that is now different for the two partners. Fig.(6.5) shows annual costs and savings computed for the two partners separately.



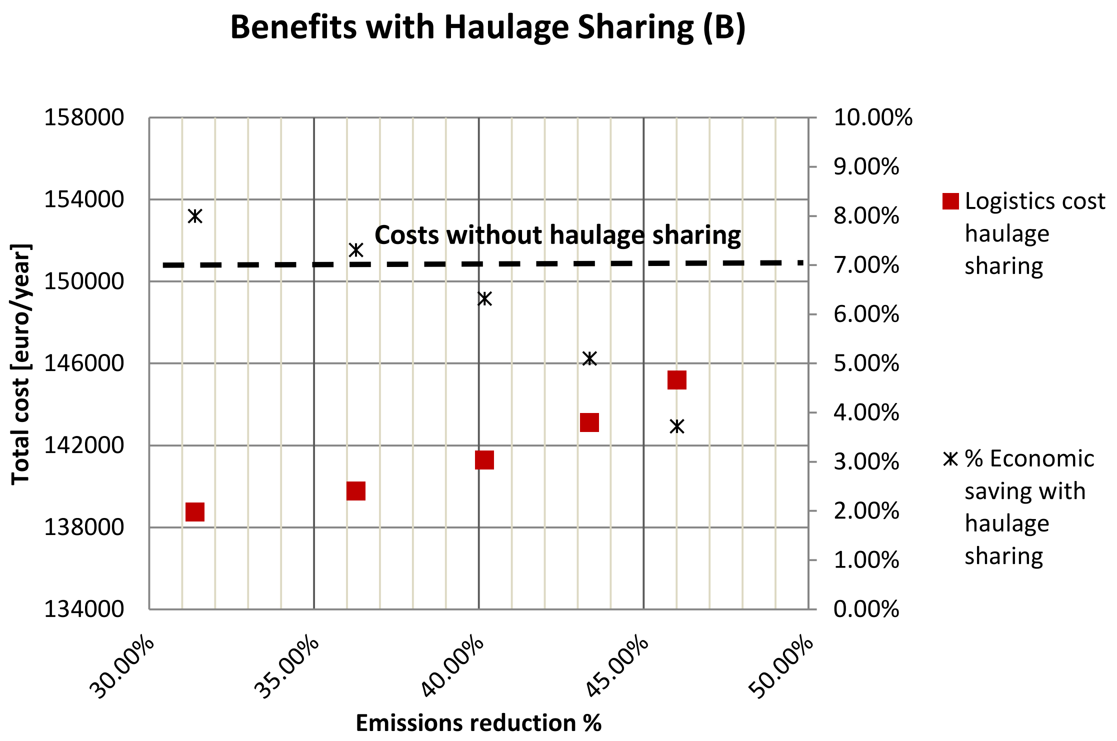


Figure 6.5. Step 3: Annual costs and % savings for each partner -analysed separately- obtained by a haulage sharing approach and comparison with the total costs of the non-cooperative solution.

Numerical case 2

The second case refers to two low-size products with medium product price and a medium annual demand. Tab.(6.6) shows the input data set of the two buyers used in the application case 2 and Tab.(6.7) shows the resulting parameters for the Equivalent Product specifications as in case 1.

Input data: buyer 1	***Value***
D_1	10,000
a_1 *[kg/unit]*	3
Apparent Density ρ_1 *[kg/m³]*	400
p_1 *[€/unit]*	50

Input data: buyer 2	***Value***
D_2	15,000
a_2 *[kg/unit]*	4
Apparent Density ρ_2 *[kg/m³]*	400
p_2 *[€/unit]*	20

Table 6.6. Specific Input data for the two buyers: case 2

Equivalent Product specifications	***Value***
D_{eq}	25,000
a_{eq} *[kg/unit]*	3.6
Apparent Density ρ_{eq} *[kg/m³]*	400
p_{eq} *[€/unit]*	32

Table 6.7. Equivalent product specifications: case 2

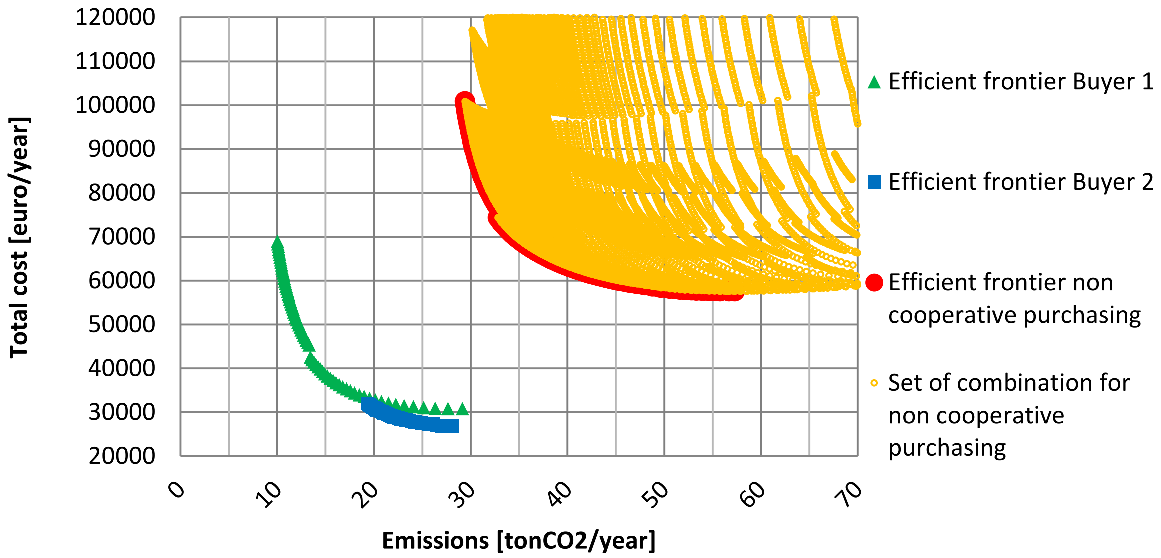


Figure 6.6. Step 1: Pareto efficient frontiers according to a non-cooperative transportation approach.

Following the three step procedure, the Fig.(6.6) reports the Pareto efficient frontiers for the two isolated buyers and for the combination of all the possible solutions adopted by the two buyers without cooperation.

As previously done in case 1, the Fig.(6.7) shows that the haulage-sharing efficient frontier shape is also in case 2 more favorable in terms of sustainability, than the classical situation (non-cooperative purchasing) since it is shorter and less steep than the other as highlighted in Tab.(6.7). It is possible to observe that the necessary growth in costs to move the system from the cost-optimal quantity to the emission-optimal quantity, is lower under a haulage-sharing approach.

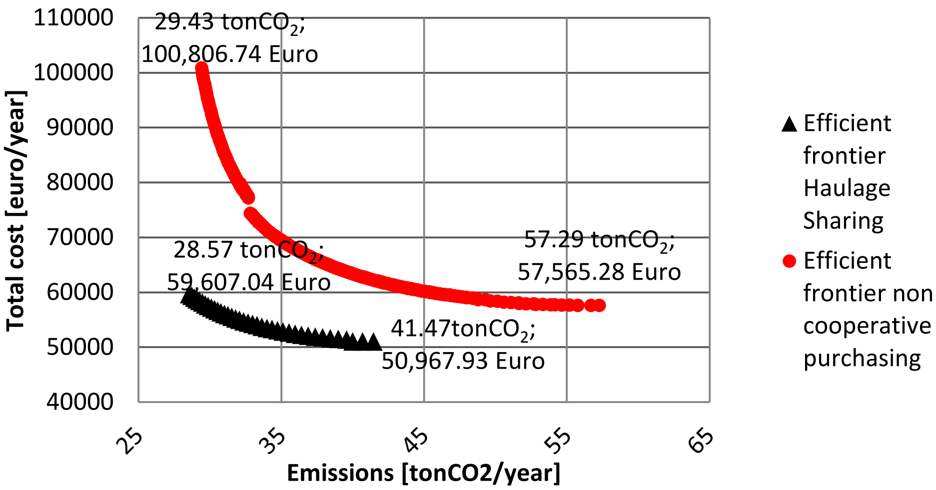


Figure 6.7. Step 1: Pareto efficient frontiers according to a non-cooperative transportation system made up by the 2 buyers and according to a haulage-sharing approach.

From Fig.(6.8) it can be noticed that the situation in case 2 is quite different with respect to case 1. Despite the efficient frontier with non-cooperative purchasing (buyer 1+ buyer2) is entirely dominated by the frontier with haulage-sharing, it is possible to find a point for which the costs of the case with sharing equals the most economical solution in the non-cooperative case. This is the so called “payback point”. Fig.(6.8) shows that the payback point provides a great improvement in terms of the whole system environmental impact, and it is possible to reduce emissions of 47.83% without any increasing in the total costs.

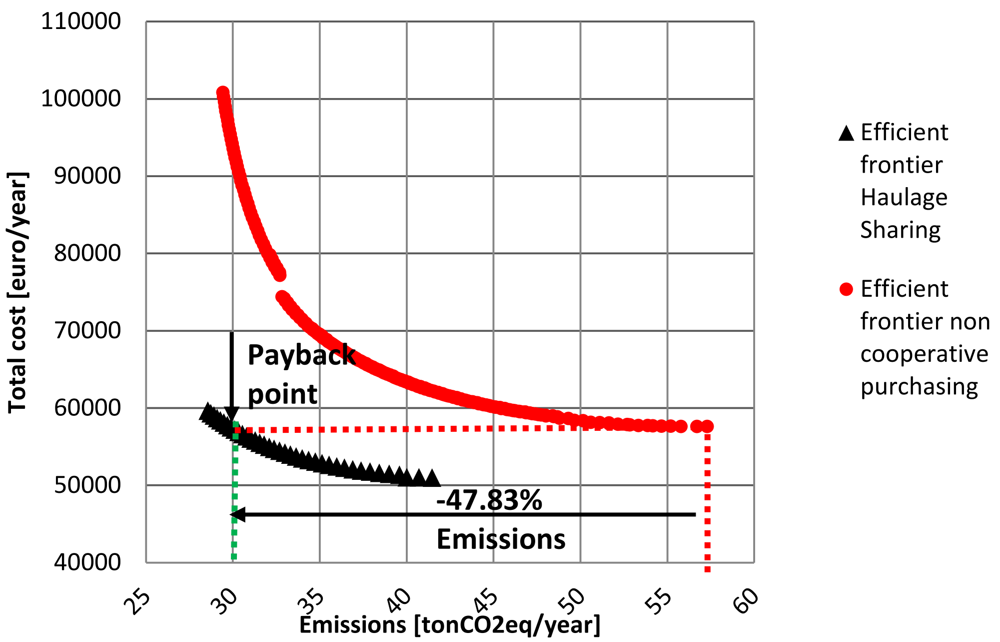


Figure 6.8. Step 1: Pareto efficient frontiers and payback point identification.

According to the Step 2 of the procedure, the analysis is then focused on the system as a whole in order to further compare the results on costs and emissions obtained in a year of period with haulage sharing with the no-cooperative system, as reported in Tab.(6.8).

	Haulage Sharing				***No-cooperative system***			
	Optimal purchasing lot size	Total cost [Euro/year]	Total emissions [tonCO_2/year]	Saturation Level [%]	Optimal purchasing lot size	Total cost [Euro/year]	Total emissions [tonCO_2/year]	Saturation Level [%]
Cost-optimal solution	3400 Eq. Items (1360 item 1 + 2040item 2)	50,967.93	41.47	92.2%	1500 item 1 + 3000 item 2	57,568.28	57.29	33.9% item 1 90.4% item 2
Emission-optimal solution	7400 Eq. Items (2960 item 1 + 4440item 2)	59,607.04	28.57	99.8%	8900 item 1 + 6600 item 2	100,806.74	29.43	100.0% item 1 98.9% item 2

Table 6.8. Step 2: Economic and environmental optimal solutions in comparison for the whole system made up by the two partners together.

The cost-optimal quantity with haulage sharing in fact, occurs at a cost of 50,968€/year (logistic costs), while the emission-optimal quantity occurs at a cost of 59,607€/year.

The same shift in the traditional case without cooperation would cost much more (from 57,568€/year to 100,807€/year). Moreover, the vehicle saturation increases from about 34% (item 1) and about 90% (item 2) in the non-cooperative case, to more than 92% in the haulage-sharing case.

However, the annual cost saving provided by a haulage sharing is not always positive when we force the purchasing system towards a higher reduction in emissions, as reported in Fig.(6.9). While the highest cost saving situation (about the 11.5% in total logistic costs) determines a carbon emissions reduction of 27.62%, the cost saving reduces up to becoming negative after the payback point. This fact determines that further improvements in environmental impact are still possible (up to a reduction of 49.8%) but they determine the total costs rise, then the decision maker is not motivated to pursue them unless Governmental actions, such as carbon reduction incentives, capable of compensate the expenditure incurred.

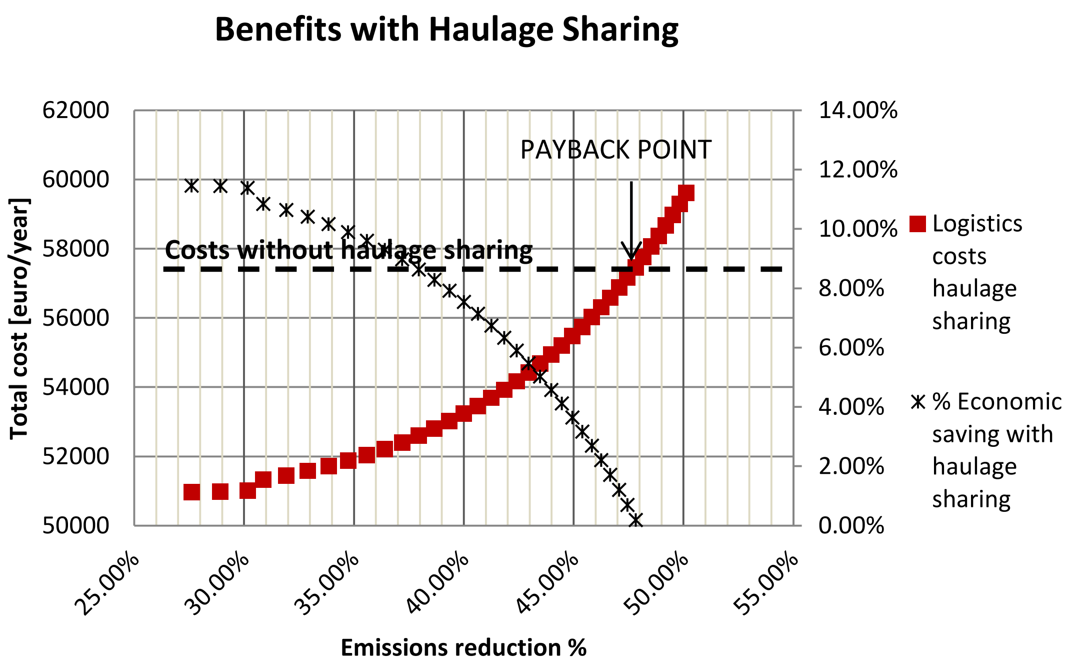


Figure 6.9. Step 2: Annual costs and % savings obtained by a haulage sharing approach according to different emission reduction rates and comparison with the total costs of a non-cooperative solution.

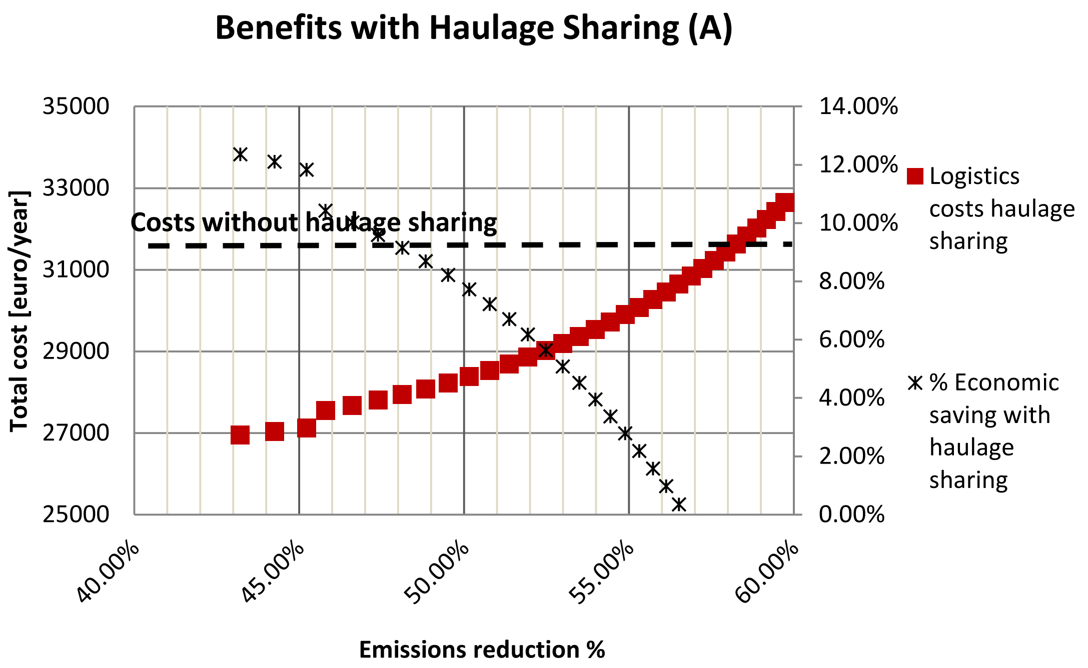
Finally, the third step of the procedure aims to analyze the situation by the point of view of the two single partners involved in the horizontal cooperation. Thus, it is necessary to correctly subdivide inventory costs and savings accordingly to the product and quantity effectively purchased by the two partners. Tab.(6.9) shows the situation of the inventory levels at the partners' warehouses.

	Haulage Sharing			***No-cooperative system***		
	Optimal purchasing lot size	Average stock level partner1	Average stock level partner2	Optimal purchasing lot size	Average stock level partner1	Average stock level partner2
Cost-optimal solution	3400 Eq. Items (1360 item 1 + 2040 item 2)	680 items	1020 items	1500 item 1 + 3000 item 2	750 items	1500 items
Emission-optimal solution	7400 Eq. Items (2960 item 1 + 4440 item 2)	1480 items	2220 items	8900 item 1 + 6600 item 2	4450 items	3300 items

Table 6.9. Step 3: Comparison of the average stock level at buyers' warehouses

Let us observe that in this case, the average stock levels at buyers' warehouses with haulage sharing are always lower than the non-cooperative system, and the major inventory reduction can be achieved with the emission-optimal solution and haulage sharing.

As performed in case 1 costs and savings are now calculated for each partner compared to his economical optimality under a no-cooperative situation. Fig.(6.10) shows the outcomes for case 2 by analyzing the two buyers' separately.



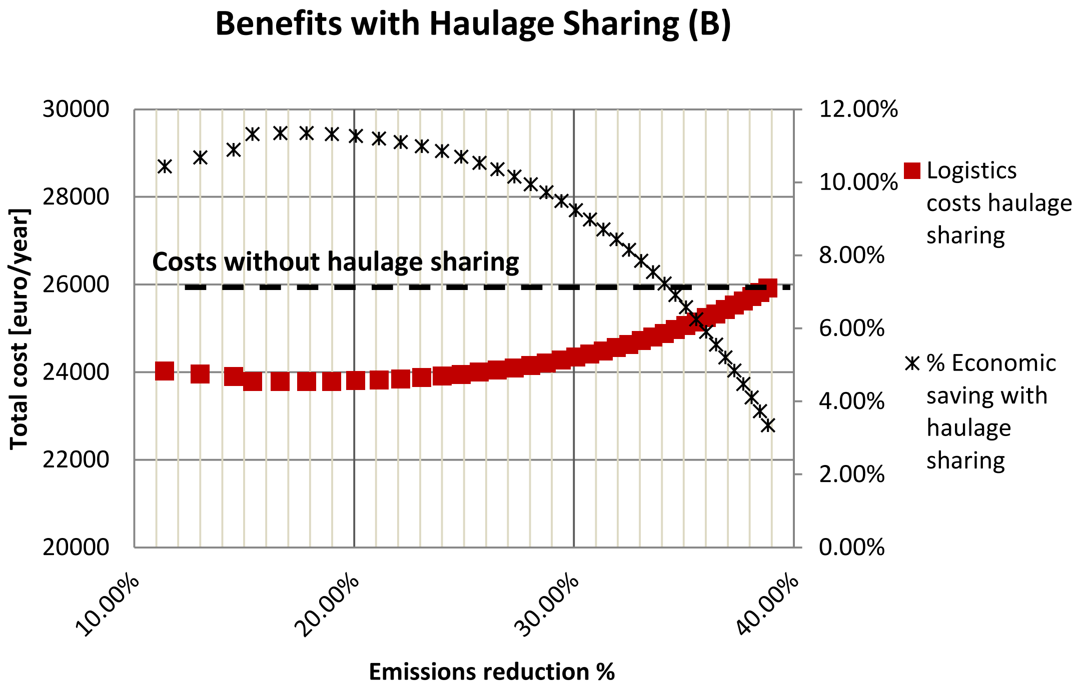


Figure 6.10. Step 3: Annual costs and % savings for each partner -analyzed separately- obtained by a haulage sharing approach and comparison with the total costs of the non-cooperative solution.

Main outcomes

Both the cases here presented find strong evidence that the haulage sharing approach could be highly beneficial both for cost and emission reduction. This concept is analytically and graphically supported here by the fact that the Pareto frontier without haulage sharing is dominated by the Pareto Frontier with haulage sharing. The maximum saving in annual cost ranges from 7% (in the case 1) to 11.5% in case 2 for the whole system, if compared with the cost-optimal solutions in the non-cooperative system, while annual emission reduction ranges from 26.5% to 42.2% according to a different lot sizing policy in case 1 and from 27.6% to 50% according to a different lot sizing policy in case 2. The vehicle saturation % increases from 50% to 66% in the case 1, and from 34% (item 1) and 90% (item 2) to 92% in case 2. These numerical results highlight that the haulage sharing approach could be high beneficial in reducing the environmental impact of material purchasing and transportation. The same successful result in emission reductions could not be reachable by a traditional no-cooperative purchasing strategy, by which, alone, the transportation vehicles cannot be efficiently saturated.

Moreover, while in case 1, the haulage sharing approach is always less expensive than the traditional one, in case 2 it presents a pay-back point in which the total cost of the no-cooperative system equalizes the haulage sharing cost. In the payback point, by hearing the same annual costs, with a haulage sharing approach it is possible to assure a reduction in emission of 47.83% for the system as a whole.

7 CONCLUSIONS

This chapter sums up the main findings of the research activities carried out in the Ph.D. course.

Chapter 2 presents a thorough literature review of the research concerning the lot sizing issue and briefly enunciates its outcomes. The first finding is that the basic EOQ model developed by Harris F.W. in 1913 is still very attractive for its simplicity and for the minimal amount of data needed. For this reason, it is frequently applied by managers in material purchasing, also right now after more than 100 years since its creation (Andriolo et al, 2014). However, nowadays we can benefit from a large and highly connected literature that is deeply analyzed in the first part of this thesis. The analysis of the literature permits us to understand the main directions of the research on Lot Sizing field carried out in the last century, and to highlight the basic requirements for the future research topics, which expect important new challenges for sustainable supply chains. Such requirements are listed above:

- The future models must design responsible inventory systems, according to Bonney and Jaber 2011, i.e. systems that reflect the needs of the environment. We need to reconsider the traditional inventory management concepts and provide new models able to include environmental aspects right from the beginning of the analysis;
- Researchers focused on sustainable lot sizing must develop new methodological approaches capable of also treating additional criteria that are difficult to quantify by traditional economical approaches, such as the social impact of inventory and purchasing decisions. Social criteria in addition to conventional economics and environmental aspects need to be assessed by applying specific approaches not always based on mathematical computations of quantitative entities. In this context, a lack of investigation is also identified in linking ergonomic aspects with lot-sizing decisions, both in production and in purchasing (Andriolo et al., 2013);
- An integrated point of view makes it necessary to assess the lot sizing problem in closed-loop supply chains. Let us only think about the planning, implementation and management of reverse and sustainable supply networks, in which waste

material becomes the raw material input to the echelon following, and CO_2 emissions must be minimized;

- According to an environmental responsible point of view, supply chain actors need to collaborate in sharing the transportations and deciding common lot sizing strategy policies in order to jointly achieve an overall sustainable development. Important results could also be achieved through horizontal cooperation among buyers.

The first innovative contribution of this PhD thesis is the development of a new methodological framework presented in *Chapter 3*, which is capable of considering all the three aspects of the 3BL paradigm (Economical, Social and Environmental sustainability) with an integrated two-step procedure. The aim of this method is to provide an easy-to-use tool to overcome the lack of quantitative methods capable of considering the social impact of inventory choices in the literature, and to couple economic and environmental aspects related to transportation and storage of the purchasing items. Logistics decisions concerning lot sizing are here divided into two main types:

- In-House decisions, that involve all the aspects and tasks performed within the production plant: Manual Material Handling (MMH) tasks, material flows, packaging, intralogistics;
- In-Bound decisions, that influences all the aspects concerning the supply of materials from the suppliers: purchasing, transportation, stock holding, waste and recycle.

The social impact of the In-House decisions is here quantified in *Chapter 4* in terms of ergonomics through the assessment of the Lifting Index developed by the National Institute for Occupational Safety and Health (NIOSH). The LI estimates the risk for the workers involved in lifting activities, which is already one of the most risky tasks for the health of workers (Murrell, 1965; Chaffin, 1972). Further refinements of the research could consider the use of different social functions, which are capable of considering different aspects of the social impact of inventory choices. The economic impact of In-House decisions includes the packaging costs and manual material handling costs, whose optimality are completely opposite respect to the social function (LI). A trade-off analysis is thus required in order to solve the problem. Such an analysis expects the definition of a "Social Responsibility Index" (SRI), that is the higher expenditure in terms of marginal cost that the decision maker is willing to incur in order to reduce the LI of an amount. The main result of this trade-off process is the determination of the most sustainable packaging unit to move on within the production plant. Further research in this field could take into account the cost of injuries, for the determination of the proper SRI that minimizes the risk for the workers without reducing the profit of the company.

Chapter 5 studies in depth the In-bound problem, and develops an innovative "sustainable EOQ model" that takes into account the environmental impact of transportation and inventory holding nearby the total cost function. The optimal Lot sizing decision depends on a bi-objective model with two different objective functions (Total costs and Carbon emissions). The model tries to describe real industrial situations, through the consideration of multimodal transportation and constraints in vehicle capacity. The total cost function includes purchasing, ordering, stock holding, obsolesce and transportation costs, while emissions depend on the amount of equivalent CO_2 generated during transportation, warehousing and waste management of the obsolete products, according to the Life Cycle Assessment. Different shape of the efficient Pareto frontiers are here analyzed and compared according to variations in four influencing parameters: product weight, product density, obsolescence risk and unitary purchasing price, starting from a set of fixed input data (i.e. the annual demand, the travelling distances and the mix of transportation modes used). This parametric analysis revealed the strong influence of product weight and price on the shape of the Pareto frontier, while product density and obsolescence risk emerged to be slightly influential. The approach here proposed permits to introduce a mathematical definition of the "Monetary Incentive" necessary to push managers from cost-efficient solutions towards emission-optimal solutions and to provide a method to estimate their effect in relation with the input parameters. The main outcomes of this study is that an unfavorable combination of product price and weight (high price and low weight) can lead to a wide and steep frontier. In such situations, incentives should be very high, therefore this way of stimulation of carbon reduction is inadequate. The aforementioned situation (high unitary price and low weight) is well known to be a typical case in which the containers travels not completely full, due to the higher cost of storage. Since transportation in long haul purchasing is the most important item both in cost and in emissions, a low saturation level of the vehicles should be avoid as much as possible.

The increasing of the saturation level of vehicles can be reached through an horizontal cooperation between buyers, as examined in *Chapter 6.* The model developed for the "single-buyer" problem is adapted to a cooperative approach, the so called "haulage sharing", in which two or more buyers can share the vehicles in the transportation through the same travelling route. In this chapter a new three step procedure is proposed in order to provide managers and logisticians with the necessary information to make a better and faster decision. The procedure is presented and applied to two different numerical cases, in which the haulage sharing approach emerged to be highly beneficial both for cost and emission reduction. The same successful result in emission reductions could not be reachable by a traditional no-cooperative purchasing strategy, by which the transportation vehicles can't be efficiently saturated. Finally, according to the results in *step* 3 of the two numerical applications, it is possible to achieve cost and emission savings for both the partners involved in the cooperation and not only for one of them. In the same way, the results demonstrate that it's possible to better saturate vehicles without increase the inventory levels at the two buyers' warehouses. The most critical task is to carefully compute, according to each specific industrial case, the payback point between the two different methodologies in order to support the decision maker towards sustainable solutions. The following aspects would be of interest to be investigated in further researches on horizontal cooperation in purchasing activities:

- The analysis of the optimal number of different partners to be involved in the logistics cooperative network and the optimal ratio among products in each load, can be helpful to maximize the performances in cost saving and carbon reduction;
- Since in most cases, the cost and emission functions yield different optimal solutions, the cost trade-offs are different from the emission trade-offs and need to be further investigated in case of different industrial sectors and different transportation modes;
- Researchers must develop new models capable of treating new additional criteria that are often difficult to quantify: for first the cost of haulage sharing that arise

when two or more partners need to be coordinated and jointly managed, and also the associated additional transaction costs;

- Legislation criteria in addition to conventional economics and environmental aspects need also to be assessed by applying specific approaches not always based on mathematical computations of quantitative entities. In this context, a lack of investigation is also identified in literature and haulage sharing method need to be supported by a consistent analysis of the available international transportation legislation.

In conclusion, this thesis has investigated the lot sizing issue, which is one of the most traditional, but still hot, topics in the inventory management field. In particular, social and environmental sustainability issues are here taken into account in order to provide useful tools for this increasingly important issue.

Innovative models have been introduced aiming to overcome some lacks in the existing literature, and their effectiveness has been evaluated using data derived from real industrial applications. The scientific value of these researches is evidenced by several publications in international journals and conferences, as visible in 1.3.

Future steps have been introduced and examined in the conclusions, in order to suggest further research activities in this important field.

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Chapter 1

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Chapter 2

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Chapter 4

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